MODELLING OF THROUGH-THE-ROAD HYBRID ELECTRIC VEHICLE

OKE PAUL OMEIZA

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To God the Father, the Son, and the Holy Spirit.

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ABSTRACT

This project report focuses on through the road architecture of hybrid electric vehicles. The main advantage of this type of architecture among many other advantages when compared to other hybrid electric vehicle's architecture is the similarity with the conventional vehicles and a potential of an all driven wheels technology, which will greatly reduce the tractive effort needed for each wheel. However, it is important to note that the interaction of the front axle and the rear axle can only occur through the vehicle chassis and on the road. This has given the need to gain adequate insight into how the actual torques of the two energy sources are generated, the nature of it power flow, how best to meet the torque request by adopting their most efficient operating region using dynamic nonlinear mathematical model. This work presents the mathematical modelling of Through-the-Road Hybrid Electric Vehicle (TtR-HEV), the model comprise of an internal combustion engine model, electric motor model, transmission model, vehicle propulsion dynamic model, and battery model. Two different models were built for MatLab/Simulink simulation, the TtR-HEV and the conventional vehicle models, the models was then applied to evaluate propose normal mode power flow design without the frequent start/stop of any of it powertrain. Using different standardized drive cycles, the TtR-HEV shows somewhat fuel consumption reduction for all the drive cycles as compared to the conventional vehicle. This study forms the basis for advance research and developments.

ABSTRAK

Laporan projek memberi tumpuan kepada seni bina jalan kenderaan elektrik hibrid. Kelebihan utama jenis ini seni bina antara banyak kelebihan lain berbanding dengan seni bina lain hibrid elektrik kenderaan adalah persamaan dengan kenderaan konvensional dan potensi sebuah roda teknologi didorong semua yang akan mengurangkan usaha tarikan yang diperlukan bagi setiap roda. Walau bagaimanapun, ia adalah penting untuk ambil perhatian bahawa interaksi gandar depan dan gandar belakang hanya boleh berlaku melalui jalan raya dan casis kenderaan. Ini memandangkan keperluan untuk mendapatkan maklumat yang mencukupi ke dalam bagaimana tork sebenar kedua-dua sumber tenaga dihasilkan, sifat itu aliran kuasa, cara terbaik untuk memenuhi permintaan tork dengan mengguna pakai kawasan operasi yang paling berkesan menggunakan model matematik tak linear yang dinamik. Kerja ini membentangkan model matematik Melalui Jalan Hibrid Kenderaan Electric (TtR-HEV), model yang terdiri daripada model dalaman pembakaran enjin, model motor elektrik, model transmisi, pendorongan kenderaan model dinamik, dan model bateri. Dua model yang berlainan telah dibina untuk simulasi MatLab / Simulink, yang TtR-HEV dan model kenderaan konvensional, model kemudiannya digunakan untuk menilai mencadangkan biasa reka bentuk mod aliran kuasa tanpa kerap mula / berhenti di mana-mana ia powertrain. Menggunakan kitaran memandu seragam yang berbeza, TTR-HEV menunjukkan agak penjimatan penggunaan bahan api untuk semua kitaran memandu berbanding kenderaan konvensional. Kajian ini membentuk asas untuk penyelidikan dan perkembangan awal.

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LIST OF SYMBOLS

δ	-	steering angle
T_{bi}	-	braking torque at i^{th} wheel (in newton meters)
T_i		torque at i^{th} wheel (in newton meters)
v	-	vehicle velocity at centre of gravity (in kilometers per hour)
$\dot{m}_{ac}$	-	air flow into the cylinder
P_{im}	-	intake Manifold Pressure
η_{vol}	-	engine Volume Efficiency
W_p	-	pumping Work
P_{em}	-	exhaust Manifold Pressure
qHV	-	heating Value of fuel
ω_i	-	tyre rotational speed at i^{th} wheel (in revolutions per minute)
F_{xi}	-	longitudinal tyre force at i^{th} wheel (in newtons)
F_{yi}	-	lateral tyre force at i^{th} Wheel (in newtons)
M_z	-	yaw moment (in newton meters)
C_f	-	nominal tyre cornering stiffness at front wheel (in newtons per radian)
C_r	-	nominal tyre cornering stiffness at front wheel (in newtons per radian)
l_f	-	distance from the vehicle center of gravity to the front axle (in meters)
l_r	-	distance from the vehicle center of gravity to the rear axle (in meters)
I_z	-	moment of inertia of vehicle body (in kilogram square meters)
g	-	gravitational acceleration = 9.81 (in meters per second squared)
M_z	-	yaw moment (in newton meters)
M	-	total mass of the vehicle (in kilograms)

θ_e	-	rotor position with electrical angle
F_z	-	normal Force
R_w	-	wheel Radius
μ_{peak}	-	peak Coefficient factor
λ_i	-	slip ratio of the ith wheel
α_i	-	tyre Slip Angle
I_{zs}	-	vehicle sprung mass moment of the z-axis
n_{vol1}	-	numbers of cylinders
δ_u	-	fuel flow control
W_{ei}	-	mass flow out of the cylinder
η_{ig}	-	ross indicated torque
K_e	-	back Electromagnetic Force Constant
V_s	-	voltage across each phase a,b,c
w_r	-	angular speed ogf the rotor
P_b	-	terminal battery power
f_0	-	pressure dependency of tyre inflation (PSI)
F_s	-	inflation Pressure (PSI)
v_{atm}	-	atmospheric wind speed
α	-	slope of the road
A_a	-	frontal Area
ρ	-	air Density (Kg/m^2)
G_{re}	-	transmission gear of the front powertrain
G_{rm}	-	transmission gear of the rear powertrain
F_p	-	propulsion Forces
J_{wi}	-	rotational inertia of the fron and the rear
P_{ICE}	-	total power of engine
n_r	-	number of engine stroke
P_{EM}	-	Total power of electric machine

LIST OF ABBREAVIATIONS

ICE	-	Internal Combustion Engine
HEV	-	Hybrid Electric Vehicle
TtR-HEV	-	Through the Road Hybrid Electric Vehicle
DOF	-	Degree of Freedom
EM	-	Electric Machine
DoH	-	Degree of Hybridization
SHEV	-	Series Hybrid Electric Vehicle
IWM	-	In-Wheel-Motor
SOC	-	State of Charge
PHEV	-	Parallel Hybrid Electric Vehicle
PSD	-	Power Split Device
CVT	-	Continuous Variable Transmission
BLDC	-	Brushless Direct Current
RC	-	Resistance-Capacitance
DC-DC	-	Direct Current to Direct Current
PID	-	Proportional Integration Derivative
EVT	-	Electronic Variable Transmission
AER	-	All Electric Range
SAE	-	Society of Automotive Engineer
EMF	-	Electromagnetic Force
TtR	-	Through-the-Road
DOD	-	Depth of discharge
NEDC	-	New European Driving Cycle
WLTP	-	Worldwide Harmonized Light Vehicle Test Procedure

CHAPTER 1

INTRODUCTION

1.1 The Need for Hybrid Electric Vehicle

The increasing existence of global warming is the fundamental cause of the fast changing, modern culture and technological development, which has led to the increase of emissions of harmful pollutants into the atmosphere. As established in [1], cars and trucks are responsible for almost 25% of CO_2 emission and other major transportation methods account for another 12%. With immense quantities of cars on the road today, pure combustion engines are quickly becoming a target of global warming blame. Other potential alternatives to the world's dependence on Internal Combustion Engine (ICE) are fuel cell vehicles, Electric Vehicles (EVs), and Hybrid Electric Vehicles (HEVs).

Hybrid vehicles improve the fuel consumption and overall energy efficiency of the driveline due to the combination of multiple power sources of dissimilar nature. Furthermore, on board these vehicles are energy storage devices and electric drives that allow negative torque to be recovered during deceleration and standstill, and also operates the ICE only in the most efficient mode [2].

1.2 Components of HEV

The term hybrid electric vehicle refers to a vehicle with two sources of power and power conversion electronics. One being fossil fuel and the other battery. The former uses ICE design, while the latter uses electric motor for propulsion. The most compulsory source of energy of a HEV is electric battery, therefore, it can have combination of the following sources like gasoline ICE and battery, diesel ICE and battery, battery and fuel cell, battery and capacitor, battery and flywheel, and, battery and battery hybrids. The arrangement of electric motor and an ICE is one of the most commonly used propulsion in HEVs. The electric motor improves the energy efficiency, by providing positive torque and also operates as a generator during negative torque. Also, the engine is downsized, with the intention of ensuring that the average load demand from the vehicle is within the engine's higher efficiency operating zone. This zone occurs during acceleration and urban driving. The design of HEVs for longer range and fuel economy highly depends on many advanced technologies of which power flow is significant. Figure 1.1 below explains the generic power flow design. The management of the duo sources determines the range of the vehicle [2].

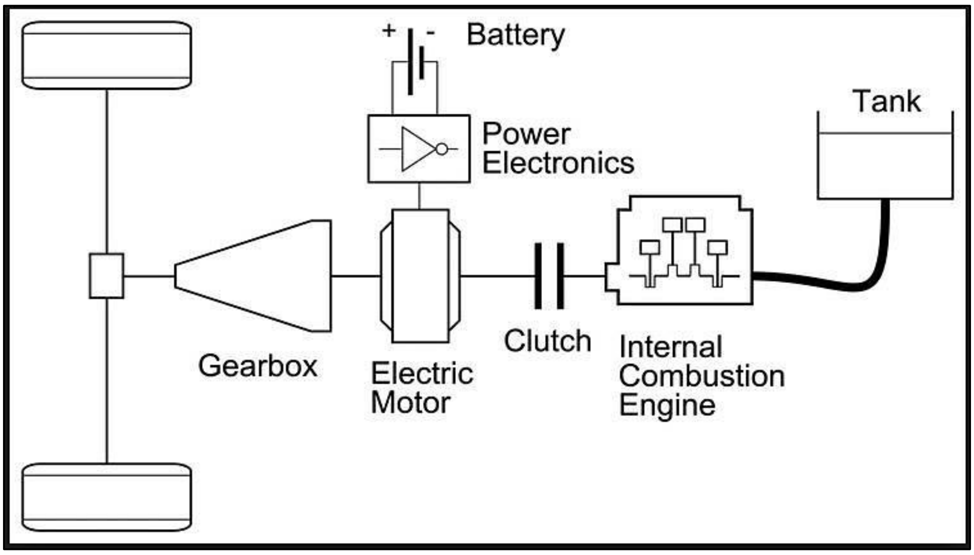

Figure 1.1: Generic Power flow (Tobias et al., 2014)

As shown in figure 1.1, the traction forces delivered to the load is from the two sources of energy. As a means to extend the range, more extensive research and developments are required. This research intends to solve many key issues in the development of HEVs.

Many studies and researches have been carried out on HEVs while most of the authors use different modelling and simulation approach as stated in [3], [4], [5], [6], [7] and [8] for performance evaluation, however, this research focuses on mathematical modelling of Through-the-Road Hybrid Electric Vehicles (TtR-HEVs) using first principle for adequate insight into the power trains interaction.

1.3 Problem Statement

A study carried out by [9, 10], describes the potentiality of a TtR-HEV that has ICE at the front axle, and a centrally located electric motor connected to the rear axle, in terms of drivability and fuel consumption. Furthermore, the authors establish the effect of increased traction as a result of all driven wheels on performance. Due to the nature of the power sources present in TtR-HEVs, namely; ICE and Electric Machines (EMs), the authors use efficiency maps to show that the torque and power curves have alternating patterns in their traction delivery. It is concluded that the summation of torque can only occur in through the road scenario. The use of efficiency maps for the two power sources simplifies the dynamics that occur in the powertrain. For example, electric motor torque characteristic favours vehicle response, in that, it produces constant torque for the region lower than the base speed, this torque reduces hyperbolically with increase motor speed and also a constant power region for high motor speed [11, 12]. Unlike the electric motor, ICE operates optimally in high vehicle speed for constant traction. As stated above there is the need to gain adequate insight to the dynamic interaction of these two dissimilar power sources that can only interact through the road using nonlinear mathematical models to ascertain drivability and fuel consumption. This is because the engine and the electric motors are not physically connected to each other, and also the traction delivered by the engine and electric motors.

Modelling and simulation are absolutely compulsory for concept evaluation, prototyping, components re-sizing, and for the best control strategy to adopt in other to improve energy consumption. Though, prototyping and testing are other means of estimating them, it has hitherto proven expensive and complex in operation. Recent researches and studies have been carried out about modelling of HEVs, however, very little research has been done on the mathematical modelling of TtR-HEVs. Having established the problem statement, this research will focus on modelling of TtR-HEV (ICE on the front axle and two individual in-wheel motors at the rear) using first principle approach and power flow design strategies.

In addition, to be able to achieve the gains of HEVs, the designs must be extensively modelled and refined using physics and thermodynamics laws for each sub system before emissions ratio and fuel economy can be implemented on a commercialized level.

1.4 Research Questions

This study will address the following issues;

i. How to improve the overall efficiency of HEVs?
ii. Which method can be used to improve the efficiency of HEVs?
iii. How to design energy management system?

1.5 Objectives of Study

The objectives of this research are as follows:

i. To develop a mathematical model for a TtR-HEV using first principles
ii. To design power flow strategies.
iii. To compare the conventional vehicle and TtR-HEV in terms of fuel consumption and emission.

1.6 Scope of Project

This research focuses on TtR-HEV. The architecture of the TtR-HEV powertrain contains the ICE mounted on front axle for the front propulsion and a two right and left In-Wheel-Motors (IWM) for rear propulsion. The limitations of this work are stated below:

i. The vehicle dynamics used will only consider the propulsion dynamics model of a TtR-HEV to test for the fuel consumption as compared to a conventional vehicle.
i. Implementation of power flow design strategy in normal operation mode.
ii. MATLAB/SIMULINK will be used to simulate the mathematical models.

1.7 Significance of study

The primary objective of this study is to develop a mathematical nonlinear differential equations for the TtR-HEV, so as to gain insight to the intrinsic characteristics of the traction sources and nature of it power flow strategies. In accordance with this objective, the first contribution of this research is the development of the mathematical models of TtR-HEV, which compare of the vehicle propulsion dynamics and powertrain dynamics with the purpose of establishing fuel savings over conventional vehicles.

A second contribution is made in the area of power flow design strategies, because TtR-HEV can function as front wheel drive for a while during its operations, and at other times as rear wheel drive, and all wheels drive, depending on the load components conditions and driver's request as it affect the efficient delivery of traction.

1.8 Organization

This project report consists of six chapters. Chapter 1 defines the research problem and presented the importance of HEVs technology. Chapter 2 reviews available classifications of various HEVs configurations and their actuating patterns are introduced based on different criteria which explains the power and energy demands from the load components on board energy storage system. Chapter 3 describes the methodology adopted for achieving the objectives of this research and the sizing and selection of components for TtR-HEVs. Chapter 4 outlines the mathematical models used for the actual generation of the driveline torques, it also presents the formulation of the vehicle propulsion dynamics and the powertrain models used for simulations, and includes the torque matching technique for the power flow design. Chapter 5 provides the simulation results using MatLab/Simulink environment, firstly, for each sub model represented in the TtR-HEV, then a combined model which is used to compare the fuel consumed with a conventional vehicle, also, diagrams showing each power flow modes are presented. In Chapter 6, some closing remarks are made and future research guidelines are proposed.

Appendix A provides a comprehensive list of the vehicle parameters used, and the MatLab m-file used.

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