Faculty of Engineering

OPTIMIZING HYBRID ELECTRIC VEHICLE ENERGY UTILIZATION BASED ON PARTICLE SWARM OPTIMIZATION ALGORITHM

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OPTIMIZING HYBRID ELECTRIC VEHICLE ENERGY UTILIZATION BASED ON PARTICLE SWARM OPTIMIZATION ALGORITHM

ABANG AHMAD LATIF BIN ABANG SARBINI

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Final Year Project Report ☑

Masters ☐

PhD ☐

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In the name of Allah, The Most Benevolent and The Most Merciful

My deepest gratitude and all praises to Allah Almighty as my journey in completing this Final Year Project with His blessings and strengths granted. I would like to express my sincerest appreciation to my supervisor, Ts Dr Mohamad Faizrizwan bin Mohd Sabri for his unwavering support and guidance in projecting me forward throughout this project with such patience.

The conclusions drawn from the project are supported by testing and verification conducted via simulation and modelling procedures. The simulated environment's assumptions, constraints, and circumstances served as the foundation for the results made from this research. The accuracy and dependability of the results should thus be confirmed by additional physical testing.

To my backbone, my family, I am indefinitely grateful for your support and love throughout this project. My days were better listening to their voices enlightening this burdened soul. My parents have always been an inspiration for me to be a better son and an engineer soon.

May Allah ease everything in my journey to become a devout child and always stay humble. Forgive me for my wrongdoings, Ameen Ya Rabb, Creator of Heaven and Hell.

ABSTRACT

Hybrid electric technology has been adapted in automobiles for over a few decades with the introduction of the Toyota Prius in 1997. The need to shift from conventional vehicles to hybrid vehicles ever since the declaration of peak oil in the world has driven car manufacturers. There are challenges in designing a vehicle, albeit improving a conventional vehicle to a hybrid electric vehicle (HEV) and achieving the optimal power balance between power sources which are the internal combustion engine (ICE) and the electric motor (EM). The introduction of more recently developed algorithms into energy management strategy (EMS) applications, particularly offline applications such as the one incorporated in this project have accelerated the field of energy management research for HEV. The adaptation of open-sourced simulation was selected for cost-effectiveness and possibilities of modification. The outcome of this project is to maximise the efficiency of a HEV model in MATLAB-Simulink by considering fuel efficiency as the objective function. To evaluate the effectiveness of the proposed EMS, extensive simulations are performed using different drive cycles, considering various input parameters. The findings demonstrate that the proposed controller outperforms the original model in terms of energy utilization. The optimized EMS effectively manages the power flow considering factors such as distance and average engine speed, while ensuring that the battery state does not fall below the minimum threshold.

ABSTRAK

Teknologi elektrik hibrid telah diasimilisasikan dalam kereta selama beberapa dekad dengan pengenalan Toyota Prius pada tahun 1997. Keperluan untuk beralih daripada kenderaan konvensional kepada kenderaan hibrid sejak pengisytiharan minyak puncak di dunia telah mendorong pengeluar kereta. Terdapat cabaran dalam mereka bentuk kenderaan, walaupun meningkatkan kenderaan konvensional kepada kenderaan elektrik hibrid (HEV) dan mencapai keseimbangan kuasa optimum antara sumber kuasa iaitu enjin pembakaran dalaman (ICE) dan motor elektrik (EM). Pengenalan algoritma yang terbaharu dibangunkan ke dalam aplikasi strategi pengurusan tenaga (EMS), terutamanya aplikasi di luar sistem seperti yang dimeteraikan dalam projek ini telah banyak memacu kepesatan dalam kajian berkenaan pengurusan tenaga dalam HEV. Penyesuaian simulasi sumber terbuka dipetik untuk keberkesanan kos dan kemungkinan pengubahsuaian. Hasil projek ini adalah untuk memaksimumkan kecekapan model HEV dalam MATLAB-Simulink dengan mempertimbangkan kecekapan bahan api sebagai fungsi objektif. Pelbagai simulasi yang luas dilakukan menggunakan kitaran pemacu yang berbeza memandangkan pelbagai parameter input untuk menilai keberkesanan EMS yang dicadangkan,. Penemuan menunjukkan bahawa pengawal yang dicadangkan mengatasi model asal dari segi penggunaan tenaga. EMS yang dioptimumkan berkesan menguruskan aliran kuasa dengan mempertimbangkan faktor-faktor seperti jarak dan kelajuan enjin purata, sambil memastikan bahawa keadaan bateri tidak jatuh di bawah ambang minimum.

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AC	Alternating Current
ADVISOR	Advance Vehicle Simulator
BEV	Battery Electric Vehicle
CO_2	Carbon Dioxide
CO	Carbon Monoxide
COVID-19	Coronavirus Disease
DP	Dynamic Programming
ECE15	Economic Commission for Europe
ECMS	Equivalent Consumption Minimisation Strategy
EM	Electric Motor
EMG	EM/Generator
EMS	Energy Management Strategy
EREV	Extended Range Electric Vehicle
EU	European Union
EUDC	Extra Urban Drive Cycle
EV	Electric Vehicle
FC	Fuel Consumption
FCV	Fuel Cell Vehicle
FTP	Federal Test Procedure
GA	Genetic Algorithm
GPS	Global Positioning System
HEV	Hybrid Electric Vehicle
HIL	Hardware-in-loop

HFWET	Highway Fuel Economy Test
ICE	Internal Combustion Engine
LP	Linear Programming
MINLP	Mixed Integer Non-Linear Programming
NEDC	New European Driving Cycle
NMPC	Non-Linear Model Predictive Control
PHEV	Plug-in HEV
PB	Personal Best
PMP	Pontryagin's minimum principle
PSD	Power Split Device
PSO	Particle Swarm Optimization
PSO-FCO	Particle Swarm Optimization - Fuel Consumption Optimizer
PHEV	Plug-in HEV
RB-EMS	Rule-Based EMS
SHEV	Series HEV
SoC	State-of-Charge
SPHEV	Series-Parallel HEV
UDDS	Urban Dynamometer Driving Schedule
WLTC	Worldwide Harmonized Light Vehicles Test Procedure Class 3

CHAPTER 1

INTRODUCTION

1.1 Project Background

Global oil consumption in the world gradually increased up to the point that the current oil reserve can sustain another 47 years [1]. Peak oil describes the speculative period when the world's crude oil output will reach its ultimate level and begin to diminish [2]. The peak theory derived from geophysicists Marion King Hubbert which claims that oil production resembles a bell-shaped curve as shown in Figure 1.1 [3]. Peak oil demand is a situation in which extraction declines because of diminishing consumption instead of resource scarcity. As cheaper oil substitutes enter the market and drive up the price of oil, it can also be brought on by a drop in output, which makes it unprofitable to explore for new sources in the seabed. This is particularly plausible if renewable technology and alternative energy sources outperform the extraction of oil in terms of cost. Peak oil also has a significant impact on the environment by eliminating the carbon footprints of businesses that are oil dependent. Petroleum, coal, and natural gas are key providers of atmospheric discharge of carbon dioxide (CO_2) and a significant contributor to human-caused climate change.

Russia-Ukraine war disrupted energy markets worldwide notably Europe since early 2022. The United States, the United Kingdom, and the European Union (EU) have declared measures to restrict importation of hydrocarbon commodities from Russia. The market value of crude oil on the world market shot up from around $76 per barrel at the beginning of January 2022 to over $110 per barrel on March 2022, when Russia attacked Ukraine [4]. Prior to the conflict, the cost of crude oil had already been inflated due to the restoration of world economies from the coronavirus disease (COVID-19) pandemic and the insufficient investment in the oil and gas sector. the prices of oil and gas skyrocketed simultaneously due to the instability in supply caused by the conflict.

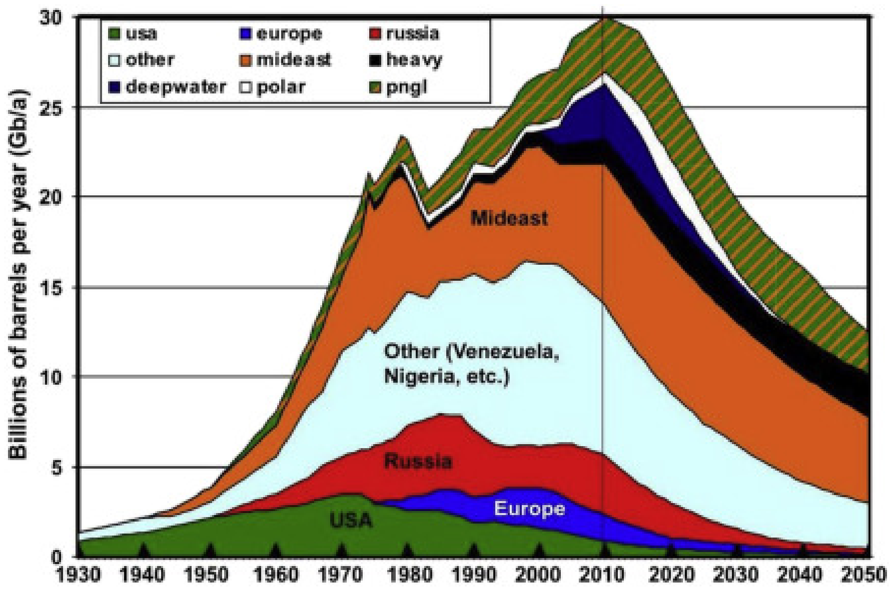

Figure 1.1 Peak Oil by Hypothetical Point of Reserves

More than 3.2 million new plug-in cars were registered worldwide in the first five months of 2022. Europe saw the fastest growth, driven by stimulus measures introduced by many European governments such as Norway [5]. Major markets have also introduced tax benefits and subsidies, which contributed to sales growth [6]. China dominated battery development industry in 2021, accounting for more than 75% of worldwide capacity however Europe is starting to catch up. Transportation industry is turning electric over the years from e-scooters to hydrogen buses in Kuching, Sarawak. Transportation is indispensable for economic growth due to its large share of the gross domestic product, it significantly contributes to Malaysia's overall CO_2 emissions [7]. Although COVID-19 regulations instigated a reduction in global emissions from the transportation sector in the past couple of years, a continual rise in energy consumption from increasing vehicle fuel burning is peaking up again following the post-pandemic era and energy transition in the oil and gas industries.

The scientific community delivered a multitude of advancements in the past decades to address this problem, presenting new approaches from the perspective of hybrid powertrain design approach. Fuel cell vehicle (FCV), battery electric vehicle (BEV) and hybrid electric vehicle (HEV) are the primary types of new energy automobiles fleet for the future [8]. Large-scale applications for FCVs demand more sophisticated fuel cell technology with low cost-effectiveness and more comprehensive supporting infrastructure requirement surrounding the production and distribution of the hydrogen fuel. One notable representative is Sarawak Energy Berhad entrusted by the Sarawak government in endorsing the first hydrogen fuel cell bus fleet in Malaysia promoting customizable power output, minimized refuelling period, less maintenance, zero emission and longer range [9], [10]. However, a transition to fully hydrogen-powered vehicles by the mass population is still far from reach. BEVs appear to be the most popular alternative among all new energy vehicles for the future fuel-free operation, improvement of air quality, and reduction of emissions. The effectiveness of BEVs however, is significantly constrained by the battery capacity since battery technology has not reach mature phase yet.

HEV is a type of vehicle that integrates a traditional internal combustion engine (ICE) with an electric motor (EM) and battery. The use of HEV dates to the late 19th century developed by Ferdinand Porsche. However, it was not until the late 20th century that hybrid electric technology became more widely used in passenger vehicles. The Toyota Prius was one of the first mass-produced HEV thus popularizing the technology [11], [12]. Since then, hybrid electric technology has continued to evolve, and HEVs are now available in a series of dimensions and configurations, including cars, trucks, and buses. The most economically feasible option currently and potentially ensuing decades seems to be HEVs.

HEVs are becoming increasingly popular to reduce reliance on fossil fuels and reduce emissions, therefore an important element of the transition to more sustainable transportation network. HEVs are designed to reduce fuel consumption (FC) and lower emission by utilizing the EM to assist the ICE without compromising driver's demand. The battery-powered EM is charged through a combination of regenerative braking and the ICE. A real-time control mechanism that can integrate the on-board power sources to optimize FC and minimize emissions is essential in achieving the abovementioned benefits. Energy management strategy (EMS) is what depicts and manage the vehicle mechanical-electrical connection to satisfy the driver's demand while sustaining the vehicular capabilities.

The non-causal and global solution approach defines offline EMS with the prerequisite data from drive cycles. The effectiveness of this technique usually is difficult to determine in real time hence used as control benchmark to online EMS. This method works well in circumstances where real-time data may not be easily accessible or if the optimisation process may be carried out beforehand.

Previous information on energy consumption trends and operational circumstances are often gathered to establish an offline EMS. These details might be loading demand patterns, environmental conditions, profiles of energy usage and battery state-of-charge (SoC). Algorithms and optimisation techniques are used to analyse and find energy-saving opportunities using this data.

Particle swarm optimization method (PSO) is a computational method used to find the optimal solution to a problem based on the idea of simulating the behaviour of a swarm of particles, each representing a potential solution to the problem [13]. The particles move around in the search space and are attracted to the best solutions they have encountered so far, like the way that a swarm of bees might search for a new hive. PSO are widely used to optimise the performance of the vehicle's powertrain elements to reduce FC and emissions while constantly satisfying the vehicle's driving requirements in the perspective EMS for HEVs.

1.2 Problem Statement

The massive increase in electric vehicle (EV) sales in 2022 paved the way for a new era of cross-industry innovation and development. Car manufacturers, utilities, and charging equipment manufacturers are collaborating with policymakers and EV enthusiasts to overcome challenges to their ambitious agenda, which includes growing domestic manufacturing, recycling, and halting unethical lithium-ion battery metal extraction practises. The EV chargers and its lack thereof in Malaysia especially stunted the automobile electrification for the population due to reliance on slow alternating current (AC) wall chargers. The implementation of fast chargers' network in Malaysia is picking up very slowly because of higher capital demand and lower demand of EV.

There are challenges in designing a vehicle, albeit improving a conventional vehicle to a HEV and achieving the optimal power balance between ICE and EM. The matter involves maximising FC and minimizing emissions while ensuring the vehicle has sufficient power to meet the driving needs of the driver. Lack of effective synchronization and its unavailability can occasionally lead to the deterioration of problems like reduced mileage capacity. One of the energy sources is indeed recyclable and therefore restore a portion if required. The alternative source of energy has a large storage reserve but is frequently irreversible.

The imprudent action in reducing energy management issues heavily depends on the objective function of interpreting the motives to be curtailed [14]–[16]. These literatures discussed the benchmark of a HEV is FC for environmentally friendly with the prospect of fewer tailgate emissions. Inefficient control system such as Rule-Based EMS (RB-EMS) with sub-optimality limitations and cannot ensure the fulfilment of fundamental requirements such as a sustained charge. It takes a significant amount of time to alter the control settings of RB-EMS for a particular transport mission. Salmasi et al. noted various concerns that demands resolution in the future, including greater control objectives and the sustainability of energy sources [17].

These essential objectives, such as emission reduction and efficiency improvement, are competing criteria, and a decent EMS should accommodate a compromise between them. From an optimization standpoint, the introduction of more recently developed algorithms into EMS applications, particularly offline applications, would be a fruitful field of study. Evaluating these novel methodologies may thus add to the discipline in terms of computing expenses, effectiveness in handling difficult multi-objective individual instances, and the possible hybridisation with conventional EMS control systems for more effectively achieving control goals.

Lack of HEV testing models in Malaysia has made electrification economically challenging for local manufactures such as Proton and Perodua. Digital mock-ups of a car built by high-performance computers enable for exhaustive testing of a new model in a variety of driving conditions before the actual vehicle emerges [18]. Consequently, the Mercedes prototypes attain a greater degree of maturity faster, permitting for more extensive evaluation on the road. Generally, the cost of producing a prototype is expensive and requires another department which is capitally exhaustive for Malaysian automobile manufacturers.

1.3 Project Objectives

The objectives of this project are as follow:

1. To modify HEV model in MATLAB-Simulink to better suit the EMS to reach maximum fuel efficiency.
2. To design a PSO controller in MATLAB focusing on optimizing FC of HEV.

3. To simulate and verify effectiveness of the EMS control system via simulations on standard drive cycles.

1.4 Scope of Project

The scope of project is simulation-based on the MATLAB-Simulink platform responding to certain input with real drive cycle data from previous studies. Plug-in HEV (PHEV) model will be utilized with the assumption of high battery SoC and fuel capacity. The project focuses on well-to-wheel efficiency neglecting heat dissipation in the engine, transmission losses resulting in better result than real-time theoretically. PSO-based EMS implemented in this study only utilize the rules and neglects further equations such as required in the detailed research. FC is initialized as objective function for PSO algorithm and FC data will be evaluated and discussed with hypothesis of less FC, less emission. The assumption of emission data is applied as the project duration is limited to a few months. Real-life performance of the model will have to be verified with a prototype for future research.

1.5 Report Outline

This report is divided into three main chapters, each explained briefly in the overview below.

Chapter 1 discussed general overview of the project. The details delivered and explained through subsections: Project Background, Problem Statement, Project Objectives and Scope of Project.

Chapter 2 evaluates the literature review for the project which clarifies related studies that rationalize the project scope in the previous years. This chapter contains explanation of previous research and experiments conducted regarding hybridization levels, configurations, software modelling and EMS.

Chapter 3 discusses the introduction of the proposed system in terms of methodology. This chapter contains an explanation project flow chart, PSO flow chart, controller mechanism, project Gantt Chart, and methodology adapted from previous study.

Chapter 4 discusses the HEV simulation and PSO controller results obtained in Simulink and MATLAB respectively. The output of HEV simulation is considered as the input for the PSO system. The comparison of data in subsections utilize averaged values from simulation for fair evaluation and discussion.

Chapter 5 concludes the project and evaluate the achievement of objectives and future recommendations.

1.6 Summary

This chapter discussed the project background, problem statement and research objectives. The project focussed on the concerning fuel depletion of the world's reserve and leading countries shift automobile focus on renewable energy. The scientific community delivered a multitude of advancements the past decades to address this problem, presenting new approaches from the perspective of hybrid powertrain design approach. There are challenges in designing a vehicle, albeit improving a conventional vehicle to a HEV and find the optimal power balance between ICE and EM. The introduction of more recently developed algorithms into EMS applications, particularly offline applications, would be a fruitful field of study from an optimization standpoint. The scope of the project is simulation-based on the MATLAB-Simulink model responding to certain input with real drive cycle data from previous studies.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

A brief description of the HEV configuration, topologies and EMS are explained in this chapter. The existing technological knowledge can be implemented to enhance the previous methods throughout the years.

2.2 HEV Electrification Degrees

HEVs can address FC challenge via powertrain with an additional propulsion mechanism containing an electric battery, EM and a device which couples together the electrical and mechanical component [19]. Fundamentally, HEVs are dissected to four electrification levels such as micro, mild, full and plug-in.

Micro HEV contains an EM in the form of small integrated or belted alternator [20]. The sole purpose is to disengage the ICE upon reaching zero velocity and re-energize the engine when the driver steps onto the gas pedal. The appealing feature of the "Stop and Start" functionality is immediately restarts using the EM whenever required to accelerate. The fuel economy presented between five and eight percent over the conventional vehicle [21]. Concurrent examples of micro HEVs are Mercedes-Benz E350e and BMW 530e.

Mild HEV shares a similar characteristic to the micro HEV with a significant increase on the alternator and battery as the vehicle propulsion catalyst. This architecture improves FC by supplying torque assistance and regenerative braking, an aspect that micro HEV was incapable of accomplishing. Both power sources must be active at the same time to propel the vehicle as the battery cannot drive the wheels independently. The FC ranges from 20 % to 25 % due to the recovery of kinetic energy through regenerative braking [21]. Examples of mild HEV are Mercedes-Benz S580e blue hybrid and Toyota Alphard hybrid.

Furthermore, full HEV have a bigger battery that can power the whole automobile independently for a period and vice versa with the ICE. Full HEV do not possess large ICE due to the proportion of the sophisticated battery as compared to the previous configurations. The matter contributes to a more complex EMS as opposed to micro and mild which utilize series, parallel, power split and multi-mode classifications which will be reviewed in the next section. This hybridization level typically improves fuel efficiency by approximately 40 % – 45 % in real world driving than that of naturally aspirated engine [19]. Prime recognized examples are Toyota Prius, Mercedes-Benz EQS and BMW iX.

PHEVs fundamentally possess the same configuration as full HEV with the addition of a charging plug and larger electric components reducing the size of ICE. There are two types of PHEV which are extended range electric vehicle (EREV) and blended PHEV [22]. The energy sources consumed for the power system service influence the PHEV's well-to-wheel effectiveness and emissions relative to the other hybrids [23]. New vehicles are utilized economically due to the higher electrical capacity which completely runs on the EM and can be drained. This issue can be resolved easily via charging for 10 hours based on the input voltage and charging stations. However, PHEVs possessed very serious issues in terms of charging as the charging period does not reflect the vehicle range. BMW X5 xDrive45e can only drive 77 miles in electric mode which took more than 6 hours to fully charge [24]. Examples are Range Rover P440e and BMW X5 xDrive45e.

2.3 HEV Powertrain Classifications

HEV powertrain can be simplified to three classifications: series, parallel, series-parallel to be assessed in the following paragraphs and tabulated in Table 2.1.

The series hybrid (SHEV) architecture implies that the vehicle is driven by the EM using electricity generated by exhausting ICE as the prime mover for the generator. This powertrain is elementary compared to other classes including configuration and the EMS [25]. The battery system behaves as an energy reservoir that can temporarily turn off ICE by storing any surplus energy [21]. Consequently, the efficiency lacks behind parallel HEVs relative to the number of components which increased energy losses. The series system has the limitation of requiring several mechanical-electrical high-power converters due to the ICE and EM/generator (EMG) driving the vehicle [26]. This configuration demands more capital compared to parallel and power-split with respect to driving situation such as urban driving.

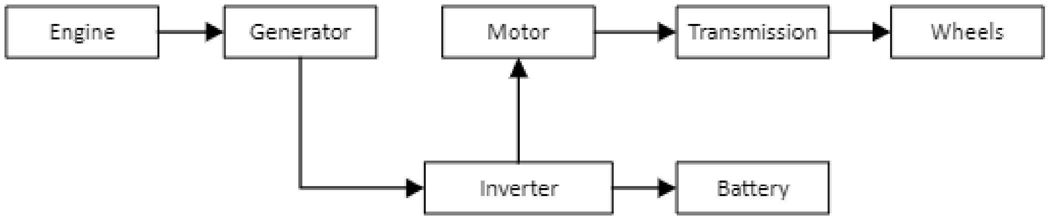

Figure 2.1 SHEV Architecture

The parallel arrangement is much more dependable and effective than the SHEV for all it can perform. Both the ICE and EMG cooperatively supply power to propel the vehicle since they are mechanically coupled to the driveline. The EMG is installed to shift the engine running points to a greater efficiency level by functioning as a generator at low speed and motor at high power demand [22]. The engine and motor torque can be regulated separately, however the engine speed and motor each have a fixed proportion to the vehicle speed [27]. Essentially, parallel HEVs are efficient in urban driving cycle of stop-and-go nature, nevertheless battery consumption also increases unnecessarily due to the strain on the mechanical link between ICE and driveshaft during traffic congestion forcing the ICE to recharge the battery inefficiently. These limitations permit the market share for parallel HEVs however the development of control algorithms gained researcher's interest due to design flexibility as discussed above.

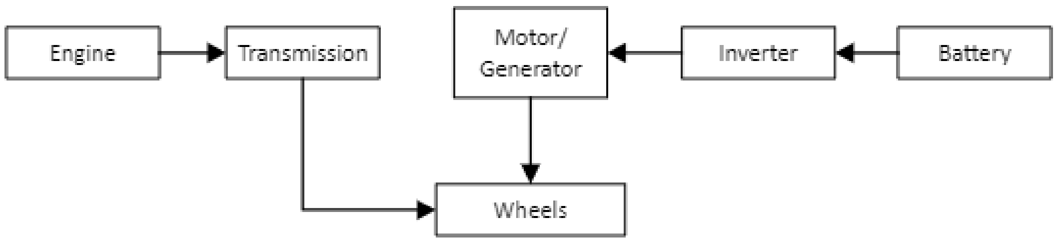

Figure 2.2 Parallel HEV Architecture

Power-split HEVs, better known as series-parallel (SPHEV) employs planetary gear system to link the ICE, EMG and driveshaft. SPHEV can be classified to three subtypes: input-split, output-split, and compound split [28] The availability of power split device (PSD) in HEVs created an electronically controlled continuously variable transmission by selecting the most efficient gear ratio for the exact scenario.[29]. The PSD allows for two paths, such that the mechanical and electrical path dictates the hybridization degree of series or parallel. The powertrain operates as series HEV, and PSD enables parallel HEV in mechanical connection connecting the ICE directly to the drivetrain. Toyota endorsed HSD or THS permitting the car to operate in combustion-only mode, electric-only mode, or hybrid [30]. Researchers established that the energy dissipation is higher than that of SHEV and PHEVs with the configuration complexity [26].

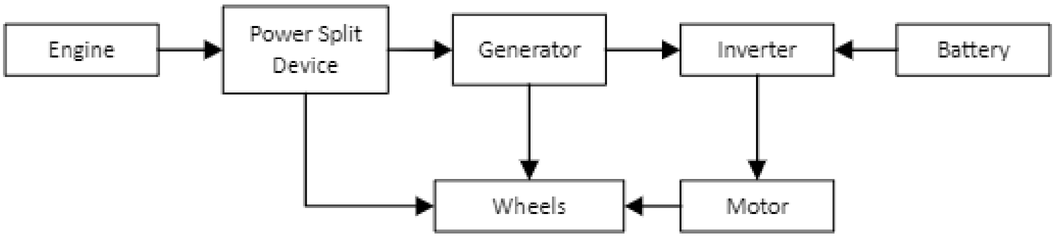

Figure 2.3 SPHEV Architecture

Table 2.1 Comparison of HEV Classification

Item	Advantages	Disadvantages
SHEV	• Efficient in urban drive • ICE operates at most efficient curve • Improved fuel economy	• ICE runs regardless of driver's demand to charge the battery • Requiring mechanical-electrical high-power converters • Cost-intensive
Parallel HEV	• Independent dual-power sources • Improved fuel economy • Efficient in sub-urban and highway driving cycle	• More complex than SHEV • Inefficient in urban driving. • Battery only being charged while vehicle is in motion thus limiting battery capacity
SPHEV	• PSD dictates which configuration to deploy • ICE operate at most efficient curve • Increased FC mode options.	• Most complex HEV configuration • More expensive than the previous configurations • EMS design is difficult.