DEVELOPMENT OF AN ELECTRIC BUS PROTOTYPE USING LITHIUM-ION BATTERY FOR THAILAND

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DEVELOPMENT OF AN ELECTRIC BUS PROTOTYPE USING LITHIUM-ION BATTERY FOR THAILAND

Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy

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สถานการณ์การใช้พลังงานจากธรรมชาติเป็นเชื้อเพลิงในภาคขนส่งโลจิสติกนับวันเพิ่มขึ้นอย่างต่อเนื่อง สิ่งที่ได้รับผลกระทบโดยตรงคือมลภาวะ รถโดยสารไฟฟ้าเป็นทางเลือกเพื่อช่วยลดปัญหานี้ได้ในหลายเมือง งานวิจัยวิทยานิพนธ์นี้มีวัตถุประสงค์นำเสนอการพัฒนา และออกแบบรถต้นแบบโดยสารไฟฟ้าที่ใช้แบตเตอรี่ลิเธียมไอออน สำหรับขนส่งมวลชนในประเทศไทย รถโดยสารไฟฟ้าต้นแบบนี้ มีขนาดความยาว 12 เมตร ใช้แบตเตอรี่ชนิดลิเธียมไอออนเป็นแหล่งเก็บพลังงานไฟฟ้า ด้วยการร่วมมือจาก มหาวิทยาลัยเทคโนโลยีสุรนารี สำนักงานกองทุนสนับสนุนการวิจัย (สกว.)โครงการพัฒนานักวิจัยและงานวิจัยเพื่ออุตสาหกรรม (พวอ.) การไฟฟ้าส่วนภูมิภาค (กฟภ.) และบริษัทอู่เชิดชัย อุตสาหกรรม จำกัด คุณสมบัติของรถโดยสารไฟฟ้าคันนี้ติดตั้งมอเตอร์ชนิดลากจูงพิกัดขนาดอัตรากำลัง 2×120 กิโลวัตต์ และมีพิกัดความจุแบตเตอรี่ขนาด 196 กิโลวัตต์ 320 แอมป์ชั่วโมง แนวคิดนวัตกรรมใหม่ได้นำมาใช้ในการออกแบบติดตั้งรถโดยสารไฟฟ้าสำหรับประเทศไทยคันนี้ กล่าวคือเป็นรถชานต่ำรองรับสำหรับคนพิการ นำเสนอเทคโนโลยีการสับเปลี่ยนแบตเตอรี่ และการเลือกใช้เทคโนโลยีการขับเคลื่อนแบบฮับมอเตอร์เพื่อช่วยลดน้ำหนักให้รถโดยสาร ในงานวิจัยนี้ได้นำเสนอการคำนวณขนาดมอเตอร์ลากจูง และแบตเตอรี่ พร้อมศึกษาทดสอบพฤติกรรมของมอเตอร์ลากจูงในห้องทดสอบ เพื่อศึกษาเปรียบเทียบอุณหภูมิการใช้งานสำหรับการออกแบบควบคุมระบบให้มีความเหมาะสมกับประเทศไทย จากผลการทดสอบพบว่าระบบควบคุมอุณหภูมิการปฏิบัติงานของมอเตอร์ต่ำกว่า 60 องศาเซลเซียสมีความเหมาะสมสำหรับการประยุกต์ใช้สำหรับประเทศไทย ยิ่งกว่านั้นได้มีทดสอบสมรรถนะบนสภาพถนนจริงเป็นระยะทางมากกว่า หนึ่งพันกิโลเมตร และศึกษาอัตราการสิ้นเปลืองพลังงาน โดยออกแบบการทดสอบ 8 รูปแบบ พบว่าอัตราการสิ้นเปลืองพลังงานมีค่าเฉลี่ย 0.883 กิโลวัตต์ชั่วโมงต่อกิโลเมตร และยังพบว่าตัวแปรสำคัญที่มีผลกระทบต่อการสิ้นเปลืองพลังงานมากที่สุดคือ ความเร็วการขับเคลื่อน จำนวนผู้โดยสาร และพฤติกรรมคนขับ ทั้งนี้งานวิจัยได้นำเสนอการวิเคราะห์เชิงเศรษฐศาสตร์เบื้องต้นด้วย

สาขาวิชา วิศวกรรมไฟฟ้า
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ลายมือชื่อนักศึกษา สุชาติ พันธุ์ไพศาล.
ลายมือชื่ออาจารย์ที่ปรึกษา

SUCHART PUNPAISARN : DEVELOPMENT OF AN ELECTRIC BUS PROTOTYPE USING LITHIUM-ION BATTERY FOR THAILAND. THESIS ADVISOR : ASSOC. PROF. THANATCHAI KULWORAWANICHPONG, Ph.D., 124 PP.

ELECTRIC VEHICLE/ELECTRIC BUS/LITHIUM-ION BATTERY/ZERO EMISSION

The situation of natural power consumption in logistic and public transportation is continue raising up. The air pollution is directly affected, electric bus is the alternative options for this issue. This thesis presents electric bus development using lithium-ion battery challenges and achievement design that suitable for public transportation in Thailand. The prototype of 12 meters long electric bus with lithium-ion battery is established by co-operation from Suranaree University of Technology (SUT), Research and Researchers for Industries of Thailand (RRI), Provincial Electricity Authority (PEA), and Cherdchai Industrial Factory Co., Ltd. The 2×120 kW rated power of traction motor and the power battery capacity of 196 kWh 320 Ah are installed for 190 km driving per charge. This electric bus design is innovated by concept of low floor bus for wheel chair, an alternative electric charging option by battery swapping technology, and wheel hub motor technology for weight reduction. In this thesis, the traction motor and battery sizing design program are provided. Moreover, the traction motor simulation and test in laboratory test bench results are compared in several operation temperature at 25, 60, and 120 °C as case study. It shows that traction motor has good performance at below 60°C that results are used to evaluate for operation temperature of vehicle control system design. Furthermore, the electric bus driving test over one thousand kilometers in real road condition results are also presented. Eight scenarios studied cases are settled to investigate the power consumption analysis. The driving test results express the power consumption rate of this electric bus is 0.883 kWh/km. Parameters of power consumption effectiveness are driving speed, amount of passenger, and driver behavior from this test. In additional, the power consumption rate comparison of electric bus and conventional engine bus are studied as same as route and condition. In power consumption rate data are interpreted to cost expense, shows electric bus can save cost by lower than engine bus 43-56% in the same route condition. This electric bus has passed qulification related to verhicle performance and safety regulation in Department of Land Transport (DLT) of Thiland prior to the public operation. The simple economic consideration analysis study is also presented.

School of Electrical Engineering Student's Signature Suchart Pumpaisarn

Academic Year 2018 Advisor's Signature

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SYMBOLS AND ABBREVIATIONS

A	is	Area
a	is	Vehicle acceleration
A_f	is	Front area of the vehicle
c	is	Tire Count
C_A	is	Acquisition cost
C_{Ah}	is	Traction battery package capacity
C_D	is	Aerodynamic drag coefficient
C_t	is	Sum of relevant Life Cycle Cost
Capacity	is	Total passengers in bus capacity (person)
f_0	is	Constant of vehicle running
f_1	is	Negligible for simplification
f_r	is	Rolling resistance coefficient
F_{drag}	is	Gravitational force (gradient force) of vehicle
F_R	is	Resistance force of vehicle
F_{RR}	is	Rolling resistance force of vehicle
F_T	is	Tractive effort of vehicle
g	is	Acceleration of gravitational constant
i	is	Sun's incidence angle on glass

SYMBOLS AND ABBREVIATIONS (Continued)

i_g	is	Gear ratio of transmission
i_0	is	Gear ratio of final drive
K_{ev}	is	Average energy consumption per kilometer
K_{soc}	is	Discharge coefficient
M	is	Total mass of the vehicle
M_{eff}	is	Total mass of vehicle
N_m	is	Motor speed
n	is	Analyzed Period
P_t	is	Tractive power
r	is	Discount Rate (time value of money)
r_d	is	Radius of the drive wheel
S_{bat}	is	Electric range
τ	is	Transmissivity of glass.
T	is	Temperature
t_a	is	Expected acceleration time
T_m	is	Motor torque
Ug	is	Overall heat transfer coefficient of glass
Us	is	Overall heat transfer coefficient of metal sheet
V_b	is	Motor-base speed

SYMBOLS AND ABBREVIATIONS (Continued)

V_{bus}	is	DC bus voltage
V_f	is	Final speed of the vehicle during acceleration speed
V_W	is	Wind speed on moving direction.
W	is	Wheel load
ρ_a	is	Coefficient of air density
η_t	is	Efficiency of the whole driveline
v	is	Longitudinal speed of the vehicle
θ	is	Slope angle
Σkm	is	Estimated Distance Travel
AC	is	Average Consumption
ASEAN	is	Association of Southeast Asian Nation
BMS	is	Battery management system
BMTA	is	Bangkok Mass Transit authority of Thailand
BSA	is	Body surface area
CAN	is	Control Area Network
CG	is	Center of gravity
CNG	is	Compressed Natural Gas
COP21	is	Conference of the Paris in the 21^{st}
DLT	is	Department of Land Transport
DP	is	Diesel Price

SYMBOLS AND ABBREVIATIONS (Continued)

EP	is	Electricity Price
EU	is	European Union
GHG	is	Greenhouse Gas
GPS	is	Global Positioning System
HDV	is	Heavy Duty Vehicle
HEV	is	Hybrid electric vehicle
HV	is	High Voltage
HVIL	is	High Voltage Interlock Loop
LC	is	Life Cycle
LCC	is	Life Cycle Cost
Length bus	is	Total bus length (m)
M_{Met}	is	Passenger metabolic heat production rate
NBV	is	Net Book Value
NISPC	is	National Innovation System Promotion Committee
NPV	is	Net Present Values
NSTDA	is	National Science and Technology. Development Agency
p.a.	is	Per Annual Year
PEA	is	Provincial Electricity Authority
PTC	is	Positive Temperature Coefficient
QAC	is	Thermal load
QAmb	is	Ambient load

SYMBOLS AND ABBREVIATIONS (Continued)

QDif	is	Diffuse load
QDir	is	Direct load
QEng	is	Engine load due to high temperature
QExh	is	Exhaust load due to high temperature
QMet	is	Metabolic load
QRef	is	Reflected radiation load
QTot	is	The net overall thermal load encountered
QVen	is	Load generated due to ventilation
RAM	is	Random Access Memory
RPM	is	Round per minute
SOC	is	State of Charge
SOH	is	State of Health
SUT	is	Suranaree University of Technology
TCP	is	Tire Change Payment
TL	is	Tire Lifespan
TP	is	Tire Price
TTW	is	Tank-to-Wheel
VCU	is	Vehicle Control Unit
VTF	is	Value of Time Factor
WTT	is	Well-to-Tank
WTW	is	Well-to-Wheel

CHAPTER I

INTRODUCTION

1.1 Background

In the light of the Paris Agreement reached at the COP21 to limit global warming to 2 degree Celsius. The transport sector has an important contribution to make to the achievement of the climate goals. The common efforts to reduce greenhouse gas emissions are becoming even more of a priority as they are already. Transport contributes to about a quarter of total GHG emissions in the world. The Energy Union strategy adopted last year by the decarbonization of transport.

Alternative fuels are part of the policy mix to achieve this decarbonization, and electrification of transport is a promising means to reach this goal. Alternative fuels will help to meet goals for reducing CO_2, but also to diversify energy sources and to improve air quality. These two benefits is tended to overlook. Mention a last benefit of alternative fuels, which is the competitiveness of cities all over the world facing similar challenges. Transport solutions are expected to strongly grow.

The electric vehicle has been on passenger cars. A lot of progress is being made regarding electric cars and manufacturers are in the process of bringing to the world market and increasing offer of such cars. But public transport has to green its credentials as well. The public transport needs to contribute its share to reaching the people objectives outlined above. Buses are a significant part of any public transport system and are the only public transport mode in many cities. However, the bus still suffer from an image problem, partly due to the fact that almost 50% buses across the world are still of Euro III standard. As such bus fleet renewal should remain on top of the political agenda for better urban vehicle. Electric bus together with the hybrid bus are a promising path to reduce the public transport carbon footprint.

1.2 Statement of the Problem

The electric bus is an upcoming technology being applied currently in developed countries such as Australia, Canada, China, Japan, Korea, US and European Union. Thailand should start considering this technology immediately. Thus, for deployment the vision, policies and road mapping approach to identify the research and development needed to support the public transport in Thailand. A chosen technology performs well only if put in its best operational conditions. Consider that new propulsion technologies should be developed continuously and tested under local, real life conditions in order to increase their availability and reliability. Furthermore, the exchange of test results and the examination is encouraged.

The focus of this thesis is to develop the prototype of electric bus that suitable for public transportation in Thailand. From this prototype achievement has the potential to be produced on commercial scale.

1.3 Objective of the Study

The main objective of this research is development of electric bus that suitable for public transportation in Thailand. In order to achieve the main objective, this research is composed of following sub-objective:

1.3.1 To study the design, development and implementation of the electric bus prototype using lithium-ion battery with suitable for transportation in Thailand.

1.3.2 To establish important parameter design such as motor and battery calculation design for electric bus by using lithium-ion battery.

1.3.3 To decide necessary parameter for one section and articulated electric bus type by using available software.

1.3.4 To study Thailand's economic for electric bus application.

1.4 Aim of Research and Limitation of Study

1.4.1 Design and development prototype of electric bus type with 12 m long.

1.4.3 The electric bus is selected to implement two traction asynchronous motors type as hub motor in two rear wheels.

1.4.4 Establish software program by Microsoft excel for motor sizing design.

1.4.5 The electric bus should have maximum speed approximate 90 km/hr.

1.4.6 The electric bus can drive more than 100 km per charge.

1.5 Expected Benefits

1.5.1 Results of this thesis is expected to have custom design of prototype of electric bus type with 12m long which is properly used in Thailand.

1.5.2 Providing an insight into the design, development and implementation of electric bus by using lithium-ion in Thailand.

1.5.3 Achievement of a design of basically scheme for Thailand's government guideline in practical implementation for public transportation in Thailand.

1.5.4 There are good potential of mass production for investor and bus manufacturing in Thailand regarding this research and study.

1.6 Organization of the Thesis

This thesis present the electric bus developoment for publication in Thailand comprised of seven chapters as follow:

Chapter I provides a brief introduction of the study including backgrounds, statement of the problem, objectives of the study, aim of the research, limitation of the research, expected benefits and the thesis organization.

Chapter II gives general review concepts and summarizes related works of electric bus in the world, ASIA, ASEAN and Thailand situation.

Chapter III presents a methodology to design the sizing of the energy storage and power compoments for electric bus.

Chapter IV proposes the case study, designed and development result by road test. In addition simulation and discusion of power consumption comparison.

Chapter V explains the effectiveness of economy and environment when electric bus are replaced in public transporation in Thailand.

Finally, chapter VI summarized the conclusions of this research and introduce the suggestions for future work.

CHAPTER II

LITERATURE SURVEY AND GENERAL REVIEW

2.1 Introduction

In this chapter a brief background and for the phenomena under investigation is presented. Many countries of the world have been realized and continue to be realized the increasing hybrid or electric buses by numerous transit operators worldwide. The content of the transport challenge situation of hybrid and electric bus situation from several countries in global, Asia and Thailand is presented.

2.2 Global Electric Vehicle Status

Issues regarding sustainability and climate change are increasing in importance on a global level. In December 2015, there are 196 member countries of the UN Framework on Climate Change met in the 21st Conference of the Parties on global climate change. At this meeting the parties signed a legally binding contract to limit the global warming to well below 2 ^{o}C. The member countries submitted national climate action plans, where they each made a plan on how to meet this global. The United Nations has set up seventeen sustainable development goals to handle the new situation. Two sustainable development goals from 2015 state that by 2030 all countries should take action to; upgrade the infrastructure with greater adoption of clean and environmentally friendly technologies, and to provide access to transport system for every one of clean and environmentally friendly technologies, and to provide access to transport systems for everyone by expanding the public transport. The transport sector has increasingly made up a larger part of total the road transport constituted 20% of the total GHG-emission. According to European Commission about a quarter about a quarter of CO_2 emissions from road transport within the EU is produced by Heavy-duty vehicle (HDV) for instance truck, buses and coaches. This represents a greater share than international aviation and shipping combined. Therefore the European Commission has established goals with the aim to reduce CO_2 emission. The EU heads of state agreed to aim at lowering emissions from HDV by 30% from 2005 levels.

The world's first electric tram line was tested in Russia, near Saint Petersburg in 1880 by Fyodor Pirotsky, while the first trolleybus dates back to 1882 and operated in Berlin under the design of Ernst Werner von Siemens (Dunbar, 1967). In time, these EVs operated either on or off rails, on the ground or underground, relying on power that came through permanent overhead lines (catenary lines) or electrified third rails. Going back to their evolution through history, by the end of the 1950s, the rapid ascent of the mass-produced automobile and the improvements in motorized buses leaded to the rapid disappearance of the tram and trolley from most western and Asian countries. These improvements transformed busses into a serious competitor to trams but their biggest advantage came from the fact that they did not require the construction of costly infrastructure. As a result most tram networks were no longer maintained or modernized. Busses gradually replaced trams, a technology that was considered archaic. This state of affairs served to discredit trams into public's eyes. However, the demise of the streetcar came when lines were torn out of the major cities by bus manufacturing or oil marketing companies for the specific purpose of replacing rail service with buses (Tennyson, 1989). Starting with the 70's, mainly in large cities, smog and sound pollution, traffic congestion and parking became problematic thus the advantages of the tram became once again visible. Since Metro construction was not a universal solution, authorities begun redefining their transport policies.

In countries like Germany, France and Spain, tram networks revived, which brought about a series of technological developments. In 2010, catenary free trams were introduced by a company named Bombardier which produces the PRIMOVE LRV tram. The tram is charged by contactless induction plates embedded in the 800 meters track-way, located in Augsburg, Austria (Bombardier Transportation, 2010).

Trolleybuses and trams are world wide spread; the majority is located in Eurasia. There are currently around 315 cities or metropolitan areas where trolleybuses are operated (Webb, 2010). In Denmark the first catenary electric tram based public transport system was operational in Copenhagen in 1899. Hellerup - Charlottenlund – Klampenborg followed in 1903, Aarhus in 1904, and Odense in 1911. Between 1880s and 1890s, the first unsuccessful attempts to use batteries to power the EV that run on tracks, were made in Australia and in the Netherlands. Also Denmark experimented with a storage battery tram since 1897 to 1902 in Copenhagen (Svenska, 2013).

Reported by Pike research, electric vehicle global market is expected to grow by 20.9% during the period 2012-2020 as shown in Figure 1 (Korosec, 2013). Among the various technologies, the pure electric bus is expected to be the biggest market share (50.8% share) in the global electric bus market in 2020. However, most of current electric buses are hybrid, this is mainly due to the short single-charge travel range offered by a pure electric bus, few available charging stations, and relatively long charging time. Nevertheless, the demand of pure electric buses is increasing rapidly due to environmental and fossil fuel concerns especially in the western countries.

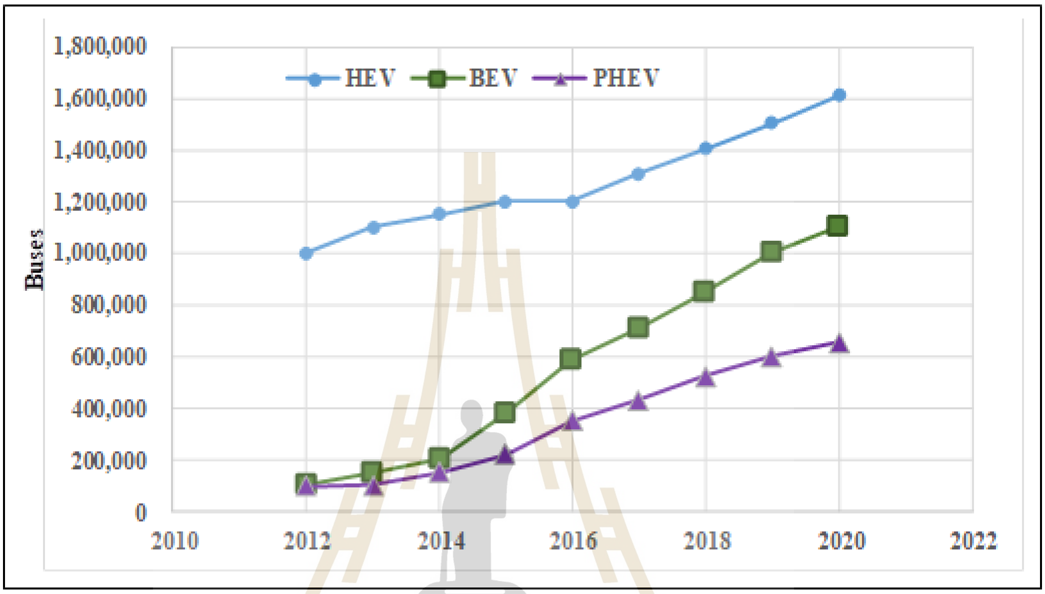

Figure 2.1 The electric vehicle annual world market 2012-2020

In European countries, United Kingdom, Germany, and France are the major electric bus demanding countries. The demand of public transportation services is highest in Brazil, Russia, India, and South Africa but the electric buses are yet to be highly accepted. China is the largest growing electric bus market in the world. It is expected to account for over 50% market share of the global electric bus market by 2025. In 2011 China produced 1,136 fully electric buses, and in 2016 the number increased to 115,700 electric buses. The biggest electric bus suppliers from China include Zhengzhou Yutong Group Co. Ltd, BYD Co. Ltd., Zhongtong Bus & Holding Co. Ltd., and Shenzhen Wuzhuolong Motors Co. Ltd. As these companies scale up, it creates more and more of an actual industry, a supply chain of parts and expertise that aspiring with cost reduction. The pure electric bus are currently competitive, on a total lifecycle-cost basis, with liquid natural gas (LNG), compressed natural gas (CNG) and hybrid diesel buses. It is worth to perpetual environment reduction by using clean energy technology that it costs more up front but saves more money over the long haul. The facility will be cranking out not just buses but electric trucks for various medium and heavy duty application.

The interesting electric bus, at Utah State University, researchers have designed the Aggie Bus: a bus capable of recharging itself at each stop using inductive charging. The prototype has a smaller battery setup that reduces downtime, lowers battery costs and free up interior space. The down side is that induction plates have to be installed at each stop. The bus's charging system tolerates up to 15 cm of misalignment from the charge plate and still receives 25 kW at 90% efficiency. One prototype bus is already being tested on the road; however there is no commercial vehicle available on the market (Barry, 2012). Protera is another company that produced a fast charge battery electric bus called: EcoRide™ BE35. The batteries use lithium-titanate chemistry and can be charged in less than 10 minutes every several hours, with a life time expectancy of 8 years. The bus as shown in Figure 2.2 has a permanent magnet motor rated at 100 kW continuous (150 kW peak) power and generates 650 Nm of torque and makes use of regenerative braking (Bullins, 2011).

Figure 2.2 Protera EcoRide™ BE35 electric bus (Bullins, 2011)

2.3 ASEAN electric vehicle status

Member states of the Association of Southeast Asian Nation announced during the 33rd ASEAN in September 2016 to adapt a target to reduce the region's greenhouse gas emissions by 20% over a period of years. ASEAN member states include Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Vietnam. Despite the growth of electric buses global, ASEAN countries are still three to five years away from becoming a commercial technology due to the cost of components with the technology and demand which caused by a lack of know how. However to achieve greenhouse gas emission goal, there are numerous pilot electric bus projects and activities in ASEAN countries developing and testing.

Brunei has just started importing electric buses, and in a few years to come an electric bus factory will be built in Berakas city from Shenglong New Energy Automobile Co., Ltd., a Chinese electric vehicle manufacturer. This factory will be a joint venture between a Chines Guangxi based company and a Bruneian government-linked company.

Currently in Cambodia there is no reported electric bus activity or operation. However, an electric vehicle car namely "Angkor EV" as shown in Figure 2.3 was recently built (Oaten, 2014). It was produced by Heng Development Company. The car can achieve 60 km/h speed with 160 kilometers per charge. Scaling up for this car model waits for financial support from the government or investor. Another electric car was produced in France and shipped to Cambodia namely "BluE-Mobility" electric car.

Figure 2.3 Cambodia electric vehicle namely "Angkor EV" (Oaten, 2014)

Figure 2.4 Makara Electric Vehicle (MEV) (Yannes, 2015)

Figure 2.5 Electric bus in Surabaya city (Romerouno, 2014)

In Indonesia, the University of Indonesia in Jakarta city launched four electric vehicles designed by campus engineering center in Depok, West Java. This project includes one electric bus and three city cars namely Makara Electric Vehicle (MEV) (Yannes, 2015). The electric bus is driven by a 120kW electric motor and 320V, 160

Ah of lithium-ion battery. Its maximum speed is 100 km/h and it can carry over 60 passengers with 150 km one charge. One of the electric city cars is designed by Molina UI team using 25 kW brushless direct current motor. The other two electric city cars use 32kW and 7.5kW AC induction motor with 32 V, 102Ah of battery respectively. The electric bus shown in Figure 2.4 will be servicing students around campus. Another electric bus project is in Surabaya city where the Electric Bus Research Team have established a 6 m long, 2.1 m width and 26 passenger capacity electric bus as in Figure 2.5 (Romerouno, 2014). The Indonesia Academy of Science, Mechatronics and Electric Power Research Center launched a mini-electric bus prototype produced by a local manufacture in Bandung city. This mini-electric bus has a maximum speed of 100 km/h, it uses DC brushless motor and lithium-ion battery, and it can carry 17 passengers as shown in Figure 2.6 (Zulkarnian, 2013). Recently, another electric bus from BYD Company successful demonstrated a trial run for Indonesia BRT system in Jakarta city.

Figure 2.6 Prototype mini-electric bus in Bandung city (Zulkarnian, 2013)

Laos's government established the E-bus project and encouraged government officials to use more public electric bus which are inexpensive and environmentally friendly. The E-bus project is sponsored by Japanese International Cooperation Aency (JICA) and operated by Lao Green Company in the UNESCO World Heritage town of Luang Prabang province as shown in Figure 2.7 (J&C Admin, 2013). Apart from the min-buses, there are other electric vehicles including tricycles. Other electric min-buses were imported from China and are operated by Vientiane Bus Company in Vientiane Capital State as shown in Figure 2.8. The main challenge with these min-buses is the charging time and battery maintenance, it takes five to six hours to charge the battery for a 70 to 80 km drive. Currently, half of 13 mini-electric buses are out of service due to battery maintenance cost. According to ALMEC corporate report, if 40 percent of vehicles in Lao are electric, the country will save US$180 million by 2020 and if percentage doubles the country will save US$938 million by 2030. Currently, Laos has more than 1.2 million vehicles registered to Department of Transport including 1% tricycle, 3% truck, 18% four wheels, and 78% motor bike.

Figure 2.7 Luang Prabang mini-electric bus (J&C Admin, 2013)

Figure 2.8 Vientian mini-electric bus (Van, 2016)

Figure 2.9 BRT electric bus in Malaysia (BYD Admin, 2015)

Malaysia launched the first electric bus running test in June 2015 and deployed fifteen eco-buses for the Bus Rapid Transit (BRT) Sunway Group line project as shown in Figure 2.9. All fifteen electric buses are produced by China's BYD Co., Ltd., to cover 5.4 km distance of dedicated lanes along seven stations in Kuala Lumpur. In 2016, the Malaysia government announced new BRT project in

Sabah to be served with the same kind of buses. In Putrajaya there is a trial run of ten electric buses sponsored by Japan's New Energy and Industrial Technology Development Organization (NEDO) since 2016. The trial run will take three years, the buses used are by manufactures by Scania and the batteries are installed in Japan. Malaysia government targets to have over 5,000 electric buses by 2020.

Philippines government push for electric vehicles. Over 20 electric mini-buses called e-jeepney as in Figure 2.10 were manufactured by a local bus manufacturer PhUV Inc. There are many e-jeepney electric mini-buses operating in Manila. Several government municipals, universities and private companies prefer to use e-jeepney for example Manila electric Co. (Meralco), the country's power distributor, Ateneo de Manila University and De La Salle University. Victory Liner Inc., the provincial bus operator in Philippines imported city electric buses from Taiwan based RAC Electric Vehicles Inc., shown in Figure 2.11. The electric bus has a 250kWh, 700Ah, 450V lithium-ion battery, and 150kW, 2500rpm, 573Nm (1400 Nm peak) traction motor.

Figure 2.10 E-jeepney in Manila (Kim, 2014)

Figure 2.11 Imported electric bus in Philippines (Kim, 2014)

Singapore government committed to reduce emissions by 7% to 11% below 2020 “business as usual” BAU levels. Nanyang Technological University (NTU), Tsinghua University and Shanghai Sunlong Bus Co., Ltd., developed the first hydrogen and lithium-ion battery electric bus namely GreenLite in Singapore in 2011 as shown in Figure 2.12. The unique dual design combination of a proton exchange membrane (PEM) fuel cell stack with lithium-ion batteries gives the bus a 40kWh energy storage capacity. From September 2016, there was a 6 month trial of electric bus namely K9 form BYD Co. Ltd., operating in Loyang Depot area. SBS transit, Singapore’s major public bus operator introduced two hybrid (diesel-electric) buses. One from Sunlong model SLK6121 and the other from Volvo model B5RLE. The trial period debut in Ang Mo Kio area by the early 2016. If the trial is successful, more of these diesel hybrid and electric buses could be deployed in future.

Figure 2.12 First hybrid public bus in Singapore (Mike, 2010)

Vietnam government has electric vehicle policy and campaign implemented under Nationally Appropriate Mitigation Actions (NAMAs) namely “production and application of hybrid and electric cars in Vietnam” to contribute the global effort to reduce greenhouse gas emission. NAMAs’ target is to have 6 million electric vehicles by 2020 (Huong, 2015). There are over 1,086 electric cars (three and four wheels) for personal use and public transportation service in Hanoi, Ho Chi Minh City and Da Nang region according to the Ministry of Transport registration report. In early year of 2015, there were 30 electric cars with 14 passengers deployed for tourist in the northern city of Hai Phong as shown in Figure 2.13. The electric cars for tourism service are adopted in other place in northern Thanh Hao province, Dong Hoi center of Quang Binh province, central of Hue city and Cua Lo Town in Nghe An province. Other two electric vehicles (Nissan Leaf and Tesla X P100D) were imported for test run in 2016, and one hundred Renault electric cars were imported from French car manufacturer by Mai Linh Taxi Company to use as taxi at Hanoi in June 2016 (Tickri, 2016), (Admin, 2016). The first diesel-electric hybrid bus was launched by Siemens and the Vietnam Motors Industry Corporation (Vinamotor) as shown in Figure 2.14 (Kim, 2015). The series production of the hybrid buses will be done by Vinamotor.

Figure 2.13 Electric car in Vietnam (Huong, 2015)

Figure 2.14 Siemens and Vinamotor hybrid bus (Kim, 2015)

2.4 Electric Vehicle in Thailand

Thailand has committed to reduce greenhouse gas emissions by 20-25% within 2030 at the United Nations Climate Change Conference (COP21) in Paris. Four sectors focused on reducing emissions at the beginning of the plan are energy, transport, waste and industry. The 20% will be achieved by the country's resources alone while the additional 5% will require international support in terms of finance, know-how and technology. Great advances have been achieved in energy and transportation section in electric bus technologies. In term of success, Thailand government raises several interested promotion and campaign for global investor and electric bus manufacture as an ASEAN EV hub such as import duty and excise tax exemption for important related parts, Board of Investment of Thailand (BOI) promotion for manufacture of electric vehicles and key components, and propose three hundred percent tax rebate for research and development. Thailand government raises EV policy and roadmap which is approved by National Innovation System Promotion Committee (NISPC) as shown in Figure 2.15. Hence, there are several enthusiastic varieties departments participate in electric vehicle campaign, and government is coordinating with university and local companies to develop and expertise R&D facilities of electric vehicle parts include storage batteries.

Provincial Electricity Authority (PEA) and Suranaree University of Technology (SUT) have achieved taken the lead by developing the first electric bus by using lithium-battery in Thailand. From this prototype achievement has the potential to be produced on commercial scale. The government will push for using of electric buses as a major mode of transport at capital city of Bangkok in the future.

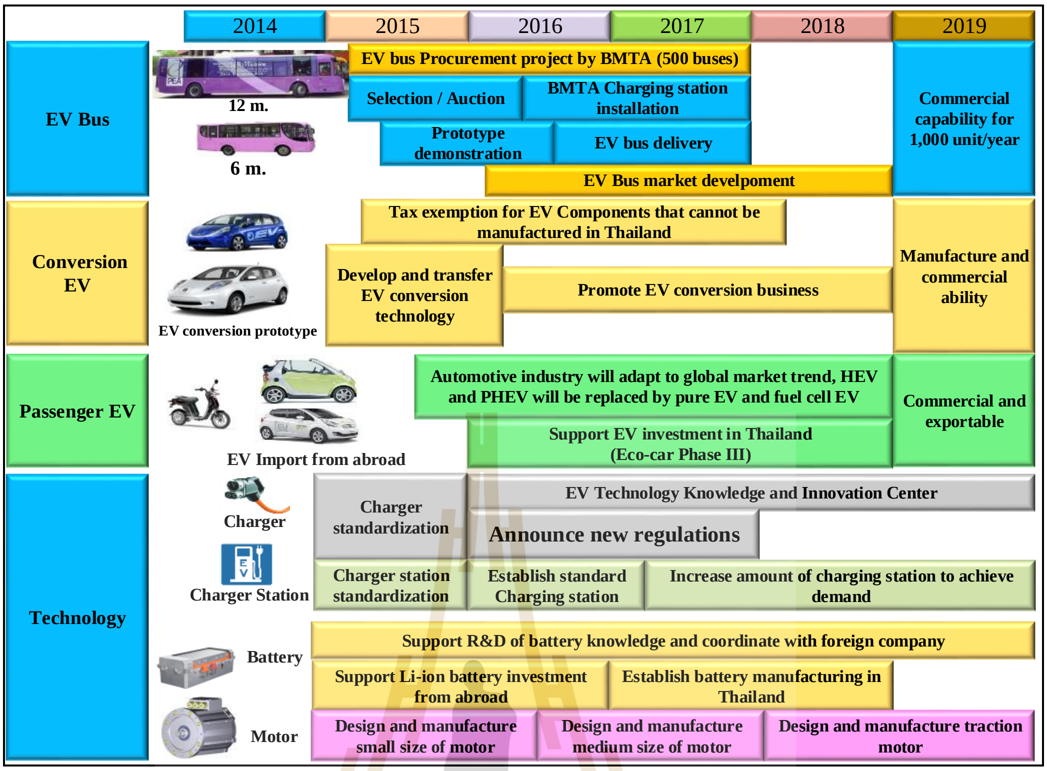

Figure 2.15 Thailand EV promotion roadmap

The Bangkok Mass Transit authority of Thailand (BMTA) in one of the responsibility propose to the Cabinet for purchasing first 200 electric buses in public transportation to improve the emission regarding the government policy. Bangkok had replaced the diesel buses with the Compressed Natural Gas (CNG) buses during the last decade in order to reduce air pollution emission, and is recently attempting to switch from the old diesel and gas buses to electric buses. The purchase from Thai local bus maker companies instead of abroad because the domestic automobile firms are able to meet the budget. It makes a chance for bus manufacture in Thailand to develop their technology. There are several interested companies in this project as Loxley Public Company Limited, SIKOR Co., Ltd., Electric Vehicles (Thailand) Public Co., Ltd., and Cherdchai Industrial Co., Ltd. The most companies has built 6 to

8.5 meters mini-bus and golf car with nickel-cadmium, nickel-zinc and NiMH batteries technology.

The first prototype of 12 meters electric bus with Lithium ion battery is produced by SUT and Cherdchai Industrial Co., Ltd., for PEA staff circling route in Bangkok as a model case of replacing the diesel bus by electric bus. Cherdchai Industrial Co., Ltd. as the bus manufacturer designs the low floor chassis and body and decreases the weight of electric bus with safety. SUT designs and develops the vehicle control unit (VCU), motor control and battery sizing design as the major electric components for this electric bus. This electric bus is tested for qualification related to vehicle performance and safety regulation in Department of Land Transport (DLT) of Thailand prior to the public operation. And also, its performance will be tuned and tested in real-world road test in order to verify whether it is able to meet the performance goal. Loxley Pcl., Thai trading investor conglomerate join venture with BYD simultaneously launch K9 electric bus and e6-crossover passenger car the Electrified Transportation scheme in Thailand. The trial run of K9 electric bus services in center area of Bangkok public route and connecting Don Mueang International Airport via to the Mo Chit Skytrain station route for three months as in Figure 2.16. Recently, BYD representatives and the bus builder company's local partner assembly for the second unit of K9 electric bus in Thailand. Furthermore, the National Science and Technology. Development Agency (NSTDA) and Loxley Plc., sign an agreement to participate and develop technologies, know-how and standard parts for future electric car production in Thailand.

Figure 2.16 Loxley Plc and BYD electric bus in Bangkok

SIKOR Co., Ltd., is a local electric bus company in Thailand. It develops plenty size type of 6, and 8 meters shuttle electric buses from a basic system for low budget to service in specific area of University, Government complex, resort and hotel. Recently, SIKOR Co., Ltd., establishes 8.5 meters electric bus with Lithium Titanate Oxide (LTO) battery system and ships to Indonesia as shown in Figure 2.17. Electric Vehicles (Thailand) Co., Ltd. (EVT) is a local manufacturing and cooperates with National Electronics and Computer Technology Center (NECTEC) to conduct researching and development variety of electric vehicles such as e-scooter bike, tree wheels, electric car, and shuttle bus. The first 5.8 meters electric minibus for 20 passengers is built as the prototype as in Figure 2.18. In the next few year, EVT will develop for another 10 and 12 meters electric bus to achieve public transportation requirement.

Figure 2.17 SIKOR's electric bus in Bangkok

Figure 2.18 EVT electric bus in Bangkok

2.5 Bus dynamic

Vehicle operation fundamentals mathematically describe vehicle behavior base on the general principles of mechanics. Its behavior sophisticated mechanical and mathematical knowledge during the vehicle movement.

2.5.1 Parameter of Bus Dynamic

The movement behavior of bus vehicle is basically determined by all the force acting on the vehicle moving direction. During the bus vehicle moving, there is a resistance against tyre to stop its movement. The resistance basis concludes variable of the rolling resistance, aerodynamic drag, and uphill resistance. The relationship among these variables can be solved by kinematic equation according to the Newton's second law of motion. The vehicle acceleration moving uphill can be shown in Figure 2.19 and expressed by equation (2.1) to (2.2) (Kulworawanichpong and Punpaisarn, 2014).

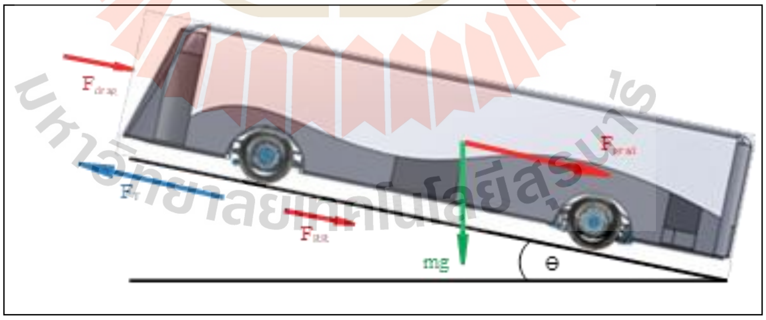

Figure 2.19 Electric traction motor torque-speed profile

$$F_T - F_R = M_{eff} a \tag{2.1}$$

$$F_R = F_{RR} + F_{grad} + F_{drag} \tag{2.2}$$

where

F_T is tractive effort of vehicle

F_R is resistance force of vehicle

F_{RR} is rolling resistance force of vehicle

F_{drag} is gravitational force (gradient force) of vehicle

F_{grad} is gradient resistance

M_{eff} is total mass of vehicle (kg)

a is vehicle acceleration (m/s^2)

2.5.2 Tractive Effort Motor Characteristic

The ideal characteristic of electric traction motor drive can principal show in variable of motor speed, power, and torque as in Figure 2.20. The behavior of an electric motor used in electric vehicles (EVs) or hybrid electric vehicles (HEVs). Motor has a constant torque in low speed region and constant power at high speed region. The traction motor characteristic can be defined by the ratio of maximum to base speed so call “speed ratio” (Punpaisarn and Kulworawanichpong, 2014). One of the nature properties of electric motor is generate high torque at zero speed. Motor exerts a constant torque (rate torque) over the entire speed range until the rated speed is reached. This operation may need necessary power electronic inverter component for controller. Once it is past the rate speed of the motor, the torque will decrease proportionally with speed, resulting in a constant power (rate power) output. At low speed region operation, the more increase voltage supply to the motor, the more increase speed through power electronic inverter while the electromagnetic of motor flux is kept constant. At the point of base speed, the voltage drop of motor reach source voltage. After base speed, the motor voltage is constant but weakened motor flux and decreased hyperbolically with higher motor speed. In constant power region, the maximum torque of motor can be increased by selection lower motor speed. However, inherent property of each motor types have limited maximum speed ratio for example permanent magnet motor has small regarding magnetic field weakening of permanent magnet, switched reluctance motor may higher than 6 of speed ratio and induction motor about 4 (Rahman and Ehsani, 1996) and (Gao et al., 2003).

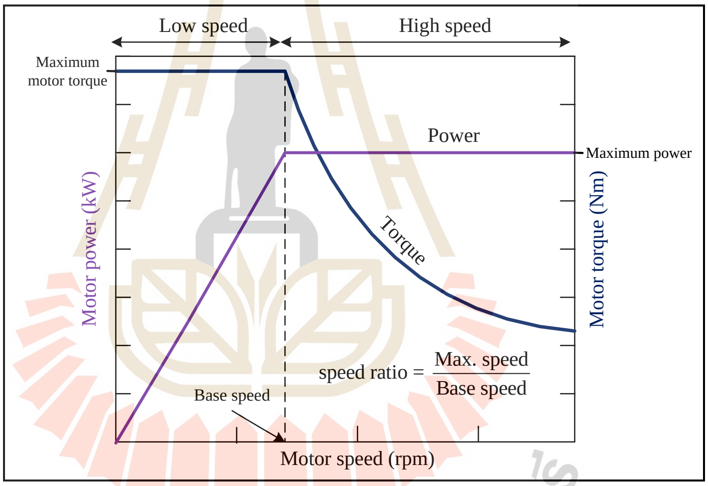

Figure 2.20 Free body bus vehicle moving uphill

In normal electric vehicle driving condition, the maximum capability of electric motor is rarely used. Also the power train operates with partial load in most of the operation time. Actual tractive effort and vehicle speed are wildly operate such as driver behavior, acceleration, deceleration, road attitude, and traffic environment. It will be difficult to describe and estimate the tractive effort and vehicle speed variation in traffic environment. Some representative driving route and schedule are developed to emulate traffic environments by correlation of vehicle speed and operating time. In Society of Automotive Engineers United States recommends to use for evaluation of electric vehicle and batteries design. The tractive effort (F_T) was developed by a traction motor on driven wheel and vehicle speed (V). It can be expressed by equation (2.3) and (2.4).

$$F_T = \frac{T_m i_g i_0 \eta_t}{r_d} \tag{2.3}$$

$$V = \frac{\pi N_m r_d}{30 i_g i_0} \tag{2.4}$$

where

T_m	is	the motor torque (Nm)
N_m	is	motor speed (rpm)
i_g	is	gear ratio of transmission
i_0	is	gear ratio of final drive
η_t	is	the efficiency of the whole driveline from motor to the driven wheel
r_d	is	the radius of the drive wheel

2.5.3 The Rolling Resistance

The rolling resistance (F_{RR}) is basically caused by hysteresis deformation in tyre material and on road surface. The result of hysteresis cause an asymmetric distribution of the ground reaction forces which opposes while the tyre is rolling. The other main cause of rolling resistance is frictional torque which includes bearing torques, gear teeth friction, and brake pad. This F_{RR} is expressed by equation (2.5).

$$F_{RR} = f_r W \approx (f_0 + f_1 v)W \tag{2.5}$$

where

W	is	the wheel load
f_r	is	the rolling resistance coefficient
f_0	is	the constant of vehicle running on asphalt or concrete road (0.005– 0.010)
f_1	is	negligible for simplification
v	is	the longitudinal speed of the vehicle (km/h)

2.5.4 Aerodynamic Drag

The force resisting vehicle motion in air encounter is referred to aerodynamic drag (F_{drag}). The main two concerning of aerodynamic drags are shape drag and skin friction. Shape drag is forward motion of the vehicle pushing the air in front. The vehicle motion creates two zone of high pressure in front and low pressure at the back which cause as pushing and pulling backward, respectively. Skin friction is the action force of air close to surface of vehicle. Aerodynamic drag is considered by vehicle speed (V), vehicle frontal area (A_f), shape of the vehicle body and air density (ρ_a) which expressed by equation (2.6).

$$F_{drag} = \frac{1}{2}\rho_a A_f C_d (V - V_W)^2 \tag{2.6}$$

where

C_d is aerodynamic drag coefficient that perform by shape of vehicle

V_W is the wind speed on moving direction.

2.5.5 Gradient resistance

For gradient force (F_{grad}) is usually called gradient resistance. It opposes and help the forward motion in grade climbing in uphill and grade descending in downhill, respectively. The gravitational force as long as the slope is constant. In some literature calls road resistance which combines of the tire rolling resistance and grading resistance together. The gradient force can be represented by equation (2.7).

$$F_{grad} = \pm M_{eff}\, g \sin\theta \tag{2.7}$$

where

g is the acceleration of gravitational constant in 9.8 m/s^2

θ is the slope angle

2.6 Conclusion

Many countries around the world are interested in more sustainable road transport solutions that contribute to societal goals such as greenhouse gas neutrallity, energy use reduction, fossil fuel independence, and reduction of health problems related to emissions. Meanwhile serveral European companies have started to manufacture electric cars and buses, some public authorities support projects aimed at increasing the electric vehicle production. In Asian countries has also started to research and develop electric vehicle in a wild range. There is a lot of opportunity for electric bus supplier investment. In ASEAN regional demand for electric vehicle is still very limited, however, countries like Thailand, Philippines and Indonesia have shown high interest in zero emission vehicle projects.

CHAPTER III

ELECTRIC BUS DEVELOPMENT AND DESIGN

3.1 Introduction

This chapter presents a methodology to design the sizing of the energy storage and power components in prototype of electric bus for using Thailand. The battery for energy storage system (lithium-phosphate battery type) are designed by the number of series and parallel circuit to meet motors' performance. The traction motor size is also described how to design to achieve specified acceleration and requirements. The fundamental components will be introduced and described how to calculate for specification of PEA Zero-emission electric bus.

3.2 Design of PEA Zero-emission Electric Bus

The specifications of electric devices were determined by the result of calculation in order to achieve the target performance of high speed of electric bus which the maximum speed rises up to 100 km/h. The electric bus can drive 195 km at approximate 35-60 km/h speed, the maximum grade ability of 25% slope and the accelerating time is 10 seconds from nominal speed of 60 km/h. The PEA Zero-emission bus is designed the light weight body and low-floor axle which has inherent characteristic of being lighter weight by 20% if compare to the equivalent bus. PEA Zero-emission has 12 m long, 43 passenger seats capacity and contain lithium-ion phosphate battery (196 kWh) on the wheel space area. In Figure 3.1 shows some important components placement installation of PEA Zero-emission bus. The swapped battery packs are installed on the wheels with consideration of weight balance and center of gravity (CG) point of vehicle and the electric devices. The plug in charger inlet is placed at the rear left side of bus body. One air conditioner module is installed on the roof in the middle of bus body.

Figure 3.1 PEA Zero-emission electric bus design

3.3 Electric Composition System

PEA Zero-emission bus is establish of numerous hardware components and software algorithms interconnected through mechanical links and electrical communications network. The system design fundamentals are in the physics of motion, energy and power and in the principles of energy conversion from one form to another, the forms being chemical, electrical and mechanical. The fundamentals hardware component can express as in Figure 3.2 comprises of vehicle control unit (VCU) (1), DC/DC converter (650 V to 24 V) (2) for power supply in vehicle and Low volt distribution box (3) are placed in control room behind bus driver seat. The steering pump inverter (4), steering pump (5), DC converter 24/12 Vdc (6), Dash board/digital gauge (7) and Auxiliary battery 24 Vdc (8) are mounted in the front of the bus. High Volt Traction 11 modules of batteries (9) for the propulsion are placed on all wheels. Air conditioner (10) driven by the combination of a motor and inverter with capacity of 15 kW is installed on the bus roof. Traction motors (2×120 kW) are in the HUB motors axle (11). Traction motor drive inverters (12), Water coolant system (13), HV distributor circuit and Battery management system for controlling the vehicle power supply system and quick charger (14), Air compressor pump inverter (15) and air compressor motor (16) are placed in the rear of bus. All electric components are controlled by the Control Area Network (CAN) communication with the vehicle control system.

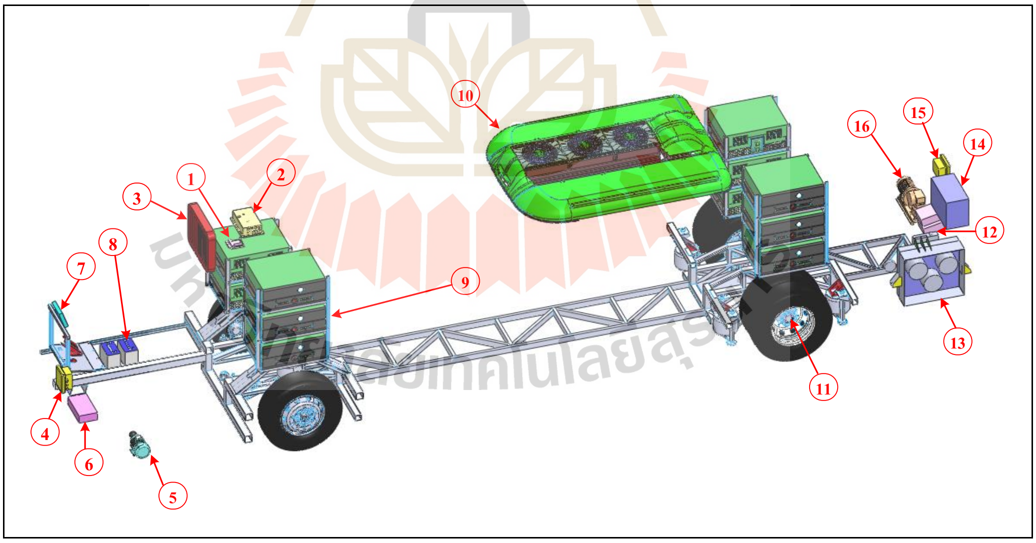

Figure 3.2 Component placement installation

The propulsion system of PEA Zero-emission electric bus is mainly comprised of the following specification as following detail and in Table A.8.

- Vehicle control unit (VCU): As a control center of the bus has the function of interface bus driver and the bas, translate the commands from driver for instance acceleration and brake, calculate the best torque of drive or brake, sensor detection and etc. In PEA Zero-emission electric bus install one master VCU 32 bit Freescale MPC 555 processor, 40 Mhz., 448 kB internal flash, 26 kB internal RAM, watchdog CPU 68 HC908 with input of 8×analog, 12×analog/digital, 8×digital and output of 16×digital 4A, 3×digital 15 A, 3×digital timer and 4×4 A PWM. The digital input unit used for receiving the switch signal of key switch, start button, acceleration paddle and brake paddle. The digital output is used to control the charge power contractor and switch to power on/off components. The software of CoDeSys 2.3 is used for control system via CANopen protocol system.

- DC/DC converter (650V to 24V) is placed between high volt 650 Vdc bus and the low volt 24 Vdc bus directly to the electronic components by changing the system voltages from high level to low level. This converter is isolated DC/DC converter type with 160 A, 4.5kW and support electrical isolation between the input and the output. The output power is mainly controlled by the input current control of the converter according to the relationship between the current and power of load consumed limitation.

- Low volt distribution box contains components of fuse, relay and electricity supply system that divides an electrical power feed into subsidiary circuits for each circuit in a common enclosure. This distribution box services for all 24 Vdc components requirement.

- Steering pump inverter and steering pump are functioned for the front rear wheel following driver manner. The electric motor pump is mounted on the steering column to drive a conventional hydraulic oil in pipe line. The three phase AC asynchronous motor type of 3 kW rate power with three phase 220 Vac 50 Hz input is used. It can supply 15 Bar of hydraulic pressure with the fan cooling with IP55 protection. The motor drive DC/AC inverter has 650 Vdc 3 kW power input and three phase 220 Vac 50 Hz output of specification. The control and communication system will operate through CAN system. When the steering wheel is turned, torque is transmitted to the pinion causing the input shaft to rotate. The torsion bar that links the input shaft and the pinion twists until the torque and reaction force equalize. During the wheel is straight, there is a bypass pipe circuit to release pressure of hydraulic oil feedback to tank for the heat exchanger.

- DC converter 24/12 Vdc is used in standby mode for step down voltage from 24Vdc auxiliary battery to 12Vdc which serve for waking up the system with start/stop button.

- Dash board / digital gauge has the function to show information to bus driver such as bus running state, SOC of energy storage, fault alarm and drive selection mode. In this PEA Zero-emission electric bus installs digital touch screen 10.4 inch size with operated button. The dash board is implement on ARM Cortex A8 processor 800 MHz CPU clock, 512 Mbyte flash memory and can be developed by using CoDeSys programming system. CAN communication system with 250 kbit/s baud rate is implemented.

- Auxiliary battery 24 Vdc is mounted in the front of the bus. It has function to supply the ignition electrical components for power on/off the electric bus system. This auxiliary battery will be connected to DC/DC converter for charging through charger device.

- Traction batteries of lithium-ion consist of 11 modules which divided and placed on the front and rear wheels. The capacity of battery is 196 kWh, 320 Ah with 633.6 V. In one battery module comprise of 16 cells in parallel and 18 cells in series so that one module has 288 battery cells as shown in Figure 3.3. There are 3,168 cells for 11 modules in PEA Zero-emission electric bus. For PEA Zero-emission electric bus consider to use of a battery exchange system (swap battery) demonstration. The time required to recharge a bus consuming is reduced to the time to replace the battery package in the bus, about the same time required to refuel a conventional engine bus. In addition, charging the battery outside the bus eliminates the requirement for rapid charging and reduces the load on the electrical infrastructure, and thus its cost.

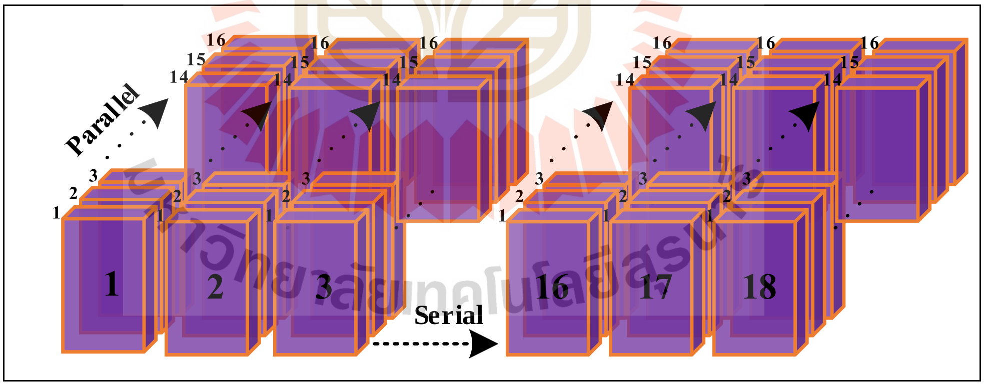

Figure 3.3 Battery cell assembly in one module

- Air conditioner contains an inverter and an AC compressor. The inverter drive has 650 V input and 3 phase 400 Vac, 0-1 kHz with 15 kW. The compressor has speed maximum at 3,600 rpm depending on cooling power needed to fulfill the climate requirements. The control system process, if the cooling demand for room temperature is very low and the minimum of 900 rpm is providing too much cooling power, the compressor is switched off for a few minute to avoid undercooling of the room temperature. The ambient temperature operates at 19-39 Celsius.

- Traction motors: the electrical driving system for PEA Zero-emission is installed the portal axle system ZF AVE130 with two asynchronous induction motors, allowing for relatively high speed of up to 10,900 rpm at maximum output of 2×120 kW. The operation frequency is lower than 6 kHz with the net power per traction motor is less than 85 kW. The nominal operation temperature is less than 65 Celsius with water cooling system. It makes to have a high efficiency powertrain and more rear space in a low-floor bus. Because these two HUB motors are independent rear wheel drives with two drive inverter, it can be improved future controller technologies at different speeds or torques depending on the road conditions and the intent of the driver.

- Traction motor drive inverters: as of electric motors in electric bus are powered by alternating current a DC/AC inverter is needed. Two 3-phase IGBT inverters modules are installed for the left and right to drive HUB motors. Each individual drive inverter can control separately by one VCU for safety and reliability. These inverters modules can control the frequency and current supplied to the motor and regulate torque and motor velocity (RPM). In these inverter modules are improved thermal performance by water coolant system and high reliability by integrating the DC-link capacitors to reduce internal inductance and allows the usage of high bus voltage less than 1 kVdc. The operation frequency bandwidth has a wide range of 2-20 kHz. The High Voltage Interlock Loop (HVIL) is also installed to prevent the hazardous voltage with 8-37 mA current range sensing for not-activated active discharge PTC and shunt resistor at 23.4 ohm. With these inverter modules can be implemented 2 control mode of speed and torque control mode system.

- Water coolant system: The electric pump conveys the cooled operating fluid from the tank through the traction HUB motor both left and right and two traction inverters that is to be cooled. It absorbs the heat by flowing back to the plate heat exchanger where it is returned to a cooler temperature by the cooling water. The cooling circuits is used traditional silicate (ethylene glycol) with 24 lite per minute flow rate. In water coolant system operating speed in 24 Vdc is of one motor pump of maximum 72 W (750-2,500 rpm) and three fan of 3×120W maximum (250-4,500 rpm). A sensor to measure coolant temperature is placed into the pipework between the thermostat housing and the radiator inlet (top pipe). This measures the temperature of the coolant as it leaves the engine. This temperature is used by the ECU to control the JWR fan speed. The electric pump will run continuously at 20% of the maximum speed for any measured temperature over 20 °C and the fans will run continuously at 10% of their maximum speed for any measured temperature over 30 °C. The CAN communication system with 250 kbps baud rate to the master VCU and temperature display.

- Battery management system (BMS) is a combination of sensors, controller, CAN communication, and computation hardware with software algorithms designed to decide the maximum charge/discharge current and duration from the estimation of SOC and SOH of the battery pack. BMS makes decision on charge/discharge rates on the basis of load demands, cell voltage, current, and temperature measurements, and estimated battery SOC, capacity, impedance, etc. Within these variables, the SOC is the most critical parameter indication for controller in VCU. This is especially important for Li-ion batteries since their overcharge can accelerate battery degradation, catch fire or in a worst case scenario, even cause explosion. On the other hand, over-discharge can result in loss of capacity and shortening of cell life.

- Air compressor pump inverter and air compressor motor is mainly to provide reliable air pressure source for brake and suspension assisted system. The motor pump has 3 kW of three phase 220 Vac, 50 Hz and supplies 9.8 Bar with 26 liter/min which is enough for 5 air tanks (25 liter capacity per tank). The motor drive DC/AC inverter has 650 Vdc 3 kW power input and three phase 220 Vac 50 Hz output.

3.4 The Drivetrain Schematic

The overview drivetrain schematic of PEA electric bus system is shown in Figure 3.4. The red line, orange line, green line and black line are represented for high voltage 650 V, low voltage 24V, CAN system bus line, and control signal, respectively. The charging system converter is generated a 650 DC voltage from AC line to High Voltage (HV) box and battery modules. The host controller from charger will have the responsibility using the information provided by the Communications Area Network (CAN) modem and temperature sensing directly with the HV box. In the HV box will include Battery management, insulation meter and power relays. For safety reasons, isolation between high voltage component and the current and voltage is also required to prevent noise currents from entering the interfering with or damaging sensitive circuitry as well as the communications CAN bus system.

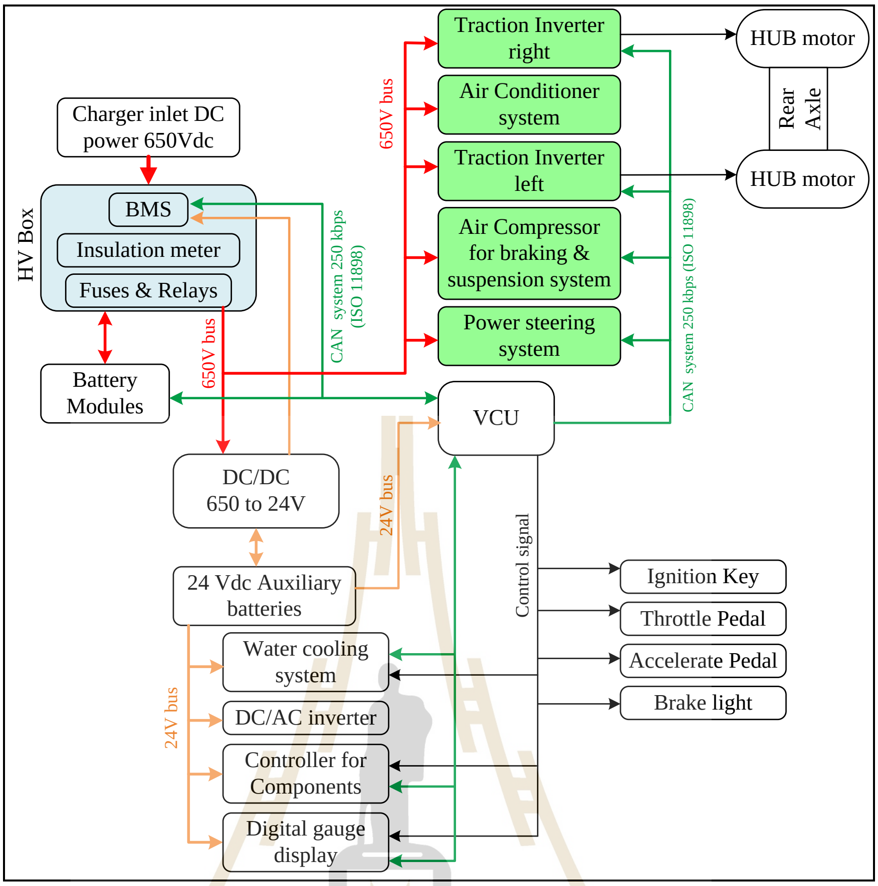

Figure 3.4 Electric bus system overview drivetrain schematic

The DC-DC converter is another electrical power management device used for DC power conversion from high-voltage to low-voltage levels. The energy flow in a vehicle starts from the batteries modules and ends at the wheels with the delivery of propulsion power. The flow path of power and energy so call as powertrain is controlled by a set of electronic controllers as the Vehicle Controller Unit (VCU). It is the master controller for coordinating the system level functions of the energy conversion and power management per control system requirement. This VCU is a key component controller in electric bus since it has to coordinate the energy conversion of multiple devices and power transmission through both the electrical and mechanical path. VCU will interacts with other components of the electric bus through a communication network, which is based on CAN protocol. The electric drives are made of two power electronic devises modules of three phase insulated Gate Bipolar Transistors (IGBT) inverters. Two IGBT inverters are electrical-to-electrical energy conversion devices that convert steady voltages with fixed-frequency into a variable voltage supply for two hub motor where place in the rear axle of electric bus. The propulsion power come from combination of two inverter modules and VCU control and transmit to HUB motor and wheels.

3.5 Battery Sizing Design

The batteries are made of Li-ion unit cells containing the stored chemical energy that can be converted to electrical energy. The combination cells in pack are enclosed in casing to form a battery module. The collection of individual battery modules connected in a series and parallel combination to deliver the desired voltage and energy to power electronic drive system. How to select the battery for vehicle is a process, dependent on several factor requirements. The basic requirements of the energy storage system include safety, reliability, high efficiency, maximum speed, acceleration time, operation distance requirements and acceleration time. There are several criteria for sizing of battery such as battery pack capacity (Ah), C-rate (capacity of a battery in an hour), peak and continuous charge and discharge power capacities (kW), maximum and minimum operating voltage (V), Maximum and minimum operating current (A), operation temperature (C), gravimetric energy density (Wh/kg), gravimetric power density (W/kg), maximum self-discharge rate (Wh/day), allowable SOC operating range (%), internal resistance, peak power, cut-off voltage, state of charge (SOC), depth of discharge (DOD), state of health (SOH), cycle life, calendar life, battery reversal, battery management system (BMS) and thermal management system. The electric bus is required to handle high power and high energy capacity within limitation of space, weight and affordable price.

A more challenging issue to electric bus is energy capability of battery design. There are two common idea to estimate the battery capacity by calculation and using simulated vehicles efficiencies data from driving cycles and excel by using standard of the New European Driving Cycle (NEDC) or U.S. Urban Dynamometer Driving Schedules (UDDS). The calculation method can be expressed by equation (3.1) where C_{Ah} is traction battery package capacity (Ah), V_{bus} is DC bus voltage (V), S_{bat} is electric range (km), K_{ev} is average energy consumption per kilometer of the electric transit bus (kWh/km) which can be estimated at 0.9-1.1 kW/km by urban drive cycle and K_{soc} is discharge coefficient which can be approximate as 0.8. (Ehsani et al., 2010)

$$C_{Ah} = \frac{1000 \cdot K_{ev} \cdot S_{bat}}{K_{soc} \cdot V_{bus}} \tag{3.1}$$

For PEA Zero-emission electric bus estimated calculation design is based on parameters requirement of driving range (S_{bat}) 190 kilometer per day with average energy consumption (K_{ev}) 0.9 kWh/km, discharge coefficient of battery (K_{soc}) 0.8 and DC bus voltage (V_{bus}) 650 Vdc. The capacity of battery can be estimated by using equation (3.1) which will be 328.8 Ah. However, the battery capacity of 196 kWh, 320 Ah, 650 V is installed to meet requirement and market support.

There is another method to calculate the battery size by using driving cycle method. It is a course of speed varies and time. It is the main parameters of average speed, idle running time and will consistent with the actual local traffic conditions as close as possible. Driving the vehicle on the roads in real traffic conditions, speed and road altitude curves trajectory are used to represent the bus behavior and electric power requirement. The relation between velocity and time can collect data by GPS tracking device that contain dataset of speed and road altitude curves trajectory in second-by-second of time.

3.6 Traction motor power sizing

The sizing of the electric motor drive involves finding the power rating, maximum torque, acceleration performance and peak load power in typical drive cycles. The higher the maximum torque required, the larger size of motor. An initial of design, the power rating of the electric motor drive can be estimate according to acceleration performance. The total tractive power for accelerating the vehicle from zero to given speed within seconds may be concerned of the rolling resistance and dynamic drag as expressed by equation (3.2) (Ehsani et al., 2010).

$$P_t = \frac{\delta M}{2t_a}\left(V_f^2 + V_b^2\right) + \frac{2}{3} Mgf_r V_f + \frac{1}{5}\rho_a C_D A_f V_f^3 \tag{3.2}$$

where

M	is	the total mass of the vehicle in kg,
δ	is	the rotational inertia factor,
t_a	is	the expected acceleration time in second,

V_b is the vehicle speed corresponding to the motor-base speed in m/s,

V_f is the final speed of the vehicle during acceleration speed in m/s,

g is the acceleration of gravitational constant in 9.8 m/s^2,

f_r is the rolling resistance coefficient,

ρ_a is the coefficient of air density in 1.202 kg/m^3,

A_f is the front area of the vehicle in m^2,

C_D is the aerodynamic drag coefficient

P_t is the tractive power in W

For PEA Zero-emission electric bus electric drive motor is estimated design by using parameter which describe in Table 3.1. The calculation result shows 245 kW of electric motor drive power should be implemented. So that the suitable electric motor with 240 kW rate power is installed by using ZF AVE130 axle HUB motor which has 2×120 kW rated power specification. In Table 3.2 describes the specification of the PEA Zero-emission electric bus.

Table 3.1 Parameter of electric motor sizing design

Parameter	**Value**
M (kg)	1,200
t_a (s)	10
V_f (m/s)	60
A_f (m^2)	8.1
C_D	0.7

Table 3.2 PEA Zero-emission characteristic design

Item		Specification
Dimension	Length (mm.)	12,000
	Width (mm.)	2,550
	Height (mm.)	2,960
	Gross Weight (kg.)	18,000
	Carry capacity weight (kg.)	20,000
	Wheelbase (mm.)	6,500
	Min. Ground Clearance (mm.)	322.5
	Front/Rear overhang (mm.)	2800/2700
	Approach/Departure angle	28°
Controller display	10 inch	Touch screen display water proof
Capacity	Driver Seat	1
	Wheelchair	1
	Standing	32
	Passenger seat	43
Motor	Type	Asynchronous induction motor
	Max. Power (kW)	2×120
	Max. Torque (Nm.)	2×465
	Degree of protection	IP6K9K
Battery	Type	Lithium-Ion Phosphate ($LiFePO_4$)
	Capacity (kWh)	196
	Capacity (Ah)	320
Tire		275 / 70R 22.5
Rim		Aluminum Alloy
Speed	Max. Speed (km/h)	100
Turning Wheel	Turning radius (mm.)	11,086
Distance per one charge	Distance (km.)	190
Grade ability (%)		28
Air Conditioner		Electrical air Conditioner (15 kW)
CAN bus system		CAN communication system

3.7 Single and Multi-articulated Bus Design

An articulated bus is a bus split in two more sections, one front section and one or more rear section, with the sections connected by a flexible interface, making the bus able to bend. In almost all larger cites there are articulated buses, since they are longer than normal buses and therefore have an increased passenger capacity. This makes the mass transit system more effective.

For many of the articulated buses that use two sections, the engine are placed in the rear section but the motor is placed in the rear of first section of electric articulated bus. The benefit of this is more space for passengers and exit doors, as well as having a lower floor throughout the bus, thus making more space and making it easier to enter and leave the bus.

3.7.1 Articulated Bus Behaviors

The advantages of articulated buses have already been mentioned, the increased passenger capacity is the driving constraint that has pushed the development of them. The advantage over a conventional bus with the same passenger capacity is that the articulated bus can utilized roads with sharper turns.

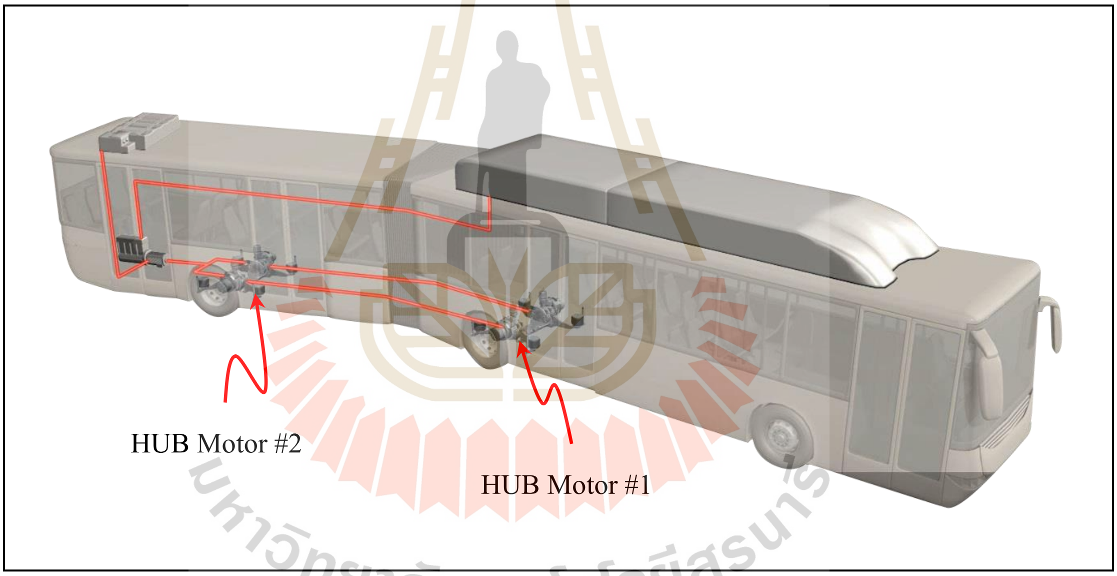

Figure 3.5 Electric articulated bus 2 section

The disadvantages of articulated buses with rear placed engines have to do with the dynamic of the bus. There are several driving cases at which the articulated bus has a safety-critical behavior, particularity on slippery surfaces such as Jackknifing (the accident of trailer to spin and collide with the cab) due to forward drive and continuously high steering angel, rear section sideway oscillations, mid-axle displacement due to rear section axle wheel-spin, also resulting in Jackknifing, Jackknifing due to reverse drive. The low friction might cause the rear section to swing out after a turn, creating a bend in the bus. A bend in the bus cause the rear section, where the engine is placed, to push the rear part of the front section sideway. This caused the whole front section to turn. It may have the result of whole bus oscillations. This behavior occurs primarily at the lane change maneuvers or evasive maneuvers. In order to limit and reduce these hazardous behaviors, these articulated buses are introduced to place motor in the rear of first section for easy control system as shown in Figure 3.5. The 240 kW rated electric powered axles of the vehicle are installed at rear of first section and at rear of second section.

3.7.2 Capacity of Articulated Bus Calculation

The capacity of articulated bus can be estimated by using equation 3.3. The equivalent of 3 m in the bus length is unusable for carrying passengers because of the driver cabin and the ingress-egress space at the doors. And also it can be assumed that the number of standing passenger is 60% of total passengers. The calculation result of articulated bus capacity can be shown in Table 3.3. (National Academies of Sciences, Engineering, and Medicine, 2013)

$$Capacity = (\text{Length}_{bus} - 3) \times 10 \qquad (3.3)$$

where

Capacity	is	Total passengers in bus capacity (person)
Length bus	is	The total bus length (m)

Table 3.3 Passenger capacity in each bus length

Bus Length (m)	6	10.8	12	15	18	24
Passengers (persons)	30	78	90	120	150	210

3.7.3 Power sizing of articulated bus

The power sizing design can be used as same as conventional of 12 m electric bus design. However, the concerning points are carry weight of passenger and the gross weight of articulated bus. In this chapter will show the result of power sizing by following equation (3.2) for each length type of articulated bus as in Table 3.4.

Table 3.4 Power sizing of articulated bus

Bus Length (m)	Articulated type	Weight (kg)	Power (kW)
18	2 section	28,000	564.17
24	3 section	39,200	783.33

The articulated bus 18 m and 24 m long represent for two and three section articulated bus type, respectively. The result show that the power requirement of 18 m and 24 m long bus require traction motor power for 564.17 kW and 783.33 kW, respectively. With this result, if the ZF AVE 130 axle HUB motor implemented, the 18 m and 24 m long must install 2 and 3 axles, respectively.

The world's first 18 m long pure electric articulated bus, fully low-floor double-articulated trolleybuses with two-axle hub motor drives have been successfully operated in line service in Geneva, Zurich, Lucerne and St. Gallen since 2015 as shown in Figure 3.6.

Figure 3.6 The first 18 m long pure electric articulated bus

3.8 Auxiliaries Component Design

Beside the power train system, this electric bus has sub systems and auxiliaries electric components such as air conditioner, DC to DC converter, auxiliary batteries, steering hydraulic pump and coolant system. The idea of design and/or calculation can be described as below.

3.8.1 Air Conditioner

The air conditioner system for bus should be selected considering a number of parameters, including passenger climatic conditions and power consumption. It is possible to determine whether a selected air conditioning system provides desired performance through estimation or testing. The cooling load calculation is implemented for this air conditioner design. The design cooling load (or heat) is the amount of heat energy to remove and maintain the room at interior design temperature. When worst case outdoor design temperature is being experienced. The overall thermal load encountered (QTot) by cabin is sum total of 1) Metabolic load (QMet), 2) Air infiltration as the exhaust load due to high temperature (QExh), 3) Blower motor heat load (such as engine load due to high temperature (QEng), generated due to ventilation (QVen), and thermal load created by air condition cycle (QAC)), 4) solar load from sheet metal (as reflected radiation load (QRef) and ambient load (QAmb)), 5) solar load glass (as direct load (QDir) and diffuse load (QDif)).

Metabolic load QMet is the sum of (M_{met} × BSA), where M_{met} is the passenger metabolic heat production rate. For driver and a sitting passenger, the value can be estimated as 85 W/m^2 (ISO8996, 2004) Ergonomics of the thermal environment determination of metabolic rate), respectively. BSA is the body surface area of bus (136 m^2). So that the QMet is 11,560 W.

Air infiltration load is amount of air leak that can be estimated at ½V m^3/h, where V is the vehicle speed in km/h Let assuming vehicle speed at 60 km/h has air volume leaked is 25 m^3/h and enthalpy of infiltration air – enthalpy of cabin air is 74 m^3/h. Air infiltration load is 25 × air density × (enthalpy of infiltration air – enthalpy of cabin air) (Ali, Sunil, and Muhammed, 2007). Thus the air infiltration load is 25 × 1 × 74 ×1000/3600 = 513.89 W

Heat generated by blower motor is blower wattage × load factor / efficiency (Ali, Sunil, and Muhammed, 2007). The blower wattage has 420 W and assuming the load factor is 0.8 with efficiency 95%. Thus the heat generated by blower is 420 × 0.8 ×0.95 = 353.68 W.

Solar load radiation hits ceiling, side wall glass etc. External surface temperature depends on solar radiation and plate absorption ratio. Vehicle body is assumed black for conservative design. Solar radiation does not hit directly for places like floor, dash board etc. Select the vehicle exterior body material with low thermal conductivity. Heat penetration from glass surface depends on respective window inclination angle. Heat load due to sheet metal can be estimated as $Us \times As \times (\Delta T)$s (Ali, Sunil, and Muhammed, 2007). The Solar load from sheet metal is overall heat transfer coefficient of roof, door, side wall, fire wall and rear wall. It can be assumed as 2.3 W/m^2K, surface cabin and passenger room temperature at 45 ^oC and 18 ^oC, respectively with the total area 36 m^2. Thus the heat load for sheet metal is 2.3 × (45-18) × 36 = 2,235 W.

Heat load due to glasses (Ali, Sunil, and Muhammed, 2007) can be estimated as $Ug \times Ag \times (\Delta T)g$ + (diffused radiation) + (direct radiation) × $cos(i) \times \tau$, where Us and Ug are the overall heat transfer coefficient roof, door and rear wall for sheet meat and glass, respectively. ΔT is the surface temperature and cabin temperature (^oC). i is sun's incidence angle on glass. τ is the transmissivity of glass. The parameter of heat transfer coefficient in SI units, as watts per square meter times Kelvin can be funded in appendix A. Solar load glass can be calculated by assuming all parameters are overall heat transfer coefficient is 7.9, and surface cabin and passenger room temperature are at 45 ^oC and 18 ^oC, respectively, the total glass area is 3.37 m^2. The diffuse radiation is calculated by glass diffusion coefficient (0.28) × solar load (1,200) × glass area × transmissivity of glass (0.84). The direct radiation is calculated by glass direct radiation coefficient from (0.72) × solar load (1,200) × glass area × transmissivity of glass (0.84). Thus the heat load from glass is 7.9 × 3.37 × (45 - 18) + ((0.28 × 1,200) × 3.37×0.84) + ((0.72 × 1,200) × 3.37 × 0.84) × cos 60 × 3.37× 0.84 = 2,892.88 W. For the radiation heat transfer coefficient values are available in Appendix A.

The overall thermal load encountered (QTot) can be calculated by 11,560 + 513.89 + 353.68 + 2,235 + 2,892.88 = 17,555.45 W. PEA Zero-emission electric bus is installed for 15 kW of air conditioner regarding available in supplier catalogue.

3.8.2 Vehicle Cooling System

The diagram in Figure 3.7 shows a simple presentation of the components in the cooling circuit, necessary for the cooling of traction motor and the traction inverters. The cooling system is designed in a way that the cold medium first flows through the traction inverters and afterwards through the traction motors. The cooling outlet of the traction motor is connected to the inlet of the heat exchanger. The throttle valve is used to adjust the flow rate which enters the cooling circuit of the electric drive system and the distribution of the cooling fluid to other components connected serial to the traction system at the same heat exchanger. The cooling fluid pump in heat exchanger is electrical operated and powered by 24 V electrical system. PEA Zero-emission electric bus cooling system is designed according to the fluid flow rate requirement at 14-22 liter/m^3 with pressure 105-240 bar of traction motor.

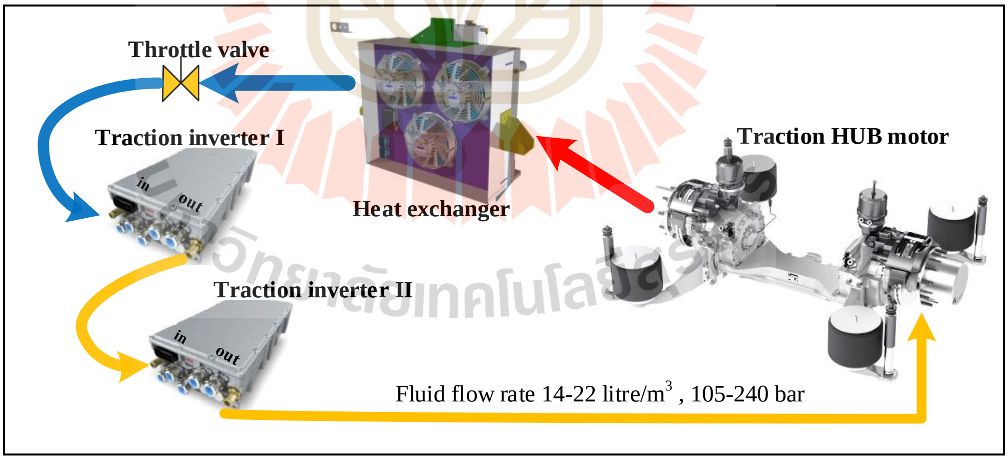

Figure 3.7 Diagram of cooling system

3.8.3 Vehicle Air Compressor System

PEA Zero-emission electric bus is equipped with pneumatic operated devices for instance pneumatically operated doors, pneumatic suspension, and braking system. The compressed air system in Figure 3.8 includes the air compressor, compressor inlet line and discharge lines, air governor with signal of pressure sensor, air dryer with oil separator, 5 compressor tanks (25 liter) , and air consumption devices. The key factor, which determines the reliability and durability of an air compressor in an application, is the amount of time the air compressor is supplying air during the vehicle operation, known as the duty cycle of the compressor. Compressor is not designed to pump continuously because compressors generate a lot of heat when pumping, which is dissipated during the time. If the compressor duty cycle is very high, the compressor will operate at higher temperatures and potentially begin to overheat, which reduces the sealing of the piston rings, allowing more oil to pass in the compressed air discharge cavity. So that the motor pump of 3 kW three phase 220 Vac, 50 Hz is installed to supply 9.8 Bar with 26 liter/min which is enough for 5 air tanks (25 liter capacity per tank). The 3 kW of motor inverter with 650 Vdc input and three phase 220 Vac 50 Hz output is designed and installed.

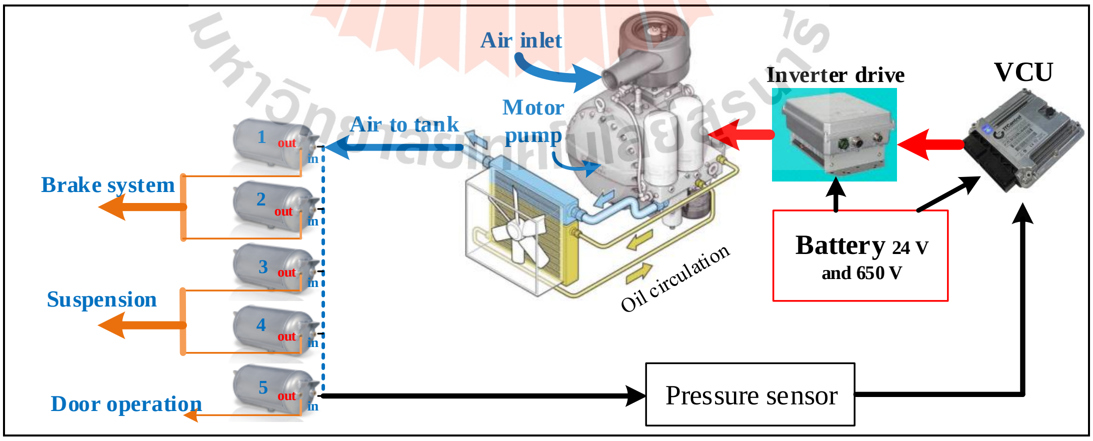

Figure 3.8 Diagram of air compressor system

3.8.4 Vehicle Hydraulic Steering System

Power steering is a system for reducing the steering effort by using an external power source to assist in turning the wheels. Conventional diesel bus power steering systems using and engine accessory belt to drive pump, providing pressurized fluid that operates a piston in the power steering gear or actuator to assist the driver. In electro-hydraulic steering system, a high efficiency pump is used which is driven by an electric motor. Pump speed is regulated by an electric controller to vary pump pressure and flow, providing steering efforts for different driving situations. In PEA Zero-emission bus is designed to use flow control method of the system by solenoid valve that is located at the pump discharge port. The electronic control device regulates the solenoid valve opening at high vehicle speeds to reduce the pump discharge volume to increase the required steering effort. The flow of hydraulic fluid to power cylinder is reduced when driving at high speeds, so that the magnitude of the steering response rate and the steering reaction force are balanced at a point of equilibrium.

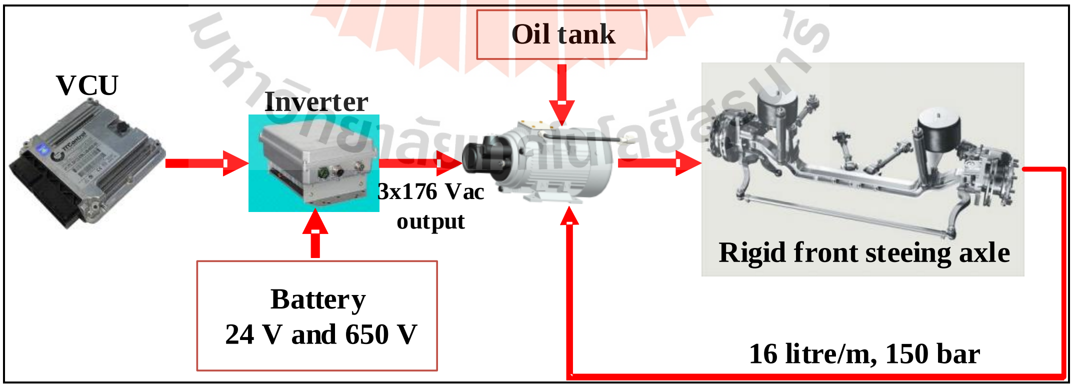

Figure 3.9 Diagram of electric power steering system

The electric power steering system is installed of 150 Bar of hydraulic pressure power steering requirement. It is found that the three phase AC asynchronous motor type of 3 kW rate power with three phase 220 Vac, 50 Hz input is met as system requirement. So that the motor drive DC/AC inverter has 3 kW power input and three phase 220 Vac, 50 Hz output of specification is implemented.

3.9 Advantages and Disadvantages of Hub Motor

The hub motor technology has a good trend in future for electric bus manufacturing. The advantages and disadvantages of hub motor can be discussed in detail.

Advantages of hub motors:

1. As hub motors are directly incorporated to chassis and bus body, it is simple and easy mounting. This feature helps to easily manufacture and fast production.

2. The bus doesn't need to install the differential gear box for wheel.

3. Hub motors are outside rotor motors so that they have a 1:1 motor ratio. Every time the motor does one revolution as the wheel does.

4. Hub motors are design in wheels, which means the motor gives a higher torque. A higher torque is critical for the initial start of the vehicle.

5. Hub motors have not any kind of gears or chain transmission which increases the operating efficiency of the vehicle compared to its counterparts. In addition, hub motors does not need to use any oil which may contaminate the product. It means that, the vehicle will have lower weight regarding absence of gears box and transmission parts.

Disadvantages of hub motors:

1. Regarding the motor in the wheel, the electrical connections must be between the wheel and the body making the harness connections more complex, stress, and increase the risk of fire hazards.

2. Although hub motors are well waterproof, but the connector for electric cable need high warning to install.

3. Motor cooling system is always an issue because of the hub motor configuration. The cooling system is suitable cooling at outer stator cage configuration but need complex technology which might get impacted on the motor reliability and performance.

Hub motors have both advantages and disadvantages but it can see the advantages outweigh the disadvantages. This is the proving that a lot of potential for hub motors configuration to be used in electric vehicle. The strong research and development effort to make sure the design able to withstand the mechanical, thermal and electrical to the motor installation. Critical aspects should be proper motor cooling and electrical water resistance while driving on road.

3.10 Conclusion

This PEA Zero-emission electric bus development is introduced alternative bus technology of design concept as low floor bus, swap batteries, plugged in charging and hub motor. The design concept of battery at 600 V system is defined by reaching maximum efficiency of traction motor power. At high voltage level design has also the advantage to save weight but it is harder to get components because they are not much supplier. The 2×120 kW rate power of traction hub motor sizing is calculated and designed by using available parameters. The battery capacity size can be calculated and estimated method and using drive cycle method. It shows the 328 Ah per calculation result for PEA Zero-emission bus for 190 km drive per charge.

CHAPTER IV

SIMULATION AND TESTING RESULT

4.1 Introduction

In this chapter presents the traction motor simulation and test in laboratory test bench to understand the characteristic of traction motor. Parameters of this motor are tested with good application with inverter for control system. It is also presented the electric bus driving test in real road condition. The testing result shows good performance in the prototype of electric bus design that can be developed and implemented for Thailand's publication bus.

4.2 Motor Simulation and Measurement

We propose to simulate the traction motor and measurement comparison with emphasize on the behavior of the induction motor. The simulation data results are calculated from principal equation of traction motor for a configuration of the asynchronous motor which implemented in prototype electric bus. For the measurement, we has the outstanding cooperation with laboratory test bench in DRIVETEK AG, Switzerland. The Drivetek lab is a tailored laboratory for testing, validation and characterizing a broad range of electric drive system and motor (DC, Brushless, AC induction, Synchronous, Asynchronous, etc.) in difference configurations as well as for parameterization and optimizations of electric machines. The high power level is up to 250 kW and the wide range of power supply as shown in Figure 4.1. The operator room is separated from the test cabins and protected for a safe and convenient test environment as show in Figure 4.2.

Figure 4.1 DRIVETEK AG test bench of traction motor

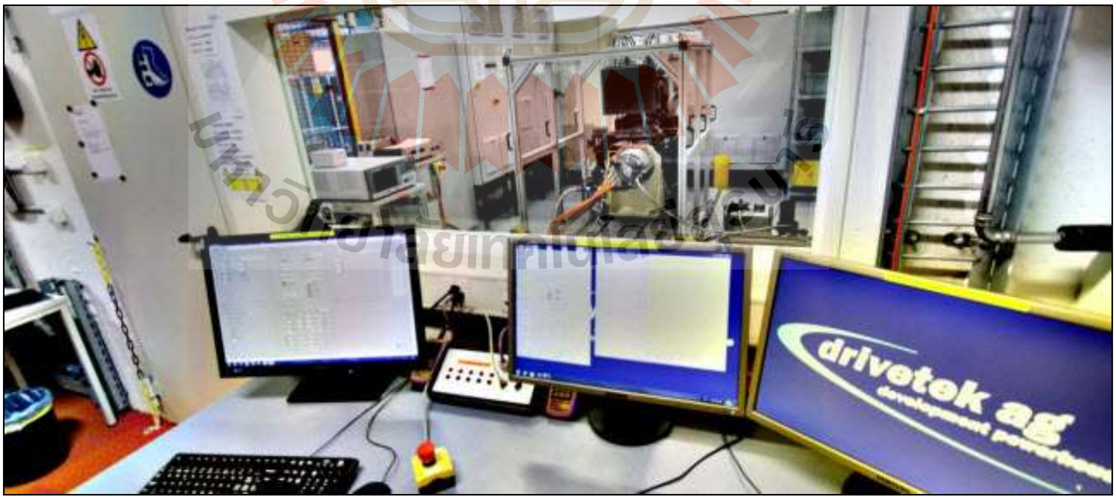

Figure 4.2 DRIVETEK AG's operator room

The simulation of speed-torque, motor power, slip and flux of motor are calculated and studied follow asynchronous principal equation. The speed-torque can be shown in Figure 4.3. The power of motor has ability to reach the maximum power at 173.35 kW at 4,548 rpm of motor speed. The comparison of power with and without limitation of torque as shown in Figure 4.4. For without limitation control system in blue line, the power of motor can reach to 173.35 kW but it will cause to damage the gear box so that the software of inverter control will limit at 120 kW rate (in red line). At heavy torque (large current), the magnetic circuit saturates and the speed-torque curve approaches constant and a straight line. The power is limited by using Id current and mutual inductance which can show the relation as in Figure 4.5. The most simply control in induction motor using two currents called direct (Id) and quadrature (Iq) are responsible for producing flux and torque as shown in Figure 4.6.

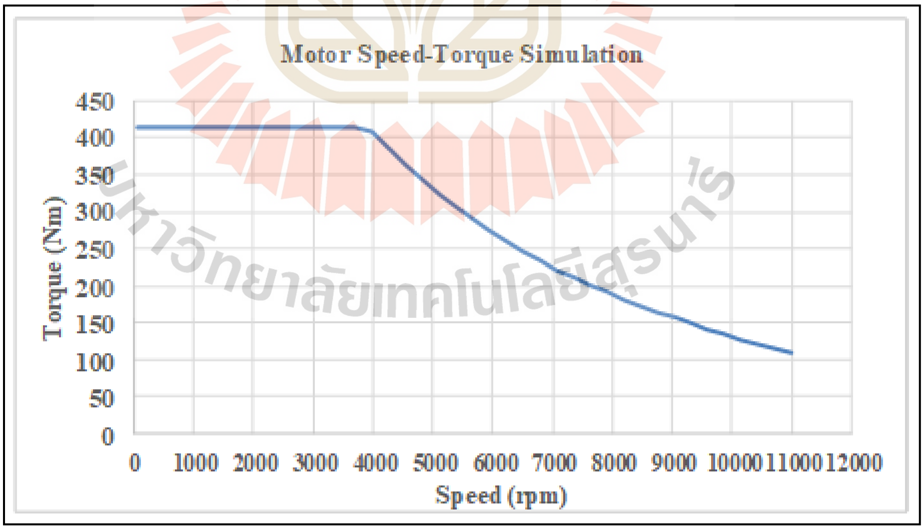

Figure 4.3 Simulation data of speed-torque curve

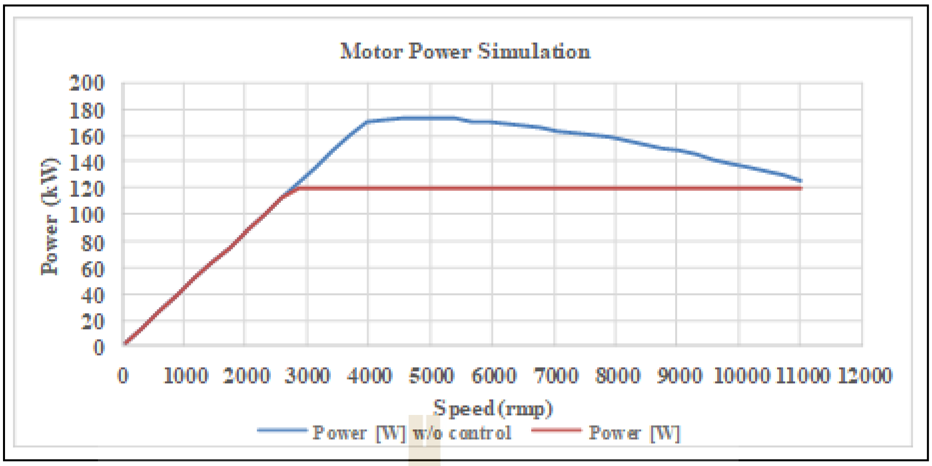

Figure 4.4 Simulation data of motor power with and without Id limitation control

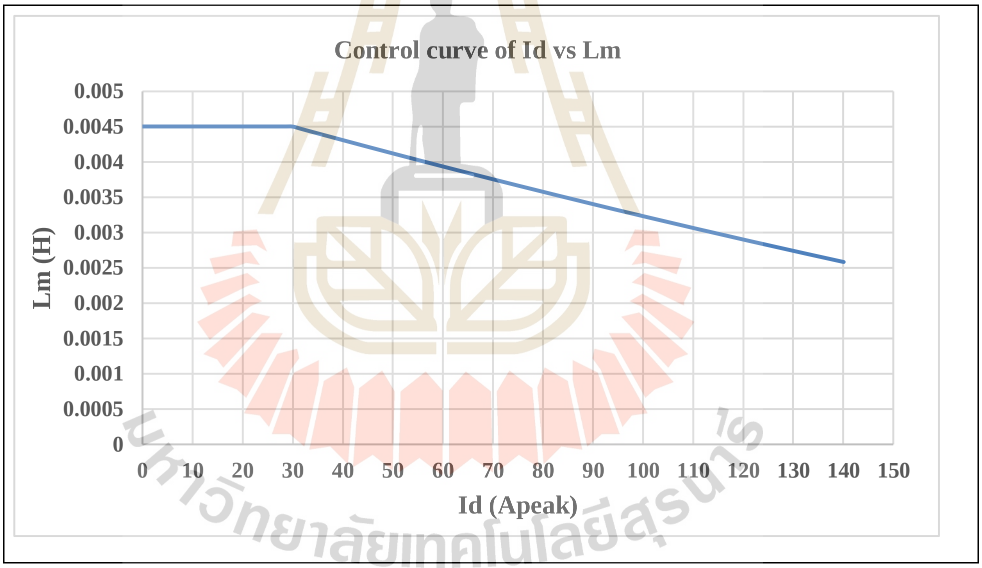

Figure 4.5 Direct current (Id) control value curve

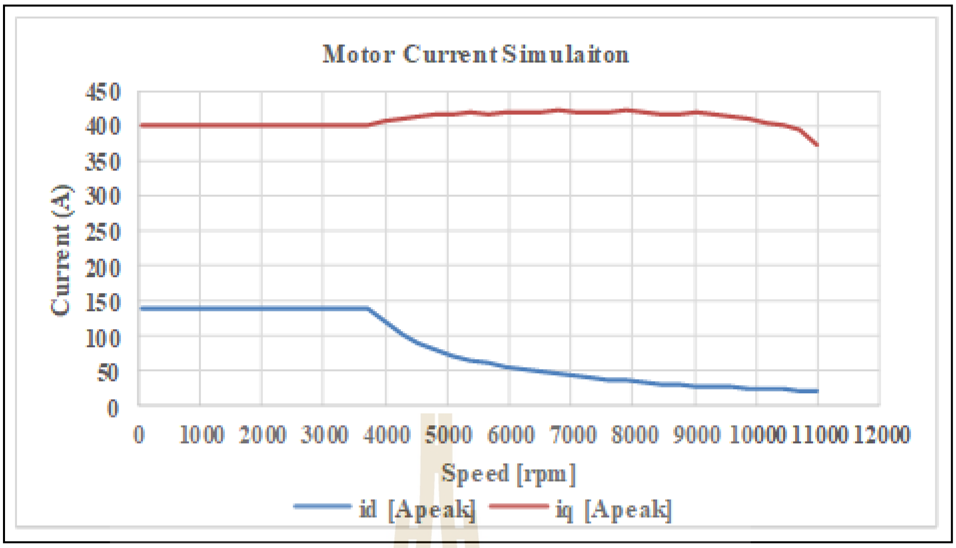

Figure 4.6 Simulation of Id and Iq result

The relative speed between the stator rotating field and the rotor so called slip speed (ω_{sl}) can be simulated as shown in Figure 4.7.

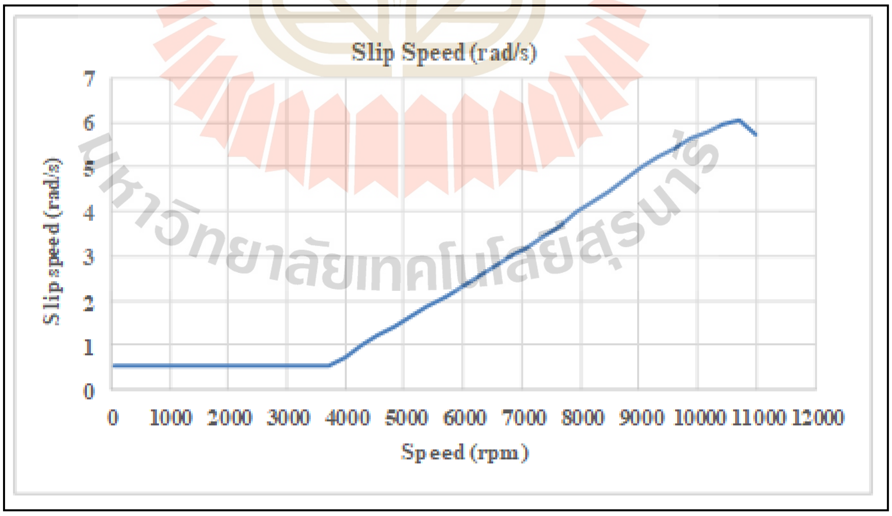

Figure 4.7 Slip speed curve (ω_{sl}) simulation

For the motor test, we will study the motor performance in that aim to implement in Thailand. We use variety of temperature condition at 25, 60 and 120 degree Celsius for our assessment by heating the coolant water system to bias motor as same as temperature environment in Thailand. The simulation compare to motor test data in three different of temperature conditions can be shown in Figure 4.8–4.11.

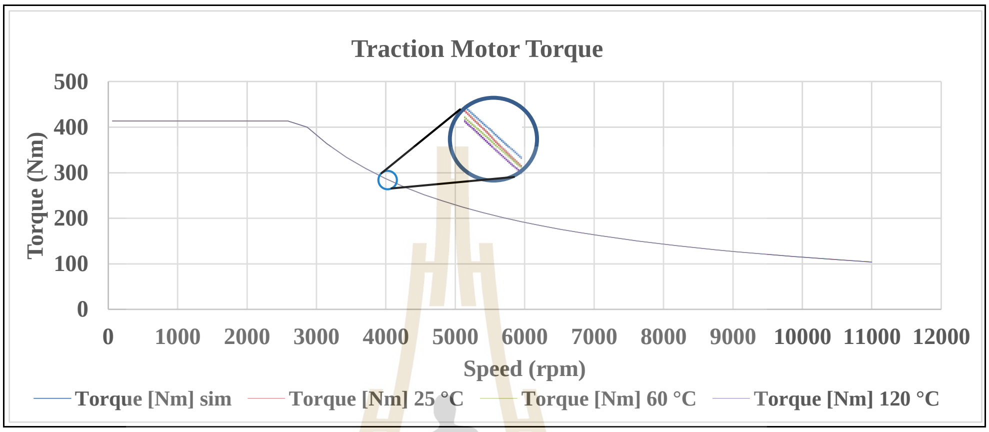

Figure 4.8 Measurement of motor torque

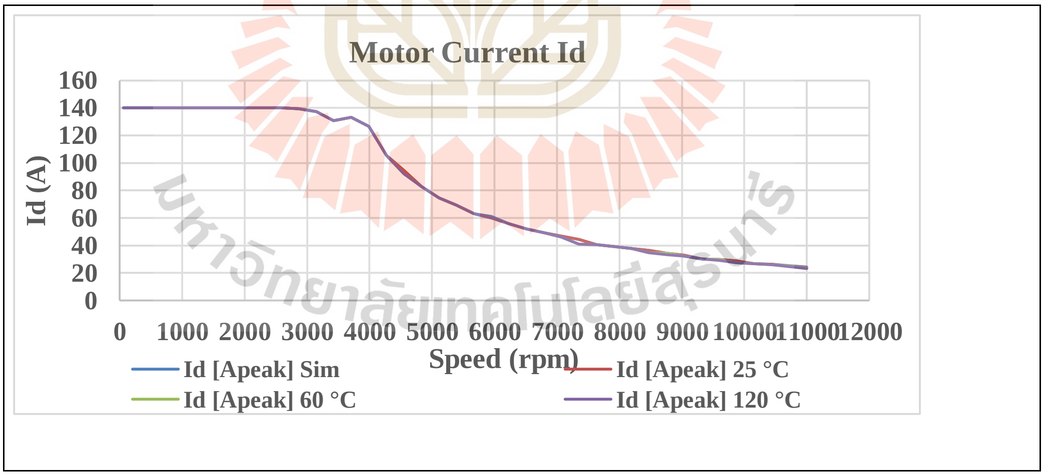

Figure 4.9 Measurement of motor current (Id)

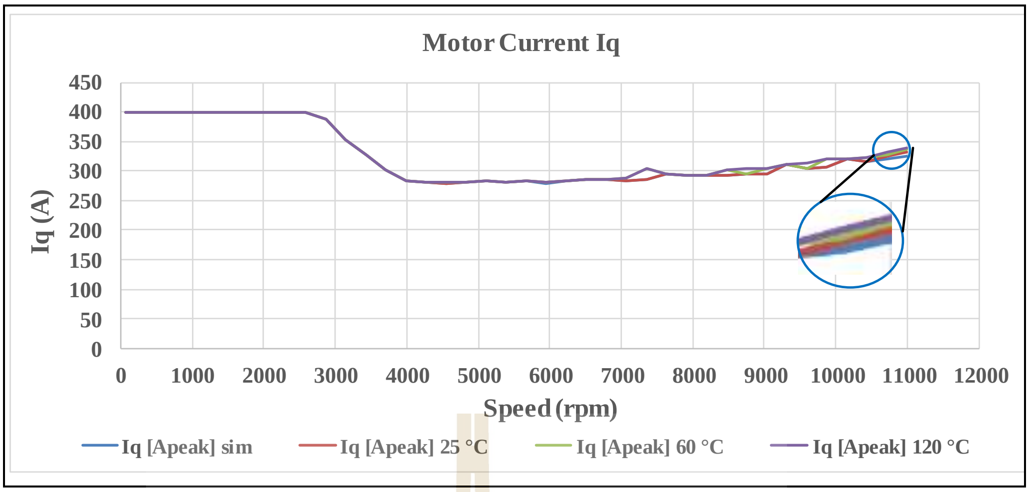

Figure 4.10 Measurement of motor current (Iq)

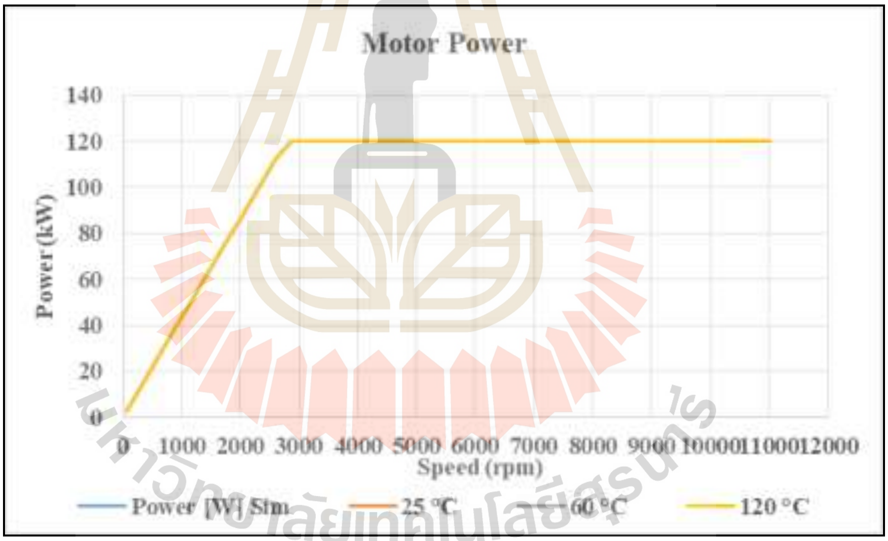

Figure 4.11 Measurement of motor power

The collected data of absolute peak voltage (Vdq) that supply to induction motor shown in Figure 4.12. The peak voltage (Vdq) rises up from 18 Vpeak to 324 Vpeak constant at motor speed 3,987 rpm.

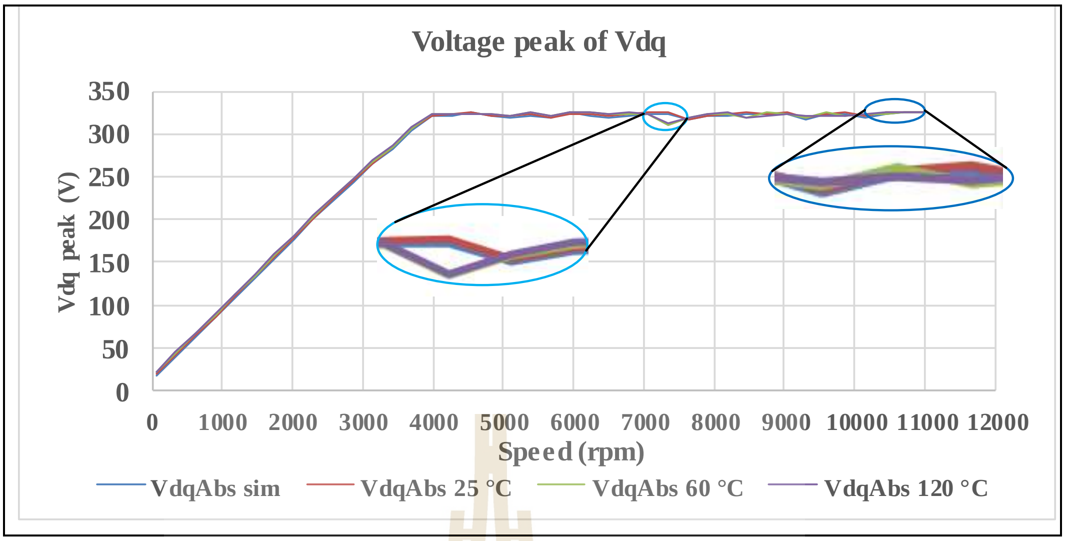

Figure 4.12 Measurement of absolute peak voltage (Vdq)

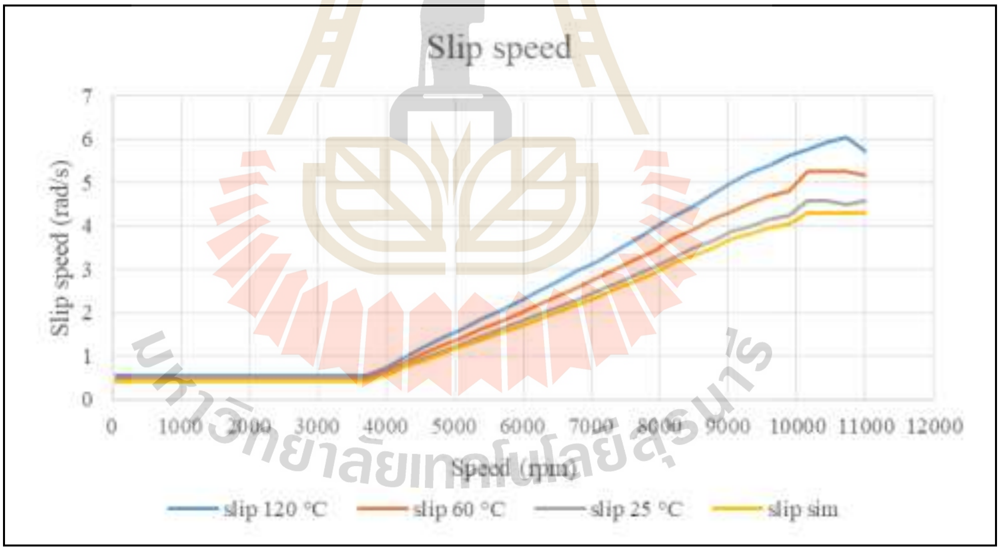

Figure 4.13 Measurement of motor slip speed

When motor speed is beyond its rate speed, the voltage reaches its rated value and cannot be increased with the frequency. In this case, the voltage is fixed at 600 V and the frequency increased continuously with the motor speed. The motor goes into the field weakening operation. The slip is fixed to its rated value corresponding to the rated frequency, and the slip speed (ω_{sl}) increases linearly with the motor speed. This control approach results in constant power operation as show in Figure 4.13. From motor test result, the result of 25 ^{o}C lines have almost the same simulation line and it could be noticed that the operation temperature control at below 60 ^{o}C is suitable for the motor application which compared to simulation result.

4.3 Electric Bus Driving Test at SUT

The road attitude condition at Suranaree University of Technology (SUT) is designed to test for this study regarding the safety issue reason. The route scenario (green line) can be shown in Figure 4.14. The distance of one round is approximate 13 km. The attitude of route has the high at 227.6-274.6 m of sea level as shown in Figure 4.15. The distance of driving test study has more than 1,000 km of data collection for power consumption analysis. There are 8 scenario testing in the same route at SUT with 10 - 40 passengers in this test scenario with full air conditioner access to control passenger's room temperature at 20 ^{o}C. The sample photo taken during driving test can be shown in Figure 4.16. The collected data of important parameters are expressed in Figure 4.17 to Figure 4.27. The data are plotted for 8 scenarios in the row by scenario 1 to 8 start time at 0, 6th, 29th, 50th, 77th, 91th, 126th, and 170th hr, respectively. The driving test results express in table 4.1. The power consumption rate of this electric bus from 1010.231 km distance is 0.883 kWh/km. The power consumption effectiveness is driver behavior and driving speed of this driving test.

Figure 4.14 Driving test route in SUT

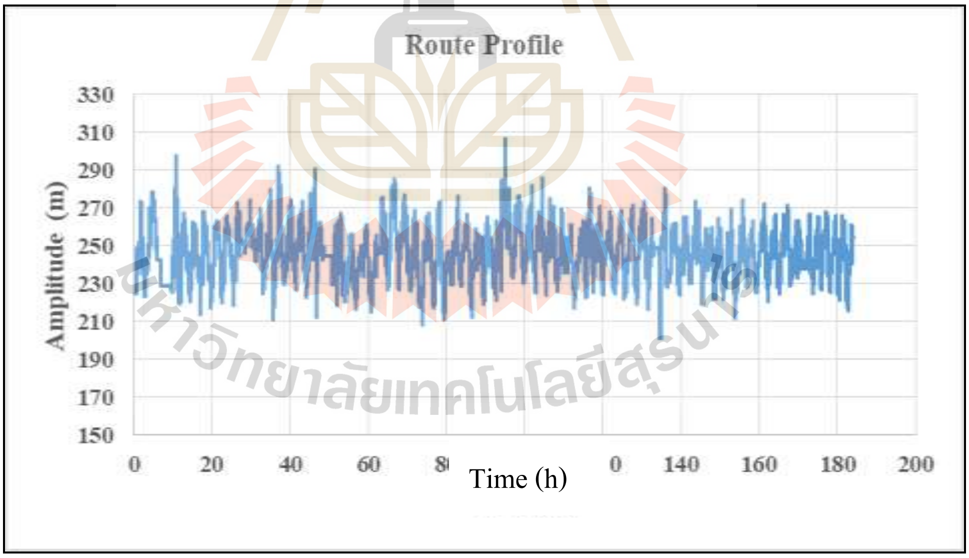

Figure 4.15 Route test attitude from sea level

Figure 4.16 Photos taken during driving test

Table 4.1 Electric bus driving test in SUT route

Scenario	Power consumption (kWh)	Distance (km)	Power consumption rate (kWh/km)	Ave. speed (km/h)	Max. speed (km/h)
1	79.184	88.262	0.897	25.262	62.442
2	147.392	145.000	1.016	26.186	69.039
3	128.576	143.809	0.894	32.694	67.487
4	141.904	153.770	0.923	32.771	76.344
5	33.712	55.409	0.608	34.215	61.683
6	138.768	134.807	1.029	30.171	71.933
7	72.912	83.645	0.872	34.612	67.129
8	149.744	205.530	0.729	30.731	65.705
Total	892.192	1010.231	0.883		

From the testing result shows that the power consumption rate is 0.883 kWh/km with 1,010.23 km test distance, approximate average speed at 34 km/h and maximum speed at 79.705 km/hr. The amount of passenger, driving speed, ambient and passenger room temperature setting up, condition and amplitude of route and driver behavior are effected with power consumption of battery. The most power consumption is driving speed. The more driving speed is used, the more power consumed. The sample collected data can be show in Figure 4.17-4.27.

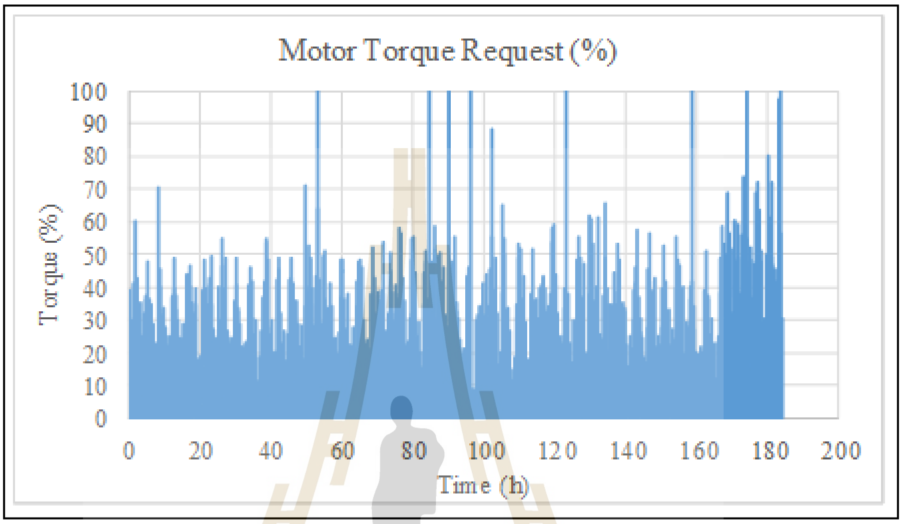

Figure 4.17 Request torque during drive test at SUT

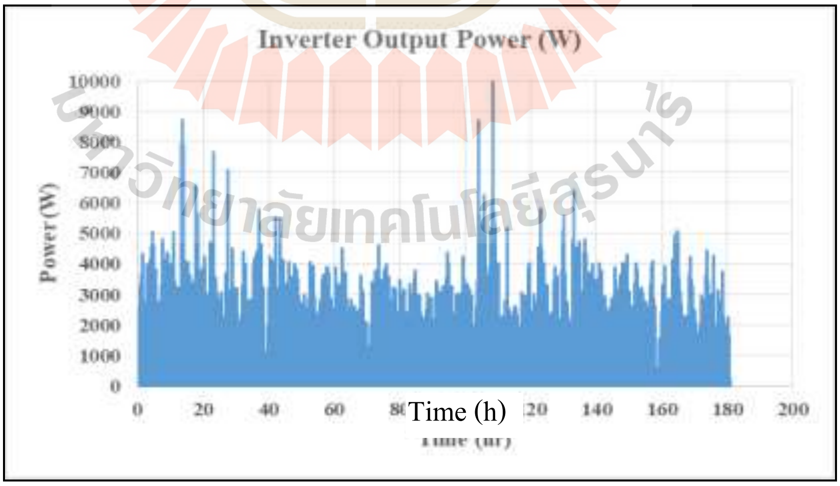

Figure 4.18 Inverter output power monitoring data during drive test

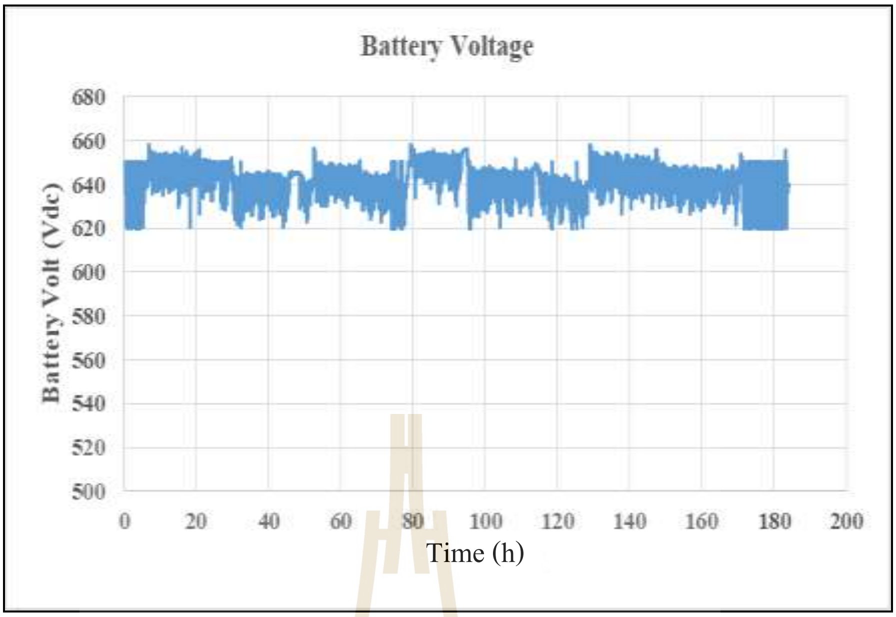

Figure 4.19 Battery voltage monitoring data during drive test

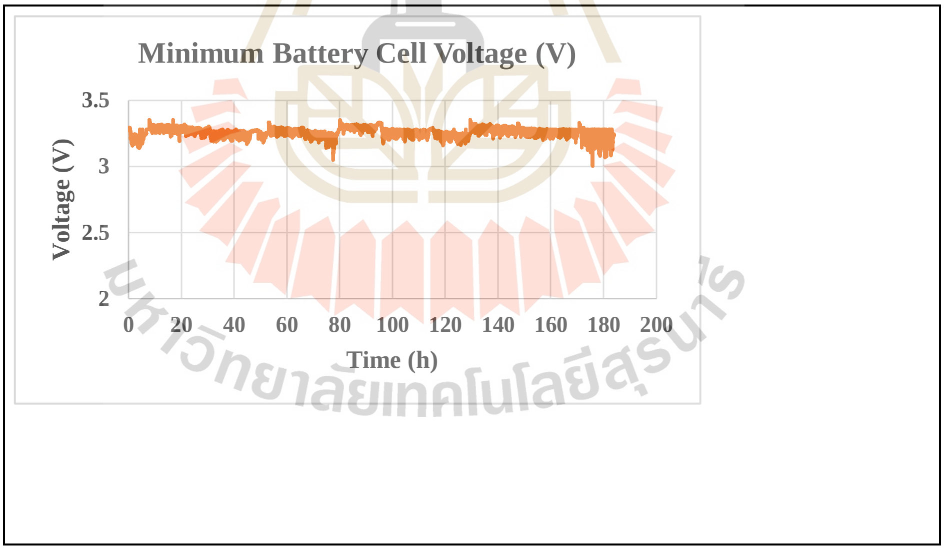

Figure 4.20 Minimum battery cell voltage monitoring data during drive test

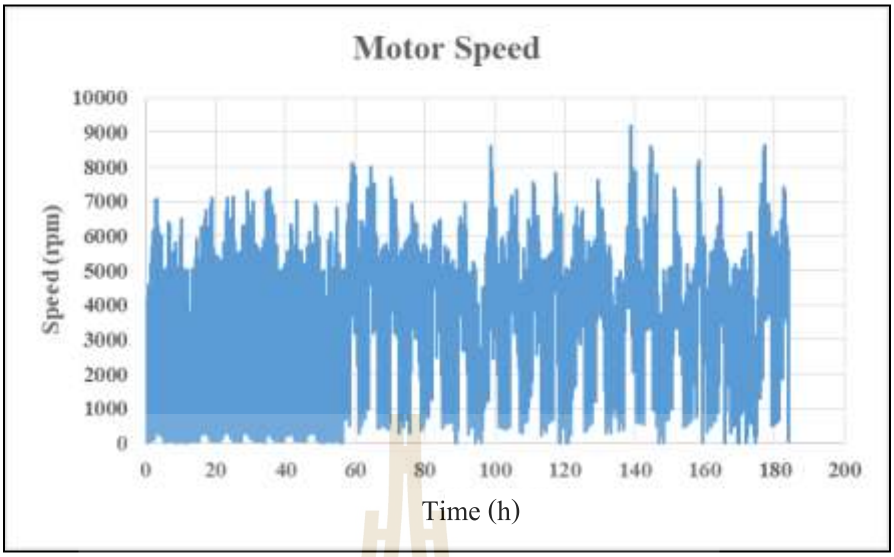

Figure 4.21 Motor speed monitoring data during drive test

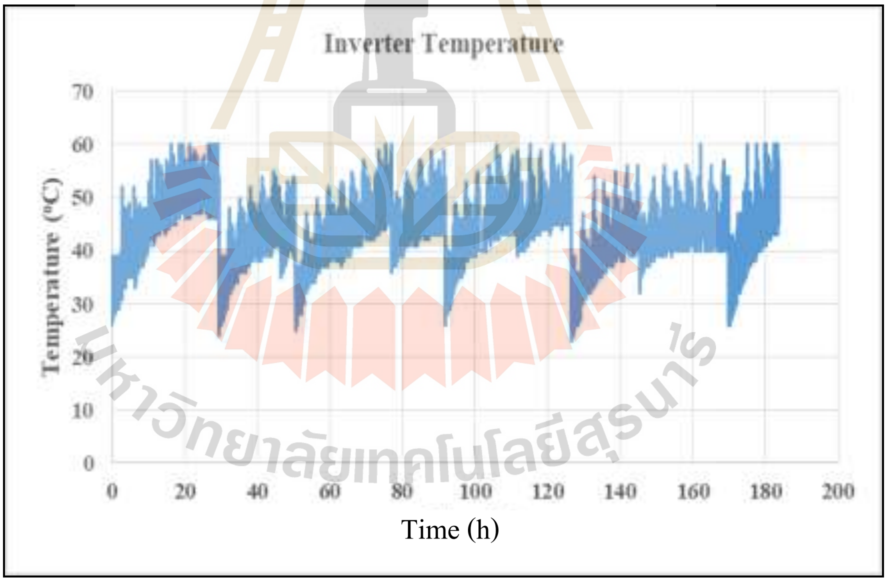

Figure 4.22 Temperature of inverter monitoring data

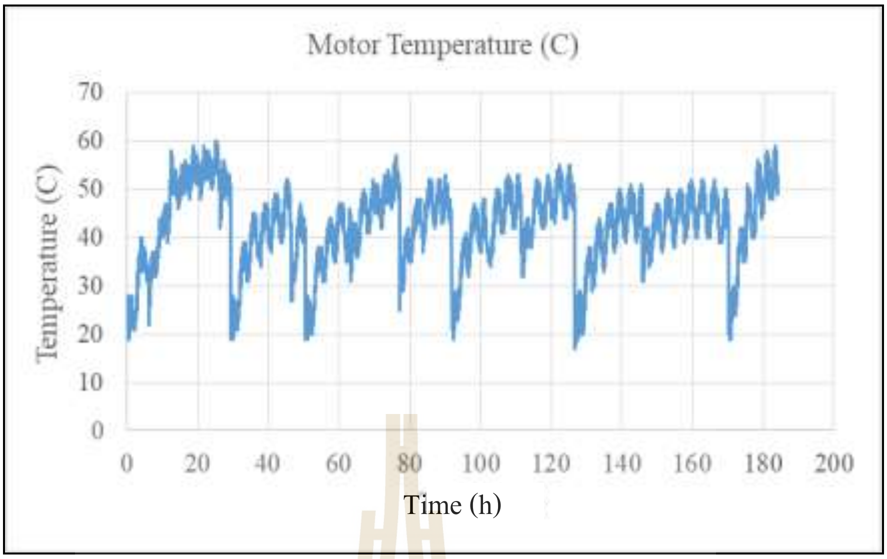

Figure 4.23 Motor temperature monitoring during testing drive at SUT

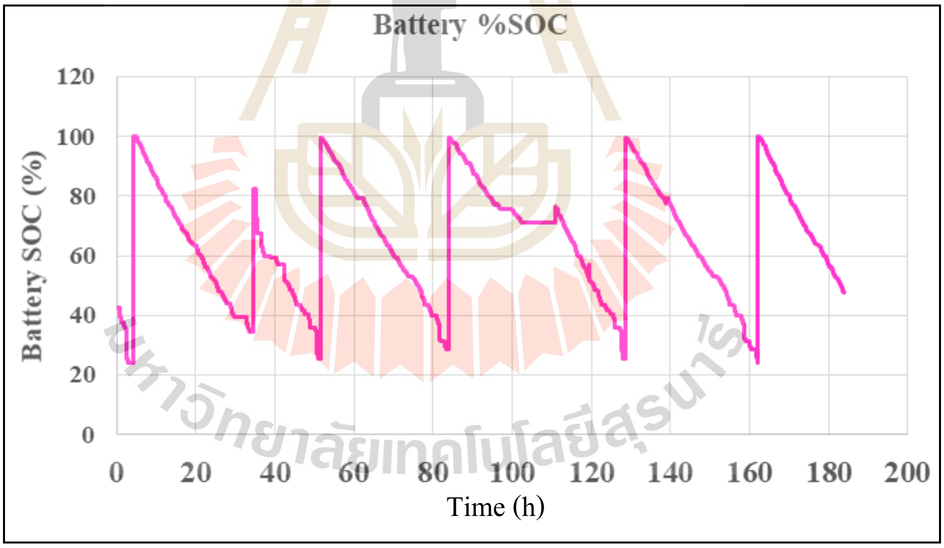

Figure 4.24 Battery SOC (%) during testing drive at SUT

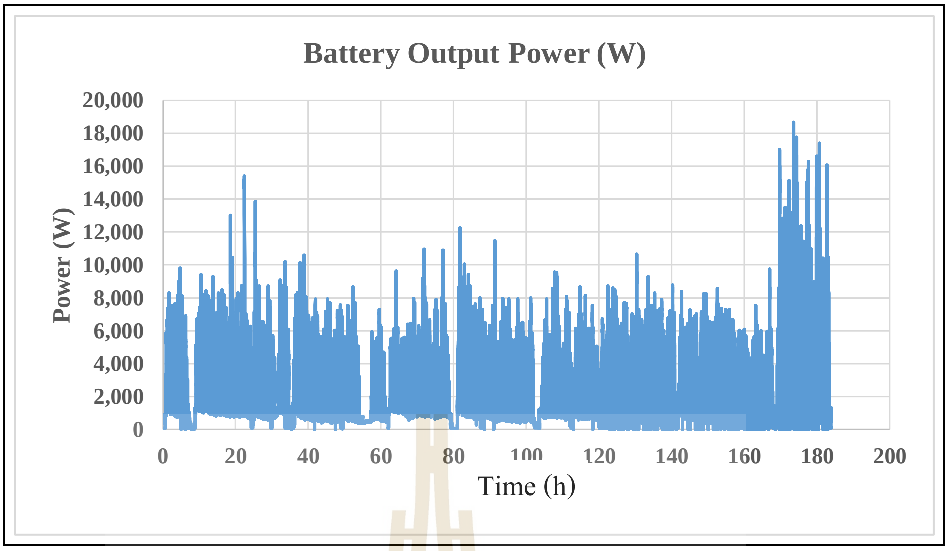

Figure 4.25 Battery power output monitoring data during drive test

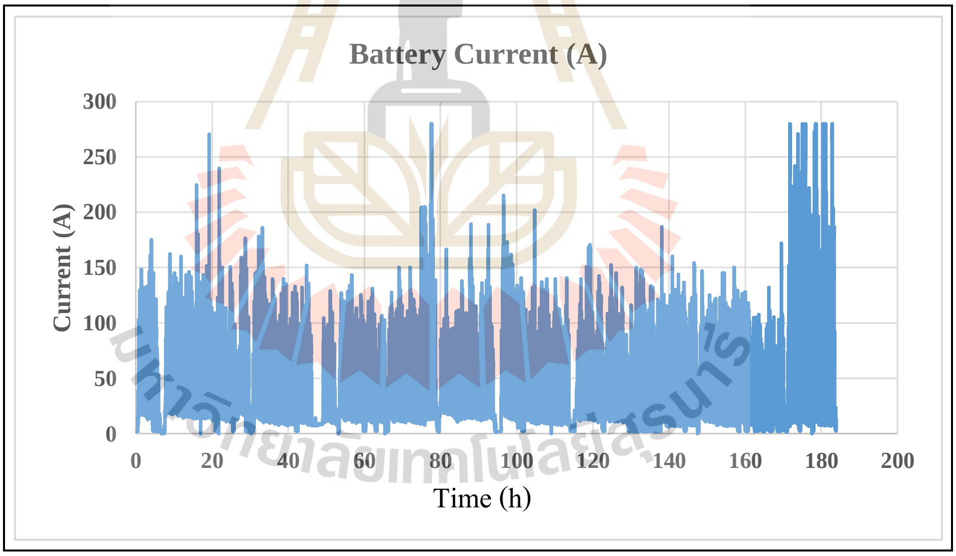

Figure 4.26 Battery output current monitoring during drive test

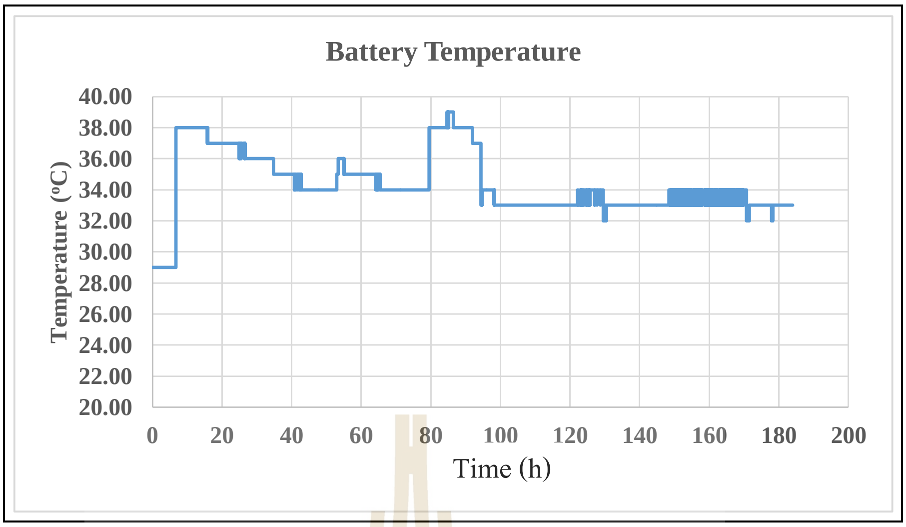

Figure 4.27 Battery maximum temperature of battery during drive test

The battery voltage output and minimum battery cell voltage stay in control of operation voltage of electric bus system design at 620-660 Vdc and 3.0-3.3 Vdc, respectively as show in Figure 4.19-4.20. The output voltage will decrease regarding the battery duration and power request of varied operation load. The speed of motor has 0-10,000 rpm with nominal speed at 4,700 rpm as in Figure 4.21. The highest operation temperature of inverter is in range of 23-60^{o}C with nominal temperature at 42^{o}C as shown in Figure 4.22. The motor temperature during driving test has 20-60^{o}C with nominal temperature at 60^{o}C as shown in Figure 4.23. The battery property can be shown in Figure 4.24-4.27. The battery SOC% decreases from 100%SOC in Figure 4.24. The maximum battery power output has 18,500W during the drive test in Figure 4.25. The maximum battery current is 275 A in Figure 4.26 and the highest battery temperature during drive test is 34^{o}C in Figure 4.27. As the result of driving test, eight scenarios with four passenger groups are studied and analysed for the power consumption. In term of power consumption, it illustrates that all alternative scenarios have fulfilled the power consumption of a trip must not be more than 80% of the battery capacity. The power consumption is direct variation of driving speed and number of passenger. In the same amount of passenger group, it significantly shows the more speed drive, the more power consume.

In the result of power consumption in some group that have not much significant different even higher driving speed in scenario 2 and scenario 3. The average speed of scenario 3 is higher than scenario 2 with less number of passenger but in scenario 3 has higher power consumption. It may cause of high power consumption of air conditioner to control temperature in passenger room. In a fact that, it is difficult to control passenger room temperature regarding the outside temperature is vary during driving test. Another one concern for power consumption in this study, the temperature of operation design is also effected with the power consumption. It will consume more power consumption when the component working in high temperature.

In the coolant controlled design, in main components such as inverter, motor and battery are seriously designed with the cooling system. In the hot country zone such as Southeast Asia countries, must have good design for the operation temperature level. In this study, the motor temperature is controlled at 60 ^{o}C maximum. It is properly implemented for this electric bus control system regarding motor studied test in laboratory result. The motor torque are good operation at below 60^{o}C and less torque in higher temperature. In above result shows that the prototype electric bus have a good design of cooling system that feasible to be applied with electric bus in Thailand.

4.4 Electric Bus Driving Test in City to City

This scenario is different with previous road test at SUT. The electric bus will drive in higher speed to simulate the city to city driving test. The Burphavidh Tollways in Bangkok is selected for the driving test from PEA-center to PEA-Rangsit was used as the test route in real traffic conditions as shown in Figure 4.28. Vehicle speed and route gradient were recorded after every second using a GPS device.

Figure 4.28 Trajectory of power consumption in Burphavidh Tollways in Bangkok

Driving the bus from PEA-Center to PEA-Rangsit and back, the recorded vehicle speed and route gradient were as shown in Figure 4.29 and Figure 4.30, respectively. The red and blue lines represent vehicle speed and route gradient respectively. Summary of the test results is given in table 4.2. Average power consumption per kilometer recorded from battery management system is 0.9 kWh/km from PEA-Center to PEA-Rangsit and 1.3 kWh/km from PEA-Rangsit to PEA-Center. From the result shows that the vehicle speed is the most effective with power consumption of electric bus. These test results can be used to estimate power consumption and battery capacity when designing other electric buses in future.

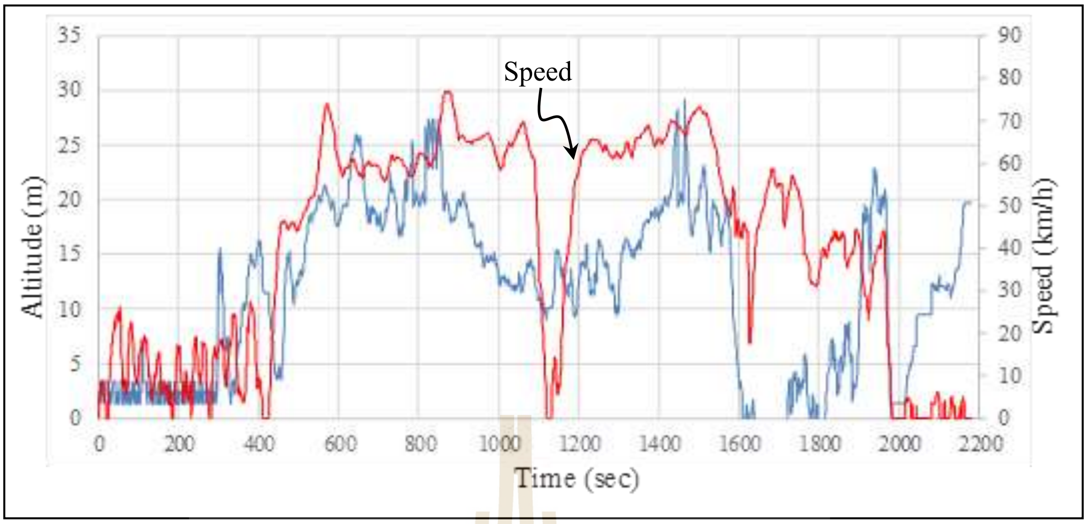

Figure 4.29 Drive test profile from PEA center to PEA Rangsit

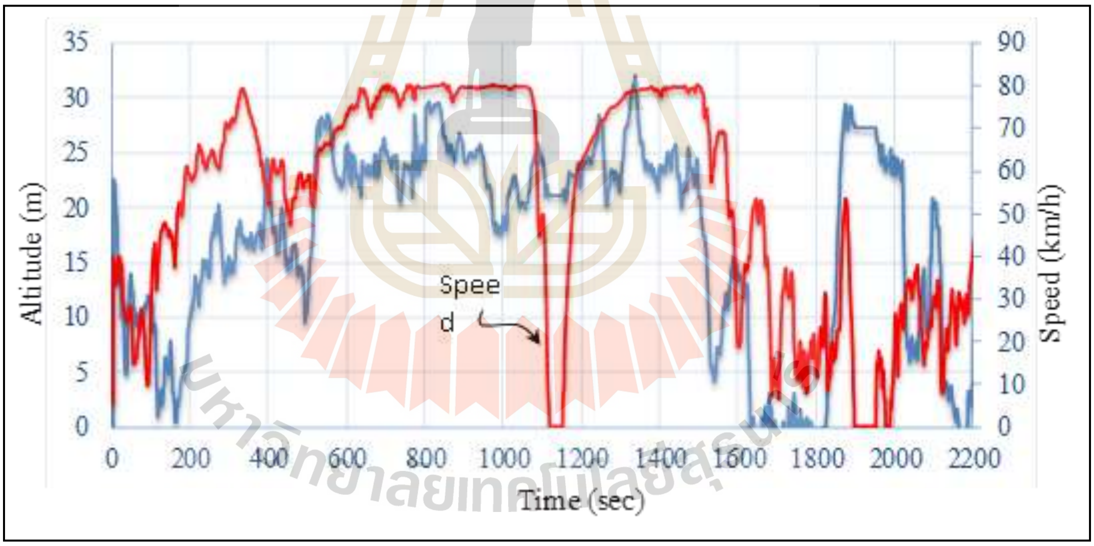

Figure 4.30 Drive test profile from PEA Rangsit to PEA center

Table 4.2 Summary of PEA Zero-emission electric bus test result

Attribute	PEA center to PEA Rangsit	PEA Rangsit to PEA center
Time (min)	37.7	40.6
Distance (km)	25.2	28.8
Maximum speed (km/h)	76.9	80.5
Average speed (km/h)	39.5	50.9
Outdoor temperature (^{0}C)	39.0	40.0
Indoor temperature (^{0}C)	23.0	23.0
Net Energy consumed (kWh)	24.8	39.2
Power consumption per kilometer (kWh/km)	0.9	1.3

4.5 Electric Versus Engine Bus Driving Test

This scenario will be studied the power consumption rate of electric bus compare with engine bus. The driving test conditions are the same route, amount of passengers, driver and approximate speed. The driving route has 30 passengers (total weight 1,971 kg) and approximate 16 km of distance as shown in Figure 4.31. The drive test result can be shown in table 4.3 and Figure 4.32-4.33. For scenario A to B and B to A point for without passenger condition has 16.188 km distance, the average velocity is approximate 62 km/h with power consumption 10.976 kWh and power consumption rate at 0.678 kWh/km. For drive test with 30 passengers has power consumption 17.248 kWh and power consumption rate at 1.096 kWh/km.

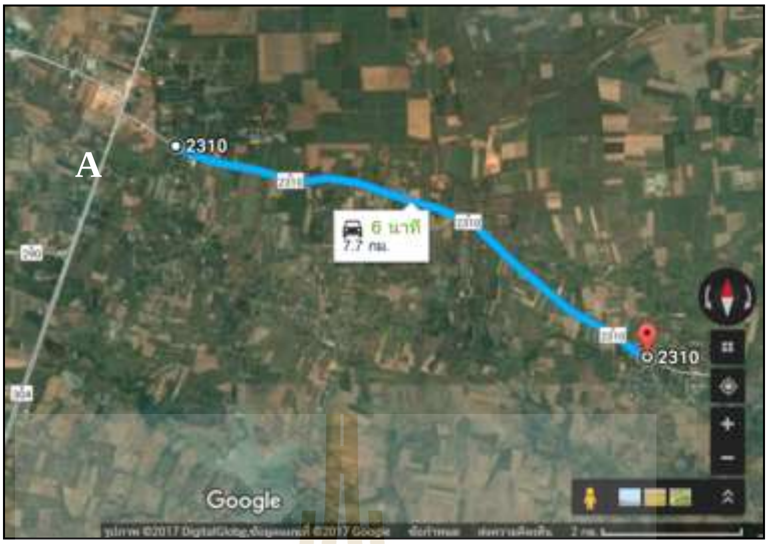

Figure 4.31 Drive test profile at out of city route

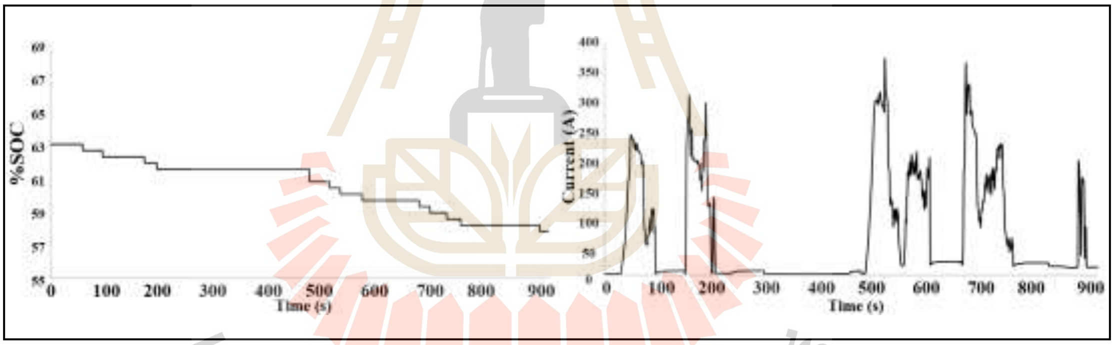

Figure 4.32 Drive test result without passenger at out of city route

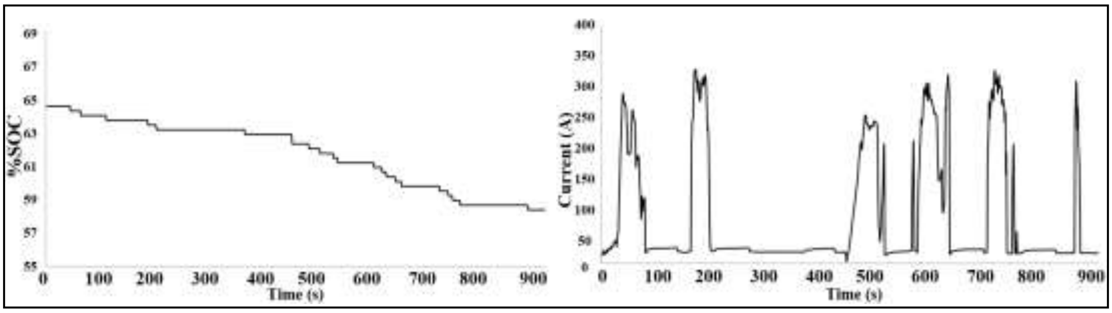

Figure 4.33 Drive test result with 30 passengers at out of city route

Table 4.3 Electric bus drive test at out of city route

Scenario	% SOC Start	% SOC End	Power consumption (kWh)	Distance (km)	Power consumption (kWh/km)	Ave. velocity (km/h)	Max. velocity (km/h)
A-B-A (without passenger)	63.60	58.00	10.976	16.188	0.678	62.94	89.05
A-B-A (with passenger)	53.60	44.80	17.248	15.731	1.096	61.56	90.66

In this drive test scenarios show that, PEA Zero-emision electric bus can drive for 259.5 km distance per charge incase of without passenger with average velocity at 60 km/h and has ability to drive for 160.5 km distance per charge with 30 pasengers in the same vehicle velocity. These evaluation are calculated for 20% SOC remaining battery capacity regarding the battery safety issue. However, it has not any problem to drive PEA Zero-emission electric bus for 176 kWh of 196 kWh at 100% SOC power battey capacity.

In the same route above, Volvo B7R 12 meters engine bus type with the same size of PEA Zero-emision bus are compared to study about cost expence through consumption (fuel consumption rate). The condition of this test drive is also the same as previous for instance driver, vehicle velocity, number of passengers and bus interior control temperature. The fuel consumption of electric bus are measured and read from bus meter report system. The engine bus drive test result can be shown in table 4.4. There are 2 scenarios by with and without passenger drive test which have the fuel consumption rate at 0.36 and 0.28 liter/km. The data collection of drive test can be shown in Figure 4.34 – Figure 4.35.

Table 4.4 Engine bus drive test at out of city route

Scenario	Drive time (min)	Max. velocity (km/h)	Ave. velocity (km/h)	Distance (km)	Fuel (liter)	Fuel consumption rate (liter/km)
Without passenger	16	92.8	74.3	14.9	4.2	0.28
With passenger	13	94.0	71.2	14.9	5.3	0.36

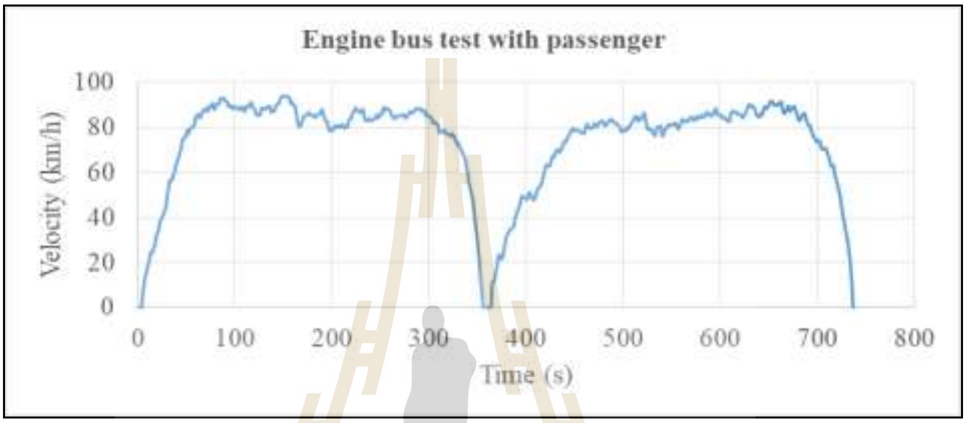

Figure 4.34 Engine bus drive test profile with passengers at out of city route

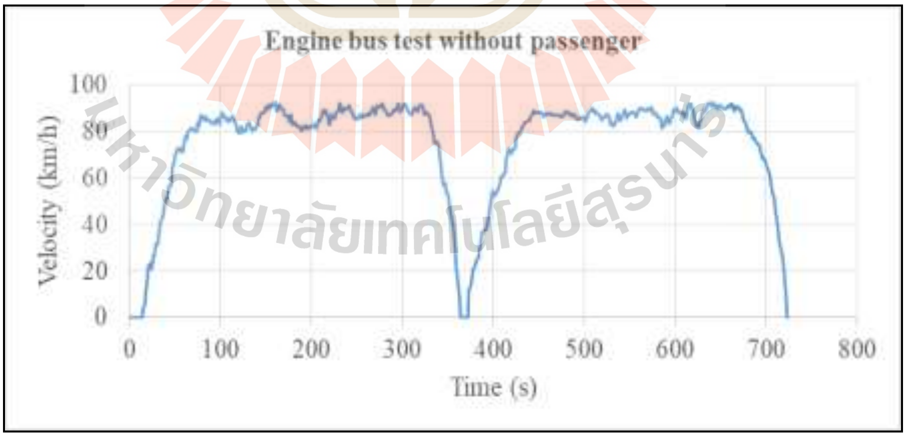

Figure 4.35 Engine drive test profile without passengers at out of city route

4.6 Cost Expense for Electric Versus Engine Bus Driving Test

From drive test result of PEA Zero-emission electric bus and engine bus in previous possition. The comparison of cost expense regarding power consumption of electric bus and fuel consumption of engine bus can be calculted and shown in Table 4.5. The electric bus can save the cost expense lower than engine bus 2 times for power electric cost rate at 4.5 baht/unit and diesel fuel gasoline cost rate at 24.59 baht/liter.

Table 4.5 Electric bus and engine bus cost expense calculation

Scenario	Fuel consumption rate		Electric power consumption rate	
	Liter/km	Baht/km	kWh/km	Baht/km
With passenger	0.36	8.75	1.096	4.93
Without passenger	0.28	6.93	0.678	3.05

4.7 Conclusion

The implemented motor in PEA Zero-emission is successfully calculated and simulated with measurement comparison in ZF motor supplier certified laboratory test bench. The drive test over 1,000 km distance result shows the power consumption rate is 0.883 kWh/km with 34 km/h and 79.7 km/h at average and maximum speed, respectively. The important parameters effected in power consumption are driving speed, driver behavior, amount of passengers and air conditioner temperature setting up. From the power consumption rate comparison of electric bus and engine bus are studied. The cost expense are interpreted by the power consumption rate data shows electric bus can save the cost expense lower than engine bus 43-56% for power electric cost rate at 4.5 baht/unit and diesel fuel gasoline cost rate at 24.59 baht/liter.

CHAPTER V

ECONOMIC AND ENVIRONMENT ANALYSIS

5.1 Introduction

In this chapter will explain the effectiveness of economic and environment when electric vehicles are replaced in public transportation in Thailand. Regarding electric vehicle will consume more electric power by demand. And it well know that electric vehicle has higher efficiency power consumption than other fuel engine vehicle at present in the other hand electric vehicle consumption ratio is lower than normal engine vehicle. Meanwhile, it is necessary to analyze and prepare the power electricity demand plan for future in Thailand.

5.2 Bus Availability

Bangkok show a significantly lower availability rate of electric versus conventional fuel buses. Reasons are more breakdowns of the bus and longer standstill time for maintenance and repair due to lack of spare parts. Electric buses are still an “exotic” product resulting in more technical difficulties, less trained maintenance staff and not readily available spare parts due also to the limited amount of units. As a result operators currently require for each diesel bus and natural gas bus operations.

5.3 Investment and Operational Cost

Generally, economic studies focus on the cost-benefit analysis of implementing electric bus in transit, environment models investigate the potential of greenhouse gas (GHG) emission reductions from electric bus and energy consumption analysis examines the energy efficiency of electric bus. With regard to the economic performance, total cost of ownership has been identified as one of main batteries for the implementation of electric bus. It includes manufactured price and also the cost for maintenance, operation, energy distribution, infrastructure, emission, insurance and end-of-life. For manufacturing price, it was found that all electric buses are more expensive that diesel counterpart. In terms of operational cost, electric bus performs better than the diesel bus with an average reduction of 80% in running cost. However, in terms of infrastructure cost, the opportunity of batteries for electric bus is considered the most expensive option. Although it is required major infrastructure modification charging stations, the higher density of charging points along the bus routes, i.e. one charging point for each 15-20 km. Although the opportunity bus is relatively cheaper than the normal charging bus (AC-charging) due to the smaller on-board battery package, the AC-charging battery is more expensive than opportunity fast charge battery based on the total cost of ownership. In spite of the various efforts to calculate the total cost of ownership of electric buses, there are a lot of uncertainty in the estimation.

The investment cost for a conventional diesel 12 m in China is around 5.5 Million Baht whilst an electric 12-meters bus has around double the cost i.e. 11 Million Baht. Prices for an electric bus are thereby based on Yutong and BYD in China. Outside China the BYD bus is known to be sold at 22 Million Baht excluded tax fee. The investment cost for a battery set is thereby around 50% of the bus investment. The electric fast-charging stations are owned by the electricity companies which thereafter sell the electricity.

In general the bus manufacturer leases the batteries or even the entire bus to the bus operator. This includes also the entire maintenance service. In theory maintenance costs should be lower for electric buses due to less revolving parts and less maintenance requirements. In practice however the experience of the operators has been that maintenance costs are higher for electric buses due to fewer suppliers of electric buses and spare parts and non-standardized spare parts which result in costlier repairs. More competition and a growing market for electric buses will bring down differential costs but at the current stage electric buses in practice cost more to maintain and repair than diesel units. This cost has therefore been included in the bus availability rate.

The batteries have a life-span of minimum 8 years which is equivalent to the life-span of buses in China (based on national regulations). Therefore no replacement cost is included. For a longer usage of buses however a battery replacement after around 10 years would need to be included.

Issues regarding sustainability and climate change are increasing in importance on a global level. In December 2015, there are 196 member countries of the UN Framework on Climate Change met in the 21st Conference of the Parties on global climate change. At this meeting the parties signed a legally binding contract to limit the global warming to well below 2 ^{o}C (NFCC, 2015). The member countries submitted national climate action plans, where they each made a plan on how to meet this global. The United Nations has set up seventeen sustainable development goals to handle the new situation. Two sustainable development goals from 2015 state that by 2030 all countries should take action to; upgrade the infrastructure with greater adoption of clean and environmentally friendly technologies, and to provide access to transport system for every one of clean and environmentally friendly technologies, and to provide access to transport systems for everyone by expanding the public transport (United Nation, 2015). The transport sector has increasingly made up a larger part of total the road transport constituted 20% of the total GHG-emission. According to European Commission about a quarter of CO_2 emissions from road transport within the EU is produced by Heavy-duty vehicle (HDV) for instance truck, buses and coaches. This represents a greater share than international aviation and shipping combined. Therefore the European Commission has established goals with the aim to reduce CO_2 emission. The EU heads of state agreed to aim at lowering emissions from HDV by 30% from 2005 levels.

Environmental performance of electric bus is introduced in form of Well-to-Wheel (WTW) assessment of greenhouse gas emission. Basically, WTW assessment integrates the generated emissions in two stages, i.e. Well-to-Tank (WTT) and Tank-to-Wheel (TTW). In particular, WTT measures the greenhouse gas emissions of fuel (i.e. diesel, hydrogen and electricity) at both production and distribution stages while TTW measures the greenhouse gas emissions of the fuel during the usage stage. Electric bus operates with zero local greenhouse gas emission for a 12-meters bus and has great potential to reduce greenhouse gas emissions. Apart from the emission reduction, it is also found that electric bus operations with lower noise and vibration due to the absence of mechanical parts.

5.4 Profitability

The following Table 5.1 shows main parameters taken into consideration for the determination of the cost and profitability of electric versus conventional units.

Table 5.1 Parameter electric bus versus diesel 12 m bus

No.	Parameter	Diesel Bus	Electric Bus
1	Investment cost (Million Baht)	6	14
2	Maintenance cost (baht per year)	> 100,000	< 10,000
3	Fuel / electric cost	0.4 l/km	0.9 kWh/km
4	Power consumption usage	9.84 Baht/km	4.63 Baht/km

Actual differential investment for the same usability, the electric bus has in reality around triple the price of a diesel unit due to the lower availability rate of the unit which results in requiring more units to maintain the same service level. Annual operational savings of electric versus diesel bus units amount to around 100,000 Baht. This figure is however insufficient to cover the differential investment for the electric bus. Annualized costs per kilometer including investment cost and fuel cost but excluding cost components which are identical between the two vehicles like liquid waste, engine belt and etc. are around 35% higher for the conventional diesel bus compare to electric bus unit.

5.5 Benefits and Costs

If all the potential benefits of EVs can be realized upon widespread utilization, greenhouse gas emissions, ambient air pollution and foreign oil dependency can all be significantly reduced. Full electric vehicle offer great CO_2 savings but their market penetration is slow, therefore conventional vehicles will play a significant role in the foreseeable future. It appears the high rate of acquisition costs in comparison to diesel vehicle. The comparison of the cost structure can be qualified by the methodical approach of Life Cycle Costing (LCC) calculation. The first international standard for property life-cycle costing BS ISO 15686-5:2008 defines LCC as the methodology for the systematic economic evaluation of life cycle cost over the analysis period, as defined in the agree scope (Liapis and Kantianis, 2015). Life cycle cost in turn, is defined as the cost of an asset or its parts throughout its life cycle, while fulfilling the performance requirement. Liapis and Kantianis declared that the LCC approach identifies all future costs and benefits and reduce them to their present value by the use of discounting techniques through which the economic worth of project options can be assessed. To achieve these objectives the following elements of LCC have been identified: initial capital cost, live of the asset, the discount rate, operating and maintenance costs, disposal cost, information and feedback, uncertainly and sensitivity analysis. The success of calculation is influenced not only by the total cost estimation but also by other factors such as the duration of the product life cycle, assumed amount of outputs during its life cycle and expected trend of the product prices. The main function is optimizing the life cycle cost of the asset or the investment project without a total performance reduction. The total interaction between all types of cost and revenue of project under consideration is a presumption of life cycle cost optimization. Human resources are an important factor influencing the accomplished expert estimations (Stacho, Urbancova, and Stachova, 2013; Lorincova et al., 2016). Time and the used method of economic assessment are key parameters of appraisal (calculation of Nett Present Value, utilization of discount rate, inclusion of inflation and interest rate) (Hajduova, Andrejkovic, and Mura, 2014).

The calculation applies to the conditions of industrial manufacturing. Utilization of LCC calculation is frequent in the construction industry (Kunttu, et al., 2015), (Seif and Rabbani, 2014[20]). The calculation is most commonly used in connection with the issue of the Environment and the Ecology, as is evident in (Brown et al., 2013; Rigamonti et al., 2016). The research of Lajunen and Lipman is interesting and states that an extensive lifecycle cost analyse indicates that electric buses are already economically competitive with diesel buses and electric buses with would become cost effective in the near future. The total life cycle cost can be determined as in equation (5.1) (Lajunen and Lipman, 2016).

$$LCC = C_A + \sum_{t=1}^{LC} C_t \times \frac{(1+r)^n - 1}{(1+r)^n \times r} \pm \left(\frac{1}{(1+r)^n} \times NBV \right) \tag{5.1}$$

where

LCC is Current Value of Total Life Cycle Cost

C_A is Acquisition cost

r is Discount Rate (time value of money)

LC is Life Cycle

C_t is sum of relevant Life Cycle Cost of property after deducting the positive cash flow

NBV is Net Book Value

Currently, the acquisition of electric bus has the potential for improving the environment and greenhouse gas production situation. However, the acquisition cost and the operating costs of the electric vehicles generate a certain cost structure that is different compared to the diesel vehicles. The amount of state support as well as the possibility of such aid for purchasing electric buses still remains uncertain.

5.6 Cost Analysis and Methodology

The estimated purchase costs are based on the value presented on producers. Lifetime of an electric bus was set to 10 years. The purchase cost is set to 14 million baht, including battery (lifetime 20,000 cycle of charge/discharge) and charging station. Purchase cost of the diesel engine bus with similar passenger capacity is set to 6 million baht. The cost of fuel and electricity corresponds to average prices in 2019 in Thailand.

5.6.1 Operation Cost

The operation cost of the fuel cost, electrical cost, maintenance costs, oil change cost, tire change cost are set by the following equation. (Dhillon, 2010)

- Fuel cost (diesel) is calculated on the basis of average consumption (*AC*) from vehicle technical documentation, estimated distance travel (*Σkm*) and expected diesel price for the current period (*DP*).

$$\text{fuel cost} = AC \times \Sigma km \times DP \tag{5.2}$$

- Electricity cost is calculated on the basis of average battery consumption (*AC*) from vehicle technical documentation, estimate travel distance (*Σkm*) and expected electricity price for the current period (*EP*).

electricity cost $= AC \times \Sigma km \times EP$ (5.3)

- Maintenance costs of diesel bus is calculated on the basis of oil change interval (l) (every 25,000 km), oil tank volume (Ov) and oil price per Liter (MOP) (Self and Rabbani, 2014)

$$\text{Maintenance engine oil costs} = \frac{(Ov \times MOP \times \Sigma m)}{l} \tag{5.4}$$

- Maintenance costs of tire will depend on tire price (TP), tire count (c), tire change payment (TCP), tire lifespan (TL) per kilometer and the mileage of a tire (Σkm). The replacement interval was set twice a year. (Self and Rabbani, 2014)

$$\text{cost of tires} = \frac{(TP \times c) + TCP}{TL / km} \times \Sigma km \tag{5.5}$$

Determination of operating costs also require the calculation of other costs such as a planned repair and maintenance (washing, disinfection, standard repairs), vehicle emission control and technical control (2 year intervals) and regular vehicle service control at a mileage of 25,000 km. (Daylan and Ciliz, 2016)

5.6.2 LCC calculation

It is required to have data about the discount rate, price rate and live cycle. Petrik states that it is necessary to modify the discount rate if the cash flow are displayed in the stable price and the inflation rate is low and stable. The discount rate would be quantified by the following equation (5.6). The 2.5% rate of return on the financial market and price inflation rate of fuel and electricity is used (Self and Rabbani, 2014; Falcone et al., 2015; Amienyo and Azapagic, 2016).

$$\text{discount rate } (r) = \frac{\text{interest rate} \times 100}{\text{inflation rate} \times 100} \tag{5.6}$$

The advantage of LCC calculation mainly including complex costs in to the decision making process through discount methods. When calculating total life cycle costs, the value of the time factor (VTF) to Net Present Value (NPV) for annuity (series of payments made at equal intervals) operating costs is also concerned as in equation (5.7) (Pavlickova and Teplica, 2014).

$$VTF = \frac{(1+r)^n - 1}{(1+r)^n \times r} \tag{5.7}$$

when

r	is	discount rate
n	is	analyzed period

In addition to costs, the major parameters for examination are time and used method for economic valuation. Thus, using of discount rate, including inflation rate and interest rate, to determine LCC value the equation (5.8) can be used to calculated, while the carrying value is disregarded after the expiration of a lifetime (Self and Rabbani, 2014; Hannouf and Assefa, 2016).

$$\text{LCC} = \text{acquisition cost} + \text{operation cost} \times \text{VTF} + \left(\text{residual price} \times \frac{1}{(1+r)^{n}} \right) \quad (5.8)$$

5.7 Case Study and Results

Additional life cycle cost calculation parameters are shown in Table 5.2. The fuel and electricity cost correspond to the average price in 2019 in Thailand. Diesel costs with VAT are set to 30.28 Baht/liter and electricity costs with VAT is set to 3.50 Baht/kWh. Inflation rate of fuel prices and electricity prices is set to 1.20% with interest rate 6.50% per annum. Base on the equation (5.6) can be indicate the discount rate as:

$$\text{discount rate } (r) = \frac{6.5 \times 100}{1.2 \times 100} = 5.42\%$$

And the VTF factor determine by equation (5.7), has the value as:

$$VTF = \frac{(1+0.0542)^{10} - 1}{(1+0.0542)^{10} \times 0.0542} = 7.57$$

With an estimated 109,800 km per year for average diesel and electric power consumption, the operation cost of consumption is based on relationship in (5.3) and (5.4) as 8,976,809 Baht/year and 499,590 Baht/year, respectively. The maintenance costs of oil and tire changing cost (determined by equation (5.4) and (5.5) as well as other repair, servicing, technical and emission control are presented in Table 5.2.

For determination of the LCC the relation (5.8) is used. So that the possible Life Cycle Cost of electric and diesel bus are declared as:

- For PEA Zero-emission electric bus:

  LCC = 14,000,000 + (1,143,768×7.57) + 0 = 17,561,534.43 Baht

- For diesel bus:

  LCC = 6,000,000 + (248,349×7.57) + 0 = 15,880,001.93 Baht

Regarding LCC analysis result, it shows that diesel bus of the total life cycle costs is higher at the alternative of electric bus acquisition as illustrated in Figure 5.1. The difference of life cycle costs between analyzed alternatives is the sum of 1,681,532.50 Baht/year, approximate 16.8 million baht for 10 year life time.

Figure 5.2 shows the cost structure development in individual years of life cycle during the use of electric and diesel buses. However, this assumption is based on the constancy of reviewed parameters (fuel price development, electricity price, interest rate) for life cycle longer than 10 years. According to the presented data, the payback has been set to 6.2 years. This data significantly exceeds the means of transport and their life cycle as well as their battery, but the potential of positive impact to the environment (Lagunen and Lipman, 2016; Reich, 2005; Petti et al., 2016; Wood and Hertwich, 2013).

Table 5.2 The structure of cost for LCC calculation

Item	Diesel Bus	Electric Bus
Acquisition cost (Million Baht)	6.00	14.00
Lifetime (p.a.)	10.00	10.00
Discount rate (average interest) (% p.a.)	5.42	5.42
Inflation rate (% p.a.)	1.20	1.20
Interest rate (% p.a.)	6.50	6.50
Diesel fuel cost with VAT (Baht/liter)	32.28	
Electricity cost with VAT (Baht/kWh)	-	3.50
Diesel and electricity price increase (last 10 years) (%)	1.20	1.20
Distance (p.a.) (km)	109,800.00	109,800.00

Table 5.2 The structure of cost for LCC calculation (continued)

Item	Diesel Bus	Electric Bus
Other cost		
Average fuel/electricity consumption (liter/km) / (kWh/km)	0.32	1.30
Fuel / electricity cost of consumption (Baht p.a.)	1,230,155.28	142,191.00
Maintenance costs - tire change cost (Baht p.a.)	24,100.00	24,100.00
Maintenance costs - oil change (Baht p.a.)	65,880.00	-
- Repairs (brake maintenance, cleaning parts of bus) (Baht p.a.)	64,144.00	24,054.00
- Technical Inspection (Baht p.a.)	2,004.00	2,004.00
- Service control (Baht p.a.)	141,000.00	56,000.00
- Residual value (% from the acquisition costs)	0	0

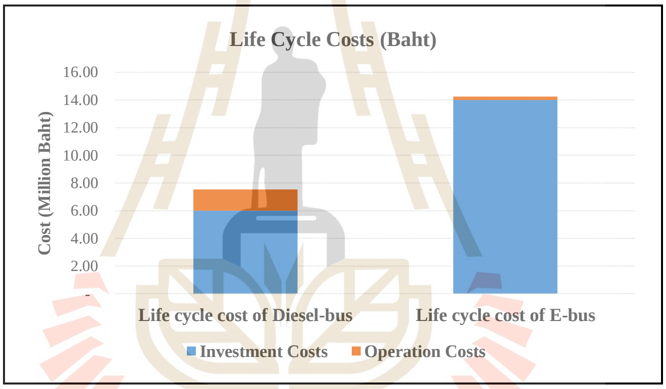

Figure 5.1 Results of Life Cycle Cost analysis

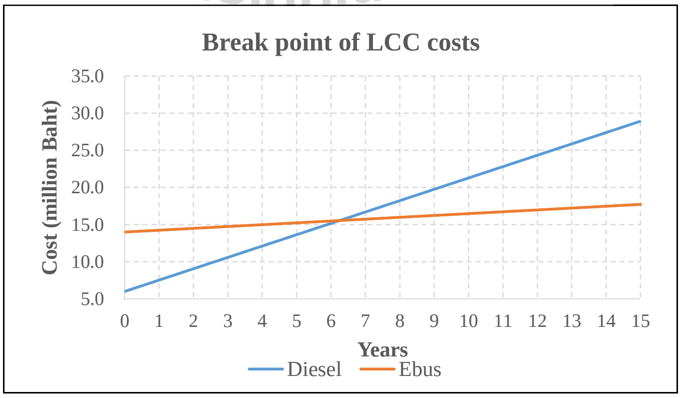

Figure 5.2 Breaking point of Life Cycle Cost

5.8 Conclusion

The reliability of electric bus is comparable to conventional fossil fuel buses and also maintenance costs, with exception of battery costs, are comparable. The differential investment, depending on make and model, can however be significant. Under normal annual operating conditions and fuel prices, electric bus can be profitable recovering the initial differential investment within 6.2 years. Carbon finance can play an important role in reducing the differential investment cost and thus making latter more popular.

Electric battery buses are still less well established. Various options are being tried to resolve the problem of range, battery weight and battery cost such as buses carrying along large battery racks, buses with fast-charge battery racks or opportunity charge bus systems like swop batteries. Such systems have a good potential of replacing electric trolley bus. Currently reliability of electric buses is still significantly below conventional diesel units therefore leading to additional investment costs (more buses are required to fulfil the same peak service level). Also maintenance costs, which theoretically should be lower compared to diesel units, is in practice higher due to less availability of spare parts, spare parts art higher costs and more stand-still time with repairs. These problems are typical of new technologies. Energy usage of electric buses is low and fuel savings can be significant. However battery costs are still very high and life-span of batteries is limited thus resulting in significant additional costs of electric buses which cannot be recovered currently with energy savings. Therefore electric buses, even with carbon finance, are not yet financially considered as viable compared to conventional units. However electric buses compared to conventional buses can be an interesting option. The cost of electric bus will come down and that battery capacity will increase whilst costs decrease. With larger fleets reliability should also improve and maintenance costs should decrease.

CHAPTER VI

CONCLUSION

6.1 Electric Bus Status

The worldwide electric bus fleet is estimated to have more than 10 million unit in 2015. China is leading this global mass deployment, with more than 98.3% of the global total. While the European is one of the leading regions for electric bus research and development (R&D) including vehicle technology. In Asia-Pacific region contributes over two-thirds of the global output of buses and coaches for domestic and leads the global electric bus market with substantial government initiatives in countries including China, Japan, Korea and lesser extent India. In Southeast Asia has begun to invest in electric bus for public transportation in their countries. Malaysia, Singapore, Indonesia and Thailand are the leader by Government's policy. Thailand government raises several interested promotion and campaign for global investor and electric bus manufacture as an ASEAN EV hub such as import duty and excise tax exemption for important related parts, Board of Investment of Thailand (BOI) promotion for manufacture of electric vehicles and key components, and propose three hundred percent tax rebate for research and development. Provincial Electricity Authority (PEA) and Suranaree University of Technology (SUT) have achieved taken the lead by developing the first electric bus by using lithium-battery in Thailand.

6.2 Electric Bus Design

The component sizing of electric bus can ensure sufficient tractive force to meet such of accelerate from zero speed to a certain speed within requirement, overcome wind resistance force, aero dynamic force, rolling resistance and climbing a certain slop (grade). The propulsion system of electric bus prototype namely PEA Zero-emission is designed for Thailand public transportation. PEA Zero-emission is introduced plenty of innovation technology such as 12 meter long with Li-phosphate battery bus for light weight, swap battery pack and plug in for charging strategies and the next generation of facility choice, two hubs motors drive for better torque, and low floor entry bus for wheel chair. The electric hub motor and battery sizing is designed by calculation. As the result, the electric hub motor has 2×120 kW rated power and the battery capacity of 196 kWh, 320 Ah 650 V is installed to meet requirement and market support. The actual range of a fully charged battery can depend on many different parameters, including vehicle efficiency, weight/number of passengers, weather conditions, and route characteristics and driving style. Moreover, different charging strategies can change the way we have to look at the definition of range for instance a broad network of high-power opportunity charging infrastructure can provide almost infinite range, even with a smaller battery on board.

6.3 Simulation and Test

The electric traction motor is simulated and tested. The simulation data results are calculated from principal equation of traction motor for a configuration of the asynchronous motor which implemented in prototype electric bus. For motor test, it is tested in the laboratory test bench in DRIVETEK AG, Switzerland. The simulation and testing data are compared and shown results of motor torque, motor current (Id), motor current (Iq), and voltage peak (Vdq peak) in vary of temperature control. The test result shown that, the higher temperature, the less motor performance.

6.4 PEA Zero-emission Bus Test

There are two different road test condition that simulate in city public transportation and city to city driving. The road condition at Suranaree University of Technology is represented for city publication and the Burphavidh Tollways in Bangkok from PEA-center to PEA-Rangsit is represented for city to city in real traffic conditions. The test result shows that the power consumption of driving test for both scenario are approximate 0.7-1.3 kWh/km. The PEA Zero-emission bus has good performance in road test and suitable to implement in Thailand public transport.

Beside road test, the power consumption rate of electric bus compare with engine bus is studied. Two scenario of with and without passenger in condition of the same route, amount of passengers, driver and approximate speed are prepared. The cost expense are interpreted by the power consumption rate data shows electric bus can save the cost expense lower than engine bus 43-56%.

6.5 Suggestion for Future Work

The primary future works need identified in this synthesis report include the following.

Further studies within should include testing throughout a whole year to get a yearly-based average energy use. To support the development of a business model tailored for electric buses in public transport, further studies should reveal data for likely costs and also develop training of bus driver, maintenance personnel, and planners to use the electric bus in an optimal way.

The control strategy of regenerative braking energy is an important link in pure electric bus development. Because of the addition of motor braking in traditional mechanical braking basis. This strategy will help to extend driver distance within the same battery size. The simulation and test may be performed.

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APPENDIX A

MOTOR TEST DATA AND PARAMETER VALUE

The DRIVETEK AG laboratory is a laboratory for testing, validation and characterizing a broad range of electric drive system and motor for ZF AVE130 in difference configurations as well as for parameterization and optimizations of electric machines. The high power level can be tested up to 250 kW and the wide range of power supply as shown in Figure A.1. The water temperature is controlled and indicated (1) with the heat transfer room by (2). The ZF AVE130 (5) is controlled by inverter by (3) with DC power supply cabinet in (4). The torque sensor are in stall at (6). The operator and control room is separated from the test cabins environment as show in Figure A.2. The test status indicator (1) and emergency stop (2) are installed.

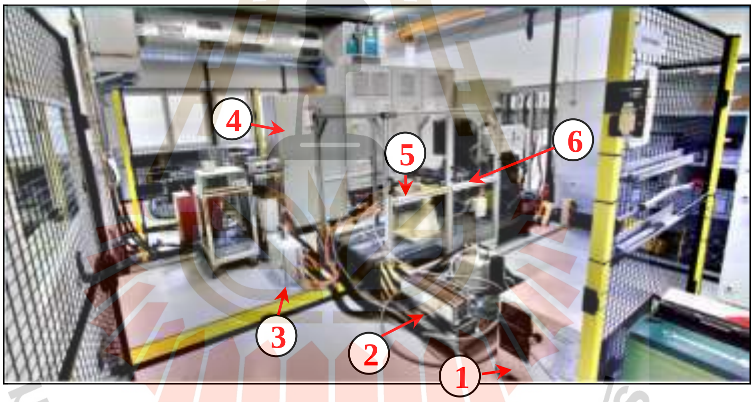

Figure A.1 DRIVETEK AG laboratory for AF AVE130 motor test bench

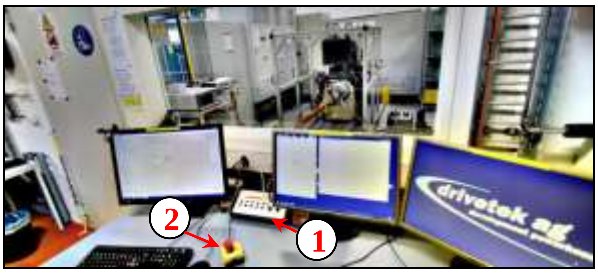

Figure A.2 DRIVETEK AG's operator room

Table A.1 Motor test result at 25 ^{o}C

Speed [rpm]	Torque [Nm]	Id [Apeak]	Iq [Apeak]	Slip speed [rad/s]	Power [W]	Efficiency [%]
60	413.9014	140.1136	400.4257	0.5259	2600.6194	0.2575
341	413.9014	140.1136	400.4257	0.1635	14759.0706	0.6630
621	413.9014	140.1136	400.4257	0.0968	26917.5219	0.7821
902	413.9014	140.1136	400.4257	0.0687	39075.9731	0.8390
1182	413.9014	140.1136	400.4257	0.0533	51234.4244	0.8723
1463	413.9014	140.1136	400.4257	0.0435	63392.8756	0.8942
1743	413.9014	140.1136	400.4257	0.0368	75551.3269	0.9097
2024	413.9014	140.1136	400.4257	0.0318	87709.7781	0.9212
2304	413.9014	140.1136	400.4257	0.0281	99868.2294	0.9301
2585	413.9014	140.1136	400.4257	0.0251	112026.6806	0.9372
2865	413.9014	140.1136	400.4257	0.0227	124185.1319	0.9430
3146	413.9014	140.1136	400.4257	0.0207	136343.5831	0.9479
3426	413.9014	140.1136	400.4257	0.0191	148502.0344	0.9519
3987	406.9662	121.3247	405.7231	0.0173	169923.2106	0.9572
4268	385.6166	101.3971	411.0205	0.0176	172336.5705	0.9573
4548	363.7591	88.6814	414.1990	0.0179	173253.7187	0.9571
4829	342.8671	79.1921	416.3179	0.0181	173374.9317	0.9569
5109	322.5933	71.7904	416.3179	0.0183	172599.4626	0.9568
5390	305.5974	65.5274	418.9666	0.0185	172483.0539	0.9564
5670	287.6764	60.4032	417.3774	0.0186	170818.7301	0.9563
5951	273.2076	55.8483	419.4964	0.0189	170252.8645	0.9558
6231	259.1754	51.8628	420.5559	0.0191	169121.8580	0.9554
6512	245.3736	48.4467	419.4964	0.0192	167323.5942	0.9552
6792	233.6485	45.2203	421.6154	0.0196	166191.5918	0.9545
7073	220.9378	42.5633	418.4369	0.0196	163640.6735	0.9545
7353	210.7286	39.9063	420.5559	0.0200	162269.2619	0.9537
7634	200.2538	37.6288	419.4964	0.0201	160085.8136	0.9533
7914	191.2698	35.3514	422.1451	0.0206	158522.4283	0.9523
8195	181.6273	33.4535	420.0261	0.0207	155866.1452	0.9520
8475	172.3543	31.7454	416.8477	0.0208	152971.3850	0.9519
8756	164.1104	30.0374	416.3179	0.0211	150475.3639	0.9512
9036	156.4878	28.5191	417.9072	0.0216	148082.9697	0.9501
9317	148.8199	27.1906	416.8477	0.0219	145198.4905	0.9495
9597	141.3190	26.0518	413.1395	0.0220	142031.4027	0.9493
9878	134.2756	24.9131	410.4908	0.0222	138896.8311	0.9488
10158	127.4942	23.9642	405.1933	0.0222	135627.2622	0.9489
10439	121.3251	23.0152	401.4852	0.0223	132628.5840	0.9487
10719	115.3108	22.2561	394.5985	0.0220	129441.2476	0.9492
11000	109.2735	22.2561	373.9386	0.0204	125874.0419	0.9529

Table A.2 Motor test result at 60 ^{o}C

Speed [rpm]	Torque [Nm]	Id [Apeak]	Iq [Apeak]	Slip Speed [rad/s]	Power [W]	Efficiency [%]
60	413.9014	140.1136	400.4257	0.5618	2600.6194	0.2307
341	413.9014	140.1136	400.4257	0.1843	14759.0706	0.6299
621	413.9014	140.1136	400.4257	0.1102	26917.5219	0.7564
902	413.9014	140.1136	400.4257	0.0786	39075.9731	0.8184
1182	413.9014	140.1136	400.4257	0.0611	51234.4244	0.8553
1463	413.9014	140.1136	400.4257	0.0500	63392.8756	0.8797
1743	413.9014	140.1136	400.4257	0.0423	75551.3269	0.8971
2024	413.9014	140.1136	400.4257	0.0366	87709.7781	0.9100
2304	413.9014	140.1136	400.4257	0.0323	99868.2294	0.9201
2585	413.9014	140.1136	400.4257	0.0289	112026.6806	0.9282
2865	413.9014	140.1136	400.4257	0.0261	124185.1319	0.9347
3146	413.9014	140.1136	400.4257	0.0239	136343.5831	0.9402
3426	413.9014	140.1136	400.4257	0.0220	148502.0344	0.9448
3987	405.7186	119.0473	406.7826	0.0201	169402.3069	0.9506
4268	383.9813	99.8788	412.0800	0.0205	171605.7533	0.9505
4548	360.2679	87.7325	412.6097	0.0207	171590.8985	0.9507
4829	340.0233	78.4329	415.2585	0.0210	171936.9002	0.9504
5109	320.7940	71.0313	416.8477	0.0212	171636.7715	0.9501
5390	302.6311	64.9581	417.3774	0.0214	170808.8371	0.9498
5670	285.7444	59.8338	417.3774	0.0216	169671.5585	0.9496
5951	271.4950	55.2790	420.0261	0.0219	169185.6627	0.9489
6231	256.1132	51.4832	417.9072	0.0220	167123.6876	0.9488
6512	244.0524	47.8773	421.0856	0.0224	166422.6599	0.9479
6792	231.5090	44.8407	420.5559	0.0226	164669.7516	0.9475
7073	220.4865	41.9939	422.1451	0.0230	163306.4433	0.9468
7353	209.0837	39.5267	420.5559	0.0232	161002.6777	0.9464
7634	198.5732	37.2492	419.4964	0.0234	158742.2944	0.9460
7914	188.7322	35.1616	418.4369	0.0236	156419.3315	0.9455
8195	180.0974	33.0739	420.5559	0.0242	154553.2435	0.9444
8475	170.7973	31.3659	417.3774	0.0243	151589.5111	0.9442
8756	162.7361	29.6578	417.9072	0.0247	149215.2702	0.9432
9036	154.6583	28.3293	415.7882	0.0249	146351.6700	0.9427
9317	147.0299	27.0008	414.7287	0.0253	143452.0852	0.9419
9597	139.7498	25.8620	411.5503	0.0254	140454.3362	0.9416
9878	132.5427	24.9131	405.1933	0.0253	137104.3542	0.9420
10158	126.3607	23.2050	414.7287	0.0270	134421.4003	0.9383
10439	119.9540	22.6357	403.6041	0.0262	131129.6864	0.9400
10719	114.0206	22.0663	393.5390	0.0255	127992.8687	0.9415
11000	108.4390	21.6867	380.8252	0.0245	124912.7670	0.9437

Table A.3 Motor test result at 120 °C

Speed [rpm]	Torque [Nm]	id [Apeak]	iq [Apeak]	Slip Speed [rad/s]	Power [W]	Efficiency [%]
60	413.9014	140.1136	400.4257	0.6065	2600.6194	0.1996
341	413.9014	140.1136	400.4257	0.2136	14759.0706	0.5860
621	413.9014	140.1136	400.4257	0.1296	26917.5219	0.7208
902	413.9014	140.1136	400.4257	0.0931	39075.9731	0.7894
1182	413.9014	140.1136	400.4257	0.0726	51234.4244	0.8309
1463	413.9014	140.1136	400.4257	0.0595	63392.8756	0.8588
1743	413.9014	140.1136	400.4257	0.0504	75551.3269	0.8787
2024	413.9014	140.1136	400.4257	0.0437	87709.7781	0.8938
2304	413.9014	140.1136	400.4257	0.0386	99868.2294	0.9055
2585	413.9014	140.1136	400.4257	0.0346	112026.6806	0.9149
2865	413.9014	140.1136	400.4257	0.0313	124185.1319	0.9225
3146	413.9014	140.1136	400.4257	0.0286	136343.5831	0.9290
3426	413.9014	140.1136	400.4257	0.0263	148502.0344	0.9344
3987	402.8841	116.0107	407.3123	0.0244	168218.7805	0.9408
4268	379.4513	98.1707	410.4908	0.0247	169581.2238	0.9409
4548	357.3001	86.2142	413.1395	0.0250	170177.3536	0.9407
4829	337.3759	77.1044	416.3179	0.0254	170598.2140	0.9402
5109	318.2411	69.8925	417.9072	0.0257	170270.8905	0.9398
5390	299.2084	64.0092	416.8477	0.0259	168877.0176	0.9398
5670	283.2105	58.8849	418.4369	0.0262	168166.9329	0.9392
5951	268.0515	54.5198	418.9666	0.0265	167039.8103	0.9387
6231	253.5554	50.7241	418.4369	0.0267	165454.6055	0.9384
6512	240.5703	47.3079	418.9666	0.0270	164048.1636	0.9378
6792	228.0134	44.2713	418.4369	0.0272	162183.3889	0.9373
7073	217.2415	41.4245	420.5559	0.0277	160902.9400	0.9362
7353	206.3438	38.9573	420.0261	0.0280	158892.7925	0.9357
7634	196.0397	36.6799	419.4964	0.0284	156716.9975	0.9350
7914	186.3856	34.5922	418.9666	0.0287	154474.4856	0.9343
8195	177.8932	32.5046	421.6154	0.0294	152661.7366	0.9328
8475	168.7608	30.7965	418.9666	0.0296	149782.0011	0.9324
8756	160.2461	29.2782	416.8477	0.0299	146932.0966	0.9318
9036	152.7085	27.7599	418.9666	0.0307	144506.5904	0.9301
9317	144.7778	26.6212	414.1990	0.0307	141254.7959	0.9301
9597	137.5215	25.4825	411.0205	0.0308	138214.7722	0.9297
9878	130.3527	24.5335	404.6636	0.0306	134838.9319	0.9302
10158	124.1010	23.2050	407.3123	0.0317	132017.6078	0.9279
10439	117.9072	22.6357	396.7175	0.0308	128892.2361	0.9298
10719	112.0253	22.0663	386.6524	0.0300	125753.0856	0.9316
11000	106.7424	21.4970	378.1765	0.0294	122958.4323	0.9329

Table A.4 Convention heat transfer coefficient (Ali, Sunil, and Muhammed, 2007)

Material	Thermal Conductivity (W/mK)	Material	Thermal Conductivity (W/mK)
Plate	58.1	Carpet	0.077
Felt	0.07	Asphalt sheet	0.744
Vinyl sheet	0.174	Rubber	0.163
Glass	0.756	Malt plain	0.035
Hardboard	0.14	A1 sheet	267
Urethane foam	0.035	Glass fiber	0.052

Table A.5 Parameter value for Air Conditioner sizing design

Parameter	Value
M_{met} (W/m^2)	85.00
BSA (m^2)	136.00
Air Vol Leak (m^3/h)	25.00
Air density (kg/m^3)	1.00
Enthalpy air flow rate (m^3/h)	74.00
Ug	7.90
Ag (m^2)	3.37
ΔT (^{o}C)	27.00
τ (W/mK)	0.84
Us	7.90
As (m^2)	36.00
Glass direct radiation coefficient (W/mK)	0.72
Glass diffusion coefficient (W/mK)	0.28
Outside temperature (^{o}C)	45.00
Inside temperature (^{o}C)	18.00

Table A.6 Reference values for C_D and A_f of vehicle type (Ehsani et al., 2010)

Vehicle	C_D	A_f (m^2)
Motorcycle with rider	0.5 - 0.7	0.7-0.9
Open convertible	0.5-0.7	1.7-2.0
Limousine	0.22-0.4	1.7-2.3
Coach	0.4-0.8	6.0-10.0
Truck without trailer	0.45-0.8	6.0-10.0
Truck with trailer	0.55-1.0	6.0-10.0
Articulated vehicle	0.5-0.9	6.0-10.0
Bus	0.6-0.7	6.0-10.0

Table A.7 Energy consumption (K_{ev}) (kWh/km) (Cauwer et al., 2015)

Type	Power consumption (K_{ev}) (kWh/km)
Electric bus (12 m)	0.8-1.3
Electric bus (18 m)	1.0-1.8
Electric bus (27 m)	2.0-2.8
Electric bus (double decker)	2.0-3.0
Truck	2.0-3.2
Van	0.13-0.20
Car	0.13-0.20

Table A.8 PEA Zero-Emission electric bus component specification

Component	Specification
Vehicle control unit (VCU)	22-32 V, 8xAnalog/digital, 2 CAN
DC/DC converter	650/24 Vdc, 160 A, 4.5kW
Steering pump inverter	650 Vdc 3 kW
steering pump motor	220 Vac 50 Hz 3 kW
DC converter	24/12 Vdc, 20W
DC converter	650/24 Vdc, 5kW
Dash board	10.4 inch, 800 MHz , 512 Mbyte, 12 V
Auxiliary battery	24 V, 90 Ah
Traction batteries	320 Ah, 633.6 V, 196 kWh
Air conditioner	650 Vdc, 15kW
Traction motors	465 Nm, 2×120 kW
Traction motor drive inverters	800 V, 300 A
Water coolant system	24 V, 432 W
Air compressor pump inverter	650 Vdc, 3 kW
air compressor motor	220 Vac, 50 Hz , 3 kW

APPENDIX B

MOTOR AND BATTERY SIZE CALCULATION PROGRAM

B.1 Traction motor sizing design program

The sizing of the electric motor drive can be calculated by presented program in Excel format file as shown in Figure B.1. The necessary input parameters of the total mass of the vehicle in kg (M), the expected acceleration time in second (t_a), the vehicle speed corresponding to the motor-base speed in m/s (V_b), the final speed of the vehicle during acceleration speed in m/s (V_f), the acceleration of gravitational constant in 9.8 m/s^2 (g), the rolling resistance coefficient (f_r), the coefficient of air density in kg/m^3 (ρ_a), the front area of the vehicle in m^2 (A_f), the aerodynamic drag coefficient that characterize the shape of the vehicle body (C_D), and the tractive power in watt (P_t). These parameters involve finding the power rating, maximum torque, acceleration performance and peak load power in typical drive cycles. The higher the maximum torque required, the larger size of motor. An initial of design, the power rating of the electric motor drive can be estimate according to acceleration performance. The total tractive power for accelerating the vehicle from zero to given speed within seconds may be concerned of the rolling resistance and dynamic drag as expressed by equation (3.2).

It can be noted that, the solution of articulated bus with only one driven axle can be installed as pusher or puller as shown in Figure B.2 and B.3, respectively. This method saves costs and weight of bus. It is recommend for in city bus and specific airport shuttle bus regarding the flat terrain route.

PARAMETER	INPUT	
δ	1.0425	
M	12,000	kg
ta	10	sec
Vf	60	km/h
Vb	0	km/h
g	9.8	m/s^2
fr	0.05	
ρa	1.202	
Cd	0.7	
Af	8.1	m^2

Motor size	OUTPUT	
Pt	245.39	kW

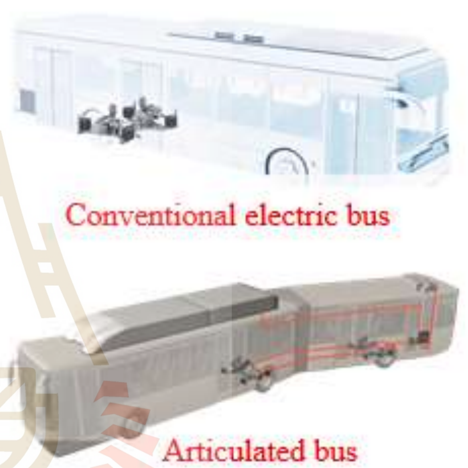

Figure B.1 Traction motor size calculation program

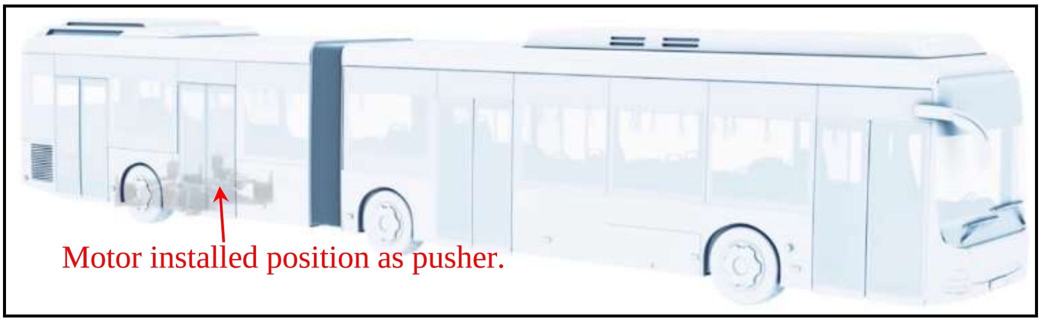

Figure B.2 The pusher motor installation in articulated bus

Figure B.3 The puller motor installation in articulated bus

B.2 Battery sizing calculation program

The battery calculation program is established in Excel file as shown in Figure B.4. This method can be expressed by equation (3.1) where C_{Ah} is traction battery package capacity (Ah), V_{bus} is DC bus voltage (V), S_{bat} is electric range (km), K_{ev} is average energy consumption per kilometer of the electric transit bus (kWh/km) which can be estimated at 0.9-1.1 kW/km by urban drive cycle and K_{soc} is discharge coefficient which can be approximate as 0.8.

BATTERY SIZING DESIGN

PARAMETER	INPUT	
K_{ev}	1	
S_{bat}	150	km
K_{soc}	0.8	
V_{bus}	650	Vdc

C_{Ah} = 1000*Kev*Sbat/(Ksoc*Vbus) (Ah)

Battery Size	OUTPUT	
C_{Ah}	288.46	Ah

K_{ev} = average energy consumption per kilometer of the electric transit bus (kWh/km) about 1.0 kWh/km by urban drive cycles

S_{bat} = electric range (km) (not less than 50 km)

V_{bus} = DC bus voltage (V)

Ksoc = discharge coefficient, which is 0.8

Figure B.4 Battery size calculation program

APPENDIX C

PUBLICATIONS

List of Publications

Kulworawanichpong, T., and Punpaisarn, S. (2014). **Dynamic Simulation of Electric Bus Vehicle**, the SIJ Transactions on Computer Science Engineering & its Application (CSEA), 2(3), pp. 82-87.

Punpaisarn, S., and Kulworawanichpong, T. (2018). **Development of Electric Bus Transportation Challenge in Thailand**, Accepted to be published by Interciencia Journal, Vol. 43, No. 10, pp. 145-161.

Punpaisarn, S., and Kulworawanichpong, T. (2019). **Electric Bus Development and Design; Case Study for Power Consumption of Public Transportation**, Accepted to be published by Wulfenia Journal, Vol. 26, No. 5, pp. 23-37.

Punpaisarn, S., and Kulworawanichpong, T. (2013), **Parameter identification for state of discharge estimation of Li-ion batteries**, Advances in Nano, Biomechanics, Robotics, and Energy Research (ANBRE13), pp. 604-609.

Punpaisarn, S., and Kulworawanichpong, T. (2014), **Traction performance and electric bus vehicle dynamic simulation**, International Symposium on Fundamental and Applied Sciences Conference (ISFAS), pp. 649-657.

Punpaisarn, S., and Kulworawanichpong, T. (2019). **Parameter identification for state of charge and discharge estimation of Li-ion batteries**, Accepted to be published by Annual Conference on Engineering and Information Technology (ACEAIT-0221) in Electrical and Electronic Engineering (2), pp. 92-103.

BIOGRAPHY

Suchart Punpaisarn. He received B. Eng. in Electronics Engineering from Vongchavalitkul University, Nakhon Ratchasima, Thailand (1998) and M. Eng. in Electrical Engineering from Kasetsart University, Bangkok, Thailand (2005). He worked as an Assistant Chief Engineer, JVC (Components) Thailand Company, Nakhon Ratchasima, Thailand (1996 – 2002) - Level IV Engineer and a Senior Engineer, Seagate Technology (Thailand) Ltd., Nakhon Rachasima, Thailand (2005 - 2007) – Level V Engineer, Plant Manager, Cherdchai Industrial Factory Co., Ltd, Nakhon Ratchasima, Thailand (2008 - present). Currently he is a Ph.D. student conducting his research in electric vehicle analysis, simulation and design. His research interests include control system, process and industrial control and instrument, electronic and digital circuit design, robotics, signal and image processing, artificial intelligence and optimization.