UNIVERSITI PUTRA MALAYSIA

OPTIMIZATION AND PREDICTION OF BATTERY ELECTRIC VEHICLE DRIVING RANGE USING ADAPTIVE FUZZY TECHNIQUE

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By

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Despite the realization of zero-emission design of Battery Electric Vehicles (BEVs) for transportation to replace the traditional fuel-based vehicles, the real challenge is the minimal driving range. The conflict between battery power supply and consumption for motor and auxiliaries such as heating, ventilation and air conditioning system (HVAC) implies the need to increase the battery energy. Since BEV battery storage is the sole source of energy, the travel distance for one charge significantly affects the driver's confidence. Hence the goal of increasing the travel distance in BEV, and maintaining the driver's confidence will be achieved by Energy Management System (EMS). EMS is an effective method to boost power efficiency by reallocating the electrical power flow inside HVAC system to obtain optimum effectiveness.

This research aims to propose solutions to achieve a more efficient power control of the HVAC consumption by using adaptive fuzzy technique for optimization and prediction of EMS in BEV. The model was based on the actual parameters using software MATLAB-Simulink and ADVISOR. The vehicle was configured according to backward facing model and the design incorporated the technical specifications of a Malaysia local car, PROTON IRIZ (BEV). An optimal solution was proposed by integrating fuzzy logic technique with brute force algorithm that gave the best system optimization, where the decision was based on the Satisfaction Ratio (SR) and State of Charge (SoC).

The study also developed an algorithm for predictive EMS using fuzzy model predictive control technique based on regression algorithm. The available parameters of speed, SoC, and power consumption had no pattern and the sample diversity was limited, therefore using simple regression was accommodating. The study also proposed a new measure named Wise Performance Measure (WPM) to achieve the balance between SoC and

auxiliaries needs of energy by setting the threshold level for SoC drop and SR, then counting any breaks of this threshold every time intervals.

For benchmarking, the results were compared with different designs based on previous studies using New European Driving Cycle (NEDC), Urban Dynamometer Driving Schedule (UDDS), Japanese 10-15 Mode Driving Cycle (Japan 10-15), and Highway Fuel Economy Test Driving Cycle (HWFET). The results showed that the basic fuzzy EMS was able to improve the power consumption by 11.7% to 12.4%; the optimized fuzzy EMS had improved by 18.8% to 26.6%, and the predictive fuzzy EMS had improved by 16.9% to 29.1%. Predictive EMS improved the city driving experience by 0.8% to 2.5% but was unable to improve the non-city driving experience.

The proposed solutions show a significant improvement in the driving range. It is clear that implementing the fuzzy logic strategy, optimization, and predictive can iimprove the power consumption of HVAC system and retain the power capacity for motor torque and speed. The work in this thesis is expected to be the best approach in formulating an adaptive fuzzy technique based on brute force and regression algorithms for optimization and prediction of EMS in BEV application.

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

PENGOPTIMUMAN DAN RAMALAN JULAT PEMANDUAN KENDERAAN ELEKTRIK BATERI MENGGUNAKAN TEKNIK SAMAR SUAI

Oleh

ABDULHADI ABDULSALAM ABULIFA

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Walaupun merealisasikan rekabentuk pelepasan sifar bagi kenderaan-kenderaan elektrik bateri (BEVs) untuk menggantikan kenderaan tradisional berasaskan bahan bakar, cabaran sebenar adalah julat pemanduan yang minimum. Konflik antara bekalan kuasa bateri dan penggunaan motor dan alat pembantu seperti sistem pemanasan, pengudaraan dan penyaman udara (HVAC) membayangkan keperluan untuk meningkatkan tenaga bateri. Memandangkan penyimpanan bateri BEV adalah satu-satunya sumber tenaga, jarak perjalanan untuk satu cas memberi kesan ketara kepada keyakinan pemandu. Memandangkan storan bateri BEV adalah satu-satunya sumber tenaga, jarak perjalanan untuk satu cas memberi kesan ketara kepada keyakinan pemandu. Oleh itu matlamat untuk meningkatkan jarak perjalanan dalam BEV, dan mengekalkan keyakinan pemandu akan dicapai oleh Sistem Pengurusan Tenaga (EMS). EMS ialah kaedah yang berkesan untuk meningkatkan kecekapan kuasa dengan mengagihkan semula aliran kuasa elektrik di dalam sistem HVAC untuk mendapatkan keberkesanan optimum

Penyelidikan ini bertujuan untuk mencadangkan penyelesaian bagi mencapai kawalan kuasa yang lebih cekap bagi penggunaan HVAC dengan menggunakan teknik samar suai untuk pengoptimuman dan ramalan EMS dalam BEV. Model ini berdasarkan parameter sebenar menggunakan perisian MATLAB-Simulink dan ADVISOR. Kenderaan ini dikonfigurasikan mengikut model menghadap ke belakang dan rekabentuknya merangkumi spesifikasi teknikal sebuah kereta tempatan Malaysia, PROTON IRIZ (BEV). Penyelesaian optimum telah dicadangkan dengan menyepadukan teknik logik samar dengan algoritma daya kasar yang memberikan pengoptimuman sistem terbaik di mana keputusannya adalah berdasarkan Nisbah Kepuasan (SR) dan Pembuangan tenaga (SoC).

Kajian ini juga membangunkan algoritma untuk EMS ramalan menggunakan teknik kawalan ramalan model samar berdasarkan algoritma regresi. Parameter kelajuan, SoC dan penggunaan kuasa yang tersedia tidak mempunyai corak dan kepelbagaian sampel adalah terhad, jadi menggunakan regresi mudah adalah sangat sesuai. Kajian itu mencadangkan ukuran baru bernama Pengukuran Prestasi Bijak (WPM) untuk membuat keseimbangan antara keperluan tenaga SoC dan tenaga alat bantu dengan menetapkan tahap ambang untuk penurunan SoC dan SR, kemudian menghitung setiap jeda ambang ini setiap selang masa.

Untuk penandaarasan hasilnya dibandingkan dengan rekabentuk berbeza berdasarkan kajian terdahulu menggunakan Kitaran Pemanduan Eropah Baharu (NEDC), Jadual Pemanduan Dinamometer Bandar (UDDS), Kitaran Pemanduan Mod 10-15 Jepun (Jepun 10-15), dan Kitaran Ujian Pemanduan Ekonomi Bahan Bakar Lebuhraya (HWFET). Hasil kajian menunjukkan bahawa EMS kabur asas dapat meningkatkan penggunaan kuasa sebanyak 11.7% hingga 12.4%; EMS kabur yang dioptimumkan dapat memperbaikinya sebanyak 18.8% hingga 26.6%, dan EMS kabur ramalan dapat memperbaikinya sebanyak 16.9% hingga 29.1%. EMS yang boleh diramalkan dapat meningkatkan pengalaman pemanduan bandar sebanyak 0.8% hingga 2.5% tetapi tidak dapat memberikan peningkatan bagi pengalaman pemanduan di luar bandar.

Penyelesaian yang dicadangkan menunjukkan peningkatan yang ketara dalam julat pemanduan. Jelas sekali bahawa perlaksanaan strategi logik samar, pengoptimuman dan ramalan dapat meningkatkan penggunaan kuasa bagi sistem HVAC dan mengekalkan kapasiti kuasa untuk tork dan kelajuan motor. Kerja dalam tesis ini dijangka menjadi pendekatan terbaik dalam merumuskan teknik samar suai berdasarkan algoritma daya kasar dan regresi untuk pengoptimuman dan ramalan EMS dalam aplikasi BEV.

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

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Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

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LIST OF ABBREVIATIONS

AI	Artificial Intelligence
AMT	Automated Mechanical Transmission
ANN	Artificial Neural Network
BEV	Battery Electric Vehicle
CVT	Continuously Variable Transmission
DMC	Dynamic Matrix Control
DP	Dynamic Programming
DPSO	Discrete Particle Swarm Optimisation
ECMS	Equivalent Consumption Minimization Strategy
ELM	Extreme Learning Machine
EMS	Energy Management System
EV	Electric vehicle
EVB	Electric Vehicle Battery
FCEV	Fuel Cell Electric Vehicle
FLC	Fuzzy Logic Controller
FMPC	Fuzzy Model Predictive Controller
UDDC	Urban Driving Cycle
GA	Genetic Algorithm
GPS	Global Positioning System
HAI	Hybrid Artificial Intelligent
HEV	Hybrid Electric Vehicle
HLSC	High-Level Supervisory Control
HVAC	Heating Ventilation and Air Conditioning
HWFET	Highway Fuel Economy Driving Test

ICE	Internal Combustion Engine
MAC	Model Algorithmic Control
MF	Membership Function
MO	Metaheuristic Optimization
MPC	Model Predictive Control
MSEV	Management System for Electric Vehicle
NEDC	New European Driving Cycle
NiCd	Nickel–Metal Hydride
pEEM	predictive Electric Energy Management
PHEVs	Plug-in Hybrid Electric Vehicle
PMP	Pontryagin’s Minimum Principle
RB	Rule Based
SLI	Starting, Lighting, and Ignition
SoC	State of Charge
SR	Satisfaction Ratio
UDDS	Urban Dynamometer Driving Schedule
VRLA	Valve Regulated Lead-Acid
WPM	Wise Performance Measurement

CHAPTER 1

INTRODUCTION

1.1 Research Background

Global temperature changes and air pollution are among the obstacles faced by today's society, which influence our beliefs in brand new technical innovations. Major eco-friendly modifications must be created at each degree of innovation and in each market. For the automotive market, this situation indicates that our principal method of transportation, now mostly based on the Internal Combustion Engine(ICE), has to introduce modifications to sustain a well-maintained atmosphere (Nanaki *et al*., 2016; Wicki & Hansen, 2017). Among the available options is the electrification of automobiles, such as vans, motorcycles, buses, and trucks. Hybrid Electric Vehicles (HEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) are the primary steps to create the switch to Battery Electric Vehicles (BEVs) within the automotive sector.

There are four types of emerging electrical power in-vehicle operations: BEVs, HEVs, PHEVs, and gas cell electric automobiles (FCVs). A BEV is powered entirely on electric electricity, normally a huge electric motor and a huge battery pack, consisting of a DC-DC converter and transmission, driving cycle, and longitudinal vehicle dynamic model. Pure electric motor vehicle is a type of EV that makes use of chemical power saved in rechargeable battery packs. BEVs use electric motors and electric motor operators instead of internal combustion engines (ICEs) for power. Hybrid electric cars are powered through both an interior ignition (powered by either fuel or even diesel-powered) and an electric engine. The internal combustion engine is dominant and the electric motor serves merely as a supplement. Therefore, a smaller battery and the burning engine, integrated along with the energy originating from the regenerative braking, give the power for the car. Unlike in BEVs, this battery cannot be recharged using a battery channel due to its small capacity, and hybrid autos are not outfitted with a billing connect.

PHEVs, HEVs, and BEVs are currently experiencing financial and specialized obstacles relating to the range of travel, battery life, and lifetime expense (de Jong, 2016; Suppes & Storvick, 2015). Batteries for electric vehicles should be able to operate in various conditions, in terms of voltage, current, and temperature for optimal efficiency, and user protection. In terms of electrical power intake, the Battery Management System (BMS) is needed to manage the superior use of power within the various working components. The BMS should be improved to enhance its efficiency and battery functionality, as well as to minimize its complication, body weight, size, and cost.

EVs have presented an excellent alternative to reduce the consumption of petrol and other high CO_2 emitting transportation gases. However, one primary constriction with EVs is the functionality of batteries to offer electricity for a driving range that approaches petrol-sustained vehicles. This insufficiency creates span stress to potential EV drivers. Different attempts were made consisting of HEV and PHEV that combine a small ICE to obtain better gas mileage (Aguilar *et al.*, 2017; Serrao *et al.*, 2011). For that reason, primary importance is placed on electricity monitoring of the EV system. The vehicle path prediction that applies the product line tracking procedure, which uses either true or anticipated vehicle rate and road grade paths, could help in getting a superior power application.

The body of an EV requires the unit of electricity control, which is primary and essential. An Energy Management System (EMS) is a computer-aided resource that drives the electrical power grids to monitor, command, and improve the generation and functionality of the gear box device. In an EV, EMS is categorised into three levels of management, namely low-level control (LLC), low-level component control (LLCC), and high-level supervisory control (HLSC) (Mohd *et al.*, 2015).

In the 1970s, the initial research on the EMS for EVs was released, and then, by the 1990s, research on the EV power monitoring system was published. As it can affect the electronic components and the efficiency sizing of the EVs, EMS is considered to be a crucial issue. Lowering the consumption of energy, minimizing exhausts, reducing the operating cost, reducing noise pollution, boosting steering functionality, and simplifying usage are the benefits that can be gained by improving the electricity management in HEVs (Hassan *et al.*, 2015). This objective can be achieved by observing and understanding drivers' behaviour, ecological and vehicle ailments, and regulating the procedure for HEV usage by utilizing intelligent power monitoring methods (Panday & Bansal, 2014).

1.2 Research Problem

An EV is a car that uses a minimum of one electric-powered motor rather than the traditional combustion engine (Guarnieri, 2012). This is a second-hand innovation since this idea has been around since the mid-1800s. Although the enthusiasm for this technology was strong during the 20th century, the demand for longer-range vehicles, the lower cost of gas, the invention of the power starter in standard cars, and the beginning of the mass development of internal burning EVs have reduced the attention on EVs until the start of the 21st century (Temiz, 2015).

The environmental issues caused by traditional transportation and increasing oil price have revived the passion for power vehicles in recent years (Eberle & von Helmolt, 2010; Temiz, 2015). While BEVs offer zero carbon footprint solution with outstanding drivetrain performance and energy efficiency, the drawback is the limitation of driving range due to constraints in batteries capacity and volume. This is for BEVs that have batteries as the only energy storage. (Tengku, 2020). BEV battery storage is the only source of energy, so that the range (travel distance for one charge) with making the driver Confidence are significant. To increase the travel distance in BEV and keep the driver Confidence will be achieved by Energy Management System (EMS). To save more energy for driving, less power must be assigned to auxiliary load which will be reached by the optimal situation between Satisfaction Driver (SR) and Drain of energy (SOC). This research has been applying Fuzzy Logic Controller (FLC), and finding the best configuration of FLC by Brute Force Algorithm (BF) then applying Advanced Predictive Algorithm to improve the optimal FLC by Regression Algorithm to increase the travel distance and at the same time keep the driver Confidence.

The electricity management system for an EV unit is the core component in the driving experience of EVs. Moreover, prediction of the vehicle path using the line tracking procedure, using either genuine or predicted vehicle rate and street grade velocities, can aid in obtaining an optimum energy application (Taghavipour, 2014; Zhang & Vahidi, 2011).The EMS needs to be maximized to enhance its performance and battery efficiency, as well as to increase the travel distance for BEVs and maintain the driver's confidence.

Artificial Intelligence (AI) techniques have been evolving rapidly particularly in EMS (Tengku, 2020). Their revolutionary applications provide efficient control strategies that increase the capabilities, efficiency and accuracy of EMS, as well as reducing EVs' energy consumption. Hence comes the need for AI approaches in energy management to provide battery power supply that fulfils power consumption for motor and auxiliaries such as heating, ventilation and air conditioning system (HVAC). Applying EMS is one of the AI approaches that can reallocate the electrical power flow inside the HVAC system to boost power efficiency and obtain optimum effectiveness. Therefore, this research is focused on the energy consumption of BEVs by developing optimization and prediction algorithms based on fuzzy logic technique to apply the best solution in EMS. Such innovative AI solutions can enhance the efficiency of smart EMS in BEVs as the future sustainable transportation.

The proposed solution addressed the problems by increasing the travel distance in BEVs and maintaining the driver's confidence by decreasing the power consumption using adaptive fuzzy technique, namely by integrating the brute-force and regression algorithms into fuzzy logic approach. The brute force algorithm has been successfully used as optimization technique in other applications and it is the best learning method based on a set of small number inputs and outputs (Pham & Månsson, 2018). However, no previous studies have used brute force with fuzzy logic technique to find the best solution or set a strategy EMS for BEVs. Therefore, the brute force algorithm has been chosen to integrate with the fuzzy controller because the algorithm is the best optimization for the system when involving the small number of inputs-outputs and also the system is not working continuously.

This technique finds the best solution from a wide range of measures, where the decision is based on two or more variables. In BEVs, the available parameters of speed, SoC, and power consumption have no pattern and the sample diversity is limited, therefore using simple regression algorithm based on recent data (current and previous) is more applicable. The adaptive fuzzy technique integrated with brute force and regression algorithms will obtain the best out of available resources and also use the known model parameters to estimate system output behavior at some specified input state to generate predictions that are more efficient and more accurate.

1.3 Research Aim and Objectives

The main aim of this study is to develop an optimal fuzzy logic control system and predictive algorithms for the EMSto increase the driving range of BEV. In order to accomplish this main goal, the aim of this research is to achieve the following objectives:

1. To develop a mathematical model of BEVs using a backward facing approach based on Proton IRIZ power specifications.

2. To develop an algorithm for the optimal control of EMS for BEVs using fuzzy brute force technique.

3. To develop an algorithm for predictive energy management using fuzzy model predictive control technique based on regression algorithm.

4. To propose a Wise Performance Measure (WPM) as a new technique measurement for EMS.

1.4 Scope of the Research

The following limitations make the research more accurate and applicable, and they also makes it more logical and closer to reality.

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

- The BEV technical specifications are adopted from a Malaysian local car, Proton IRIZ, manufactured by Proton.

- This study focuses only on battery system to improving the power consumption and maintain driver confidence by controlling HVAC system.

- All modelling and simulation works are performed in MATLAB/Simulink and ADVISOR workspace environment. No actual or field experiment was conducted.
- Some complementary conditions, such as automobile air-condition and environmental weather, were not included in the simulation process.

1.5 Research Contribution

As a novel approach, this thesis deals with the concept, design and implementation of EMS for BEVs. This study is important as it contributes to one of the most recent environmental concerns in the world, namely green solutions. Batteries are the main source of energy in a BEV, but battery range, as well as driver confidence, are of significant concern. The majority of the previous works are limited to either time charging battery or grid assimilation. Meanwhile, this research is focused on the energy consumption of a BEV, by developing advanced algorithms based on optimize the EMS. This study is carried out to encourage consumers to choose pure electric vehicles in order to promote a good environment.

The desired contributions of this work can be summarised as follows:

1. Modelling of BEV using a backward facing approach based on Proton IRIZ power specifications.

In this study, the mathematical model of BEV (using a backward-facing approach based on Proton IRIZ power specifications) has been developed in MATLAB/Simulink and ADVISOR simulation environment. The model topology based on backward-facing approach is a simplified model of BEV and it does not require a driver model. The user only has to input the driving pattern and a velocity profile called the speed.

2. Developing a new algorithm for the optimal control of EMS for BEVs using fuzzy brute force technique.

The study provides a new algorithm for optimal control of EMS using a fuzzy logic technique by integrating with the brute force algorithm in order to finding the best configuration of the adaptive fuzzy technique. The brute force algorithm is suitable to be used when the system is not working continuously and also when involved with very small inputs-outputs as BEV model. In addition, the proposed system can be recalibrated based on user behaviour. No previous studies have used brute force with fuzzy logic technique to find the best solution or to set a strategy to reset brute force at any time for BEVs.

3. Developing a new algorithm for predictive energy management using fuzzy model predictive control technique based on regression algorithm.

The research provides a new algorithm for predictive EMS using fuzzy logic technique by integrating the regression algorithm. The proposed system is supposed to provide an active adaptation system, which is different from the optimization technique based on fuzzy brute force system. The proposed prediction technique based on regression algorithm can be applied for BEV which only involves a few samples and without having a clear pattern. In the BEV, the power source is only batteries and the power is reducing continuously while the vehicle is being driven (No recharge). The available parameters of speed, SoC, and power consumption have no pattern and the sample diversity is limited, therefore using simple regression based on recent data (current and previous) can be applicable. No previous studies have used the regression strategy with brute force integrated in fuzzy logic technique as adaptive fuzzy technique for BEVs. The solution is dynamic and working continuously.

4. Proposing a new technique measurement called a Wise Performance Measure (WPM) for EMS

This study proposed a new technique measurement to create the balance between State of Charge (SoC) and Auxiliaries needs of energy. This is done by setting threshold level for SoC drop and Satisfaction Ratio (SR) and then counting any breaks of this threshold in every time interval. To compare between different designs is not an easy task especially when we have to consider increasing the driving range and maintaining the driver's satisfaction. This study provides a technique to make this measure by providing a new composed scale.

1.6 Thesis Outline

The thesis is divided into five chapters:

Chapter 1 is the introductory chapter to present the background information of the EMS and the EV, to set out the research problem, and to state the research objectives and questions. This chapter also discusses the research scope, contribution, and structure.

Chapter 2 of this thesis presents the Literature Review, which includes an overview of the technology for EVs, available models, the components, optimal parameters and variables for EVs, and the EMS based on previous studies.

Chapter 3 of this thesis introduces the research methodology. The chapter also includes the proposed designs, specifications, and parameters for this study.

Chapter 4 of this thesis reports the research findings for validating the system and it also reveal the improvements from the two proposed designs, namely the hybrid optimal fuzzy logic EMS and the hybrid regression fuzzy logic EMS.

Chapter 5 of this thesis presents the summary, conclusion, and recommendations for future research regarding solutions for extending the BEV range.

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