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REGENERATIVE BRAKING MODEL FOR ELECTRIC VEHICLES WITH MODIFIED SUPER-TWISTING SLIDING MODE CONTROL

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By

ANITH KHAIRUNNISA BINTI GHAZALI

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

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Chair : Mohd Khair Hassan, PhD
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As global warming comes and the prices of fuel keep rising, the clean and environmental friendly features of electric vehicles are increasingly focused. The electric vehicle is ideally compatible with the existing situation due to its efficiency compared to the Internal Combustion Engine (ICE). For full electric vehicles, the battery is the only source of energy, and the battery faces issues such as longer charging period. In general, Battery Electric Vehicle (BEV) has limited driving range due to battery capacity storage. The regenerative braking system (RBS) became important for electric vehicles that could allow motor vehicles function as a generator and alternator for the recovery process of kinetic energy during a braking event.

During regenerative braking, the kinetic energy produced by the engine during deceleration and the energy needs to be recycled to extend driving range. The energy will be transmitted to charge the battery or store it in the energy storage. If the braking force distribution is not adequately regulated, the controller might fail to generate the necessary braking torque. In reality, the battery pack will cause harm due to overcharging induced by uncontrolled recovery. Appropriate braking system are required to be established in order to optimise the energy transferred during the regenerative braking process.

The presence of classical regenerative braking is to optimise the regeneration of kinetic energy by reconciling regenerative technology with braking efficiency and vehicle behaviour. However, the existing result is insufficient where only 1056.6 kJ per cycle for the Urban Dynamometer Driving Schedule (UDDS) and 4599 kJ per cycle for New European Driving Cycle (NEDC). This research introduced new topology of Integrated Regenerative Braking Force Distribution (IBFD) for optimum braking and vehicle stability by combining average speed distribution of the braking force with National Renewable Energy Laboratory (NREL) braking design. The average speed level for the urban driving cycle in Malaysia is 31.89 km/h. The average braking force is used to optimise the default braking distribution mechanism.

This research verify conventional Sliding Mode Control Super-Twisting (SMCST) controller because it is useful due to it robustness against the disturbances and uncertainties. Even though the conventional SMCST controller confirms the stability, nevertheless it gives unsatisfied performance to obtain the desired State of Charge (SoC). Thus, the modified Sliding Mode Control Super-Twisting with hybrid fuzzy-gain scheduling optimisation component was proposed. The proportional gain was added to the switching control for faster response to the desired sliding surface. The modified SMCST is pairing with IBFD. Based on the results for NEDC, driving cycle using modified SMCST with IBFD braking, the energy transmitted is 600 kJ more than NREL, average motor efficiency increase to 0.85, overall efficiency 2.799 and the SoC is 0.899. The slip ratio output at 32 km/h deceleration is -0.19 that proved the stability of this topology. The proposed methodologies successfully integrate the regenerative and friction braking forces to achieve the control goal.

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

MODEL BREK REGENERATIF UNTUK KENDERAAN ELEKTRIK DENGAN PENGENDALIAN MOD GELONGSOR BERPUSING DIUBAHSUAI

Oleh

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Ketika pemanasan global dan harga bahan bakar terus meningkat, ciri-ciri kenderaan elektrik yang bersih dan mesra alam semakin menjadi perhatian. Kenderaan elektrik sesuai dengan keadaan sekarang kerana kecekapannya berbanding dengan Mesin Pembakaran Dalaman (ICE). Dengan kenderaan yang dikendalikan sepenuhnya tenaga elektrik, bateri adalah satu-satunya sumber tenaga, dan bateri tersebut menghadapi masalah seperti masa pengisian dan memerlukan pengisian yang lebih lama. Secara amnya Kenderaan Elektrik Bateri (BEV) mempunyai jarak pemanduan yang pendek kerana kapasiti bateri yang terhad. Sebagai perkembangan pesat dari pelbagai jenis kenderaan elektrik untuk memelihara bahan bakar karbon dan menyelamatkan iklim, sistem brek regeneratif (RBS) menjadi penting bagi kenderaan elektrik yang memungkinkan kenderaan bermotor berfungsi sebagai penjana dan pengganti untuk proses pemulihan tenaga kinetik semasa membrek.

Semasa brek regeneratif, tenaga kinetik yang dihasilkan oleh enjin semasa nyah pecutan dan tenaga perlu dikitar semula untuk meningkatkan jarak pemanduan. Tenaga akan dihantar untuk mengecas bateri atau menyimpannya di stor tenaga. Sekiranya pengedaran daya brek tidak diatur dengan secukupnya, pengawal mungkin gagal menghasilkan tork brek yang diperlukan. Pada hakikatnya, pek bateri akan menyebabkan bahaya akibat pengecasan berlebihan yang disebabkan oleh pemulihan yang tidak terkawal. sistem brek yang baik diperlukan untuk mengoptimumkan tenaga yang dipindahkan semasa proses brek regeneratif.

Kehadiran brek regeneratif klasik tidak mencukupi untuk mengoptimumkan penjanaan semula tenaga kinetik dengan menggabungkan teknologi regeneratif dengan kecekapan brek dan tingkah laku kenderaan. Walau bagaimanapun, hasil yang ada tidak mencukupi di mana hanya 1056.6 kJ setiap kitaran untuk Jadual Pemanduan Dynamometer Bandar (UDDS) dan 4599 kJ setiap kitaran untuk Kitaran Pemanduan Eropah Baru (NEDC). Penyelidikan ini memperkenalkan topologi baru pengagihan daya brek regeneratif bersepadu untuk brek dan kestabilan kenderaan yang optimum dengan menggabungkan taburan kelajuan purata daya brek dengan rekaan brek Laboratorium Tenaga Diperbaharui Nasional (NREL). Tahap kelajuan purata bagi kitaran memandu bandar di Malaysia ialah 31.89 km/j. Daya brek purata digunakan untuk mengoptimumkan mekanisme pengedaran brek sedia ada.

Penyelidikan ini mengimplementasikan pengawal super-putar mod gelongsor (SMCST) konvensional kerana ia terkenal dengan ketahanan terhadap gangguan dan ketidakpastian. Walaupun pengawal SMCST konvensional mengesahkan kestabilan, namun ia memberikan prestasi yang tidak memuaskan untuk mendapatkan State of Charge (SoC) yang diinginkan. Oleh itu, mod gelongsor yang diubah super-memutar dengan komponen pengoptimuman penjadualan gandaan fuzzy hibrid dicadangkan. Gandaan berkadar ditambahkan pada kawalan pensuisan untuk tindak balas yang lebih pantas ke permukaan gelangsar yang diingini. pengawal SMCST yang diubah suai dipasangkan dengan pengedaran daya brek bersepadu. Berdasarkan hasil untuk kitaran pemanduan NEDC menggunakan SMCST yang diubahsuai dengan pengereman bersepadu, tenaga yang dihantar adalah 600 kJ lebih banyak daripada NREL, kecekapan motor rata-rata meningkat menjadi 0.85, kecekapan keseluruhan 2.799 dan SoC adalah 0.899. Keluaran nisbah slip pada perlambatan 32 km / j adalah -0.19 membuktikan kestabilan topologi ini. Metodologi yang dicadangkan berjaya mengintegrasikan daya brek regeneratif dan geseran untuk mencapai matlamat kawalan.

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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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LIST OF ABBREVIATIONS

ABFD	Average Braking Force Distribution
AC	Alternating Current
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AEV	All Electric Vehicle
BEV	Battery-Driven Electric Vehicle
BLDC	Brushless Direct Current
CVT	Continuously Variable Transmission
DC	Direct Current
ECE	Economic Commission for Europe
EREV.	Extended Range Electric Vehicles
EV	Electric Vehicles
FCEV	Fuel Cell Electric Vehicles
FLC	Fuzzy Logic Controller
FOC	Field-Oriented Control
FTP 75	Federal Test Procedure
GHG	Greenhouse Gas
HEV,	Hybrid Electric Vehicle
IBFD	Integrated Braking Force Distribution
ICEV	Internal Combustion Engine Vehicle
IM	Induction Motors
ISMS	Intelligent Sliding Mode Scheme
NEDC	New European Driving Cycle
NiCad	Nickel-Cadmium
NiMh	Nickel-Metal Hydride

NMPC	Nonlinear Model Predictive Controller
NN	Neural-Network
NREL	National Renewable Energy Laboratory
OCV	Open Circuit Voltage
PHEV	Plug-In Hybrid Electric Vehicle
PID	Proportional Integral Derivative
PM	Permanent Magnet
PMSM	Permanent Magnet Synchronous Motor
PSO	Particle Swarm Optimisation
SMC	Sliding Mode Control
SMCST	Conventional Sliding Mode Control Super-Twisting
SoC	State Of Charge
SR	Switched Reluctance
UDDS	Urban Dynamometer Driving Schedule
US EPA	United States Environmental Protection Agency
WVUCITY	West Virginia University City Cycle

CHAPTER 1

INTRODUCTION

Electric vehicles (EV) are entirely relying on an electrical propulsion system, and no internal combustion engine is used. All control is dependent on batteries as a source of energy. Thus, the quality of electrical energy is the most significant benefit during power conversion through its proposition scheme. Massive research and development activity has recently been documented in both academics and industry [1]. Electric powered vehicles promise a significant reduction in carbon emissions, local air pollution, and greenhouse gas emissions. They will also be more efficient, environmentally sustainable, quiet and secure [2], [3].

Due to environmental concerns and increasing energy demands, electric vehicles have steadily expanded their exposure to customers and producers in recent years. In line for to the decrease in air quality, which is a problem for the environment, and the increase in oil prices, EVs are the alternative option for transport. Electrical Energy Storage (EES) technology refers to transferring energy from one source to a storage form and keeping it in energy storage. The energy collected can be transformed back to electrical energy as desired [4]. Unlike a hybrid electric vehicle (HEV), a battery-driven electric vehicle (BEV) is entirely powered by an electric motor and a battery without any assistance of a traditional internal combustion engine. As a consequence, BEV is the most effective vehicle to reduce emissions and reduction in fossil fuel energy [5], [6]. A battery-driven electric motor replaces the need for an Internal Combustion Engine (ICE) vehicle and a fuel tank. While not in service, BEVs may be plugged in for charging.

Electric vehicle will minimise emissions, which energy supply should be available worldwide for potential usage as well as the cost should be low with a great performance of the vehicle. In addition, electric vehicles are perfectly adapted as electric vehicle drivetrain is much more efficient than the ICE vehicle. The motor performance is about 90%, battery efficiency is approximately 75% and power converter efficiency is around 90%. Therefore, electric vehicle performance's overall efficiency is approximately 75%, which in contrast to ICE vehicles is very high. The effectiveness of the ICE is very low. The engine itself has about 30-37% gasoline efficiency and about 40% diesel, but when energy is on the wheel it only has 5-10% efficiency [7], [8]. Moreover, the EV and ICE powertrain efficiency is approximately 70% and 20%, respectively, although this gap will substantially decrease when considering primary energy efficiency [9]. Besides, when the energy sources used in an electric vehicle are produced from renewable energy, these vehicles contribute to a to a reduction in fossil fuel energy and emission [6].

Malaysia plans to introduce 100,000 units of electric vehicles and 2,000 electric buses with the national car company's capacity by 2030. The EV launch would reduce fossil fuel reliance for the transport industry and reduce greenhouse gas (GHG) emissions [10]. In addition, the energised BLDC motor took up the first 4 seconds. The motor was stopped by its own inertia after 4 seconds, and regenerative braking was performed after that period. Voltage was expected to be induced in phases as the motor decelerated. To store the generated energy in the battery, this voltage must be increased to a higher value than the battery voltage [11].

The comparison of the major components of the ICE and BEV is defined in Table 1.1. The battery serves the same function in an electric vehicle as the fuel tank in an ICE, storing energy until it is desired. An ICE uses a fuel injection system to control the flow of energy in order to regulate the speed and acceleration of the vehicle. In a BEV, a controller controls the flow of energy. At the required rate, the controller provides electrical energy to the motor. The rate is varied according to the position of the accelerator pedal. The power output is used for rotating the drive wheels in both vehicle types.

Table 1.1: Comparison of an ICE and EV [6]

ICE	Purpose	EV
Gasoline tank	Stores the energy to run the vehicle	Battery
Gasoline pump	Replaces the energy to run the vehicle	Battery charger
Gasoline engine	Provides the force to move the vehicle	Electric motor
Fuel injection system	Controls acceleration and speed	Controller
Generator/ alternator	Converts AC to DC to charge the battery and run the accessories	Inverter and DC/DC converter
Not needed	Converts DC to AC to power traction motor	Inverter
Emission	Reduces pollutants from the exhaust	Not needed
Mechanical to heat	Energy conversion during braking	Kinetic to electrical

1.1 Problem Statement

For battery operated EV, the battery is the only energy source, and these batteries are confronted with problems such as longer charging and recharging times and limited performance in the driving range. Electric vehicles have faced a limited driving range compared to traditional vehicles. Running out of energy is the same as braking down. A maximum charging cycle takes an average of 1-2 hours, which is about 120 times the time required to refuel a car [12]. Regenerative braking is more crucial in city driving, where the brakes are used more frequently[13]. In addition, at average city speed, 33.23 km/h the final SoC is 37.55 % which is drop 12 % of state of charge (SoC) for 10.93 km [14]. In addition, to maximise the lifespan of the battery, regenerative should perform at 10% to 90% SoC to avoid overcharging process at temperature range 20 °C to 60 °C. The solution using Neural Network Sliding Mode Control (NNSMC) able to improve the energy saving and driving range to 6% [15]. However, NNSMC does not provide any temperature state of energy storage to avoid overheating and degradation of battery.

Regenerative braking in BEV, which can efficiently increase automotive fuel economy by restoring kinetic energy throughout deceleration cycles, has been used in different electrified vehicles as one of the main innovations. The regenerative brake should be synchronised with the mechanical brake to achieve high regeneration efficiency and guarantee protection for the vehicle's brake. Consequently, the mechanical braking system's layout and the brake mixing control method can significantly impact the regenerative braking control efficiency.

One of the practical approaches to enhance EV's energy rate is cooperative regenerative braking force distribution, whereby the energy consumed during acceleration is recovered during braking. Regenerative braking can currently contribute to a 20 % to 50% improvement in fuel usage. However, the electric vehicle's most critical issues are their capacity to recover a large amount of braking energy. The presence of traditional regenerative braking does not make it feasible to optimise the regeneration of kinetic energy by reconciling regenerative energy with braking efficiency and vehicle behaviour.

Generally, like the traditional fuel-driven vehicle braking system, it consists of brakes and power to slow the engine down or stop it. In electric vehicles a regenerative braking system is available that can benefit from the engine control system that decelerates the braking energy back into the battery to ensure regeneration.

Moreover, the need to increase overall efficiency has contributed to the design of the regenerative braking system. In regenerative braking, the energy during deceleration is converted to electricity and used to expand the driving range. The harvested energy will be used to charge the battery or store in the energy storage [19] [20] [21] [22]. Therefore, efficient braking control designs are necessary to be determined in order to maximise the transmitted energy while regenerative braking is executed.

If the braking force's distribution is not effectively controlled, the controller may fail to produce the required braking torque. The battery pack can cause damage due to overcharging produced by unregulated recovery. In technological trends, the Sliding Mode Control (SMC) design has become attention due to its robustness, good performance and disturbance rejection. Besides that, SMC also approaches critical issues such as elimination of chattering, adaptability to the uncertain system and enhancement of the dynamic performance of the closed loop system. However, the traditional SMC configuration produces a chattering phenomenon in control, which is why it is not applicable in real practise. The solution provided using the Intelligent Sliding Mode Scheme (ISMS) on 2018, which has a primary logic-based torque limiter, provided an excellent tracking of the required slip during an extreme braking scenario with high braking performance. It successfully achieved a significant energy recovery without overcharging the battery pack by efficiently implementing the chosen brake torque distribution. However, this method produced an overshoot of about 0.24 while tracking the slip ratio which exceeding the ideal value 0.2 [16].

As a key device of the regenerative braking mechanism, the efficiency of the motor specifically influences the recovery of energy. The amount of energy transmitted using the dynamic low-speed cut-off point detection for maximising energy transmitted can only transmit 1056.6 kJ per cycle for the UDDS driving cycle and 4599 kJ per cycle for NEDC driving cycle. Next, the amount of recovered braking energy through the fuzzy logic control strategy introduced by is 2145 kJ [13]. Furthermore, the current regenerative motor efficiency of RBS is 0.75.

In addition, fuzzy logic for regenerative has been proposed by [17] using Sugeno method due to its viable and effective. The simulation results show that the fuzzy logic control strategy can obtain more regenerative braking energy than the default strategy, as well as an increase in overall vehicle system efficiency. In addition to enhancing the vehicle's overall efficiency, regeneration can significantly increase the life of the braking system by reducing damage on its components [18].

Based on previous studies, electric regenerative braking can help to improve fuel efficiency by 20-50% depending on electric motor size. Various efforts were made earlier to increase the regenerative braking energy by the proposed control strategy by adjusting the Continuously Variable Transmission (CVT) gear ratio to sustain the motor at a high-efficiency motor region. However, only 8% improvement of regeneration energy through this strategy [19], thus appropriate new regenerative braking control strategy needed in order to maximise transmitted regenerative braking energy.

1.2 Aim and Objectives

This research aims to design an algorithm for optimum energy recovery without overcharging the battery (regenerative only perform at 10% to 90% SoC). Lower SoC higher inner resistance of batteries, and charging current should be decreased at high SoC to prevent the deposit of Li-on (Lithium-ion). The following are objectives of the research.

1. To develop Integrated Braking Force Distribution (IBFD) for optimum braking and vehicle stability.
2. To develop hybrid Modified Sliding Mode Control Super-Twisting (SMCST) with hybrid fuzzy-gain scheduling optimisation component in order to reduce control error of vehicle speed based.

3. To evaluate the performance of Modified Sliding Mode Control Super-Twisting (MSMCST) with hybrid fuzzy-gain scheduling optimisation component with conventional Sliding Mode Control Super-Twisting (SMCST) and National Renewable Energy Laboratory (NREL) default design.

4. To analysis IBFD the driving cycle's performance in terms of SoC, energy transmitted, motor efficiency, temperature, slip ratio, and overall efficiency.

1.3 Contribution

This research focuses on parallel braking force distribution based on vehicle speed based. The main contribution of this research is development of integrated braking force distribution by considering the average city driving speed in order to obtain maximum energy transmitted during braking. The integration of average speed will act as optimize component for the existing braking force distribution. Next, the Modified Sliding Mode Control Super-Twisting has been introduce by introduce the proportional gain. The output speed able to track the input driving cycle and reduce the steady state error. In addition, fuzzy-gain scheduling has been introduce as tuning component in order to improve the SoC level and provides better performance.

1.4 Scope

This research demonstrates an algorithm of braking force distribution passenger electric vehicle with specification of total mass 903 kg without passenger. The mass was considered 592 kg of vehicle mass without component, 34 kg energy storage system, 91 kg electric motor, 50 kg transmission and 136 cargo mass. The mathematical model has been formulating for vehicle dynamics that consists of rolling resistance, aerodynamic drag and grading resistance. The parallel braking force distribution strategy was design by considering Malaysia’s average city speed at 31.89 km/h and the maximum ratio for regenerative braking is at 60 km/h. The braking strategy is designed to recuperate maximum energy without overcharging the battery while maintaining the vehicle stability. The energy storage system was designed to execute the regenerative braking at 10% to 90% of SoC to prevent from overcharging. This algorithm has been test for dry asphalt condition with four types of driving cycle to investigate the proposed algorithm performance such as New European Driving Cycle (NEDC), Federal Test Procedure (FTP 75), Urban Dynamometer Driving Schedule (UDDS) and West Virginia University City Cycle (WVUCITY) driving cycles.

1.5 Summary

This thesis is organised into five chapters. Chapter 1 briefly introduces the research work, which includes research background, problem statement, aim and objectives, and scope of the work.

In the second chapter, all related literature review with refer to regen are reviewed. The principle of regenerative braking consists of vehicle dynamics, electric motors, batteries, braking force distribution, regenerative braking control and sliding mode control in regenerative braking. Summary of existing finding, advantage and disadvantage is tabulated.

In the third chapter, the methodology of design the integrated braking force distribution through Malaysia's average speed at 31.89 km/h method is presented. Next, the controller algorithm design using conventional sliding mode super-twisting and hybrid sliding mode super-twisting with fuzzy and gain scheduling as optimisation mechanism is discussed.

Chapter 4 presents the results and findings obtained through four types of driving cycle comprehensive analysis on NREL default topology, conventional SMCST, and modified SMCST. Also, comparative evaluation for several important parameters such as SOC, motor efficiency, overall efficiency, energy transmitted, and temperature are presented.

Chapter 5 concludes the work, contribution of the research, and suggestions for future works.

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