Hybrid Electric Vehicle Powertrain Laboratory

HYBRID ELECTRIC VEHICLE POWERTRAIN LABORATORY

BY

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Abstract

Personal vehicles have made great contributions to our life and satisfy our daily mobility needs. However, they have also caused societal issues, such as air pollution and global warming. Further to the recent attention to low-carbon energy technologies and environmentally friendly mobility, hybrid electric vehicles play an important role in the current automotive industry. As a leading center and an educational institution in Canada, McMaster University wants to build a Hybrid Electric Vehicle Powertrain Laboratory for introducing undergraduate students to hybrid powertrain architectures, instrumentation and control.

A phased development of the hybrid powertrain teaching laboratory is being pursued. The first phase is to design a electric motor laboratory, as a platform for demonstrating motor characteristics. A LabVIEW based interface is designed to enable electric motor characterization tests. This laboratory set-up is still under construction. Real experiments would be implemented, once finishing the utility connections.

For the hybrid powertrain laboratory, an innovative design architecture is proposed to enable different hybrid architectures, such as series, parallel, and power-split modes to be investigated. Instead of a planetary gearbox, bevel gearboxes with a continuous variable transmission (CVT) are used for making the laboratory more compact and flexible for demonstrating hybrid functionalities. The additional generator provides the ability of input power-split for allowing the engine to operate at a narrow high-efficiency region. After designing the hybrid laboratory, a novel rule-based energy management strategy is applied to a simplified simulation model.

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Introduction

1.1 Issues Related

Automobiles are amongst the greatest innovations of modern technology. The personal vehicle has made great contributions to our society, especially by satisfying the mobility needs of our daily life. From statistical data, there are more than 1 billion automobiles in use all around the world. However, this enormous number of vehicles in use worldwide have caused and will continue to generate large social issues, such as air pollution and global warming caused by Greenhouse Gas (GHG) emissions. At the same time, population growth and urbanization are increasing the demand for personal vehicles which result in further depletion of the Earth's petroleum resources and affect energy security [1].

1.1.1 Global Warming and Air Pollution

In the late 20th century, concerns about global warming provoked public and media attention and placed a spot light on the automotive industry. Due to its dependency on fossil fuels, the transportation sector has been regarded as one of today's top contributors and fastest growing sectors impacting the GHG emissions globally. From the statistical database of U.S. Energy Information Administration (EIA), the total worldwide energy consumption by end-use sectors are shown in Fig. 1.1, and carbon dioxide (CO_2) emissions by end-use sectors are shown in Fig. 1.2. Transportation sector stood almost at 27% of total energy consumption and 33.7% of GHG emission in 2012 [2].

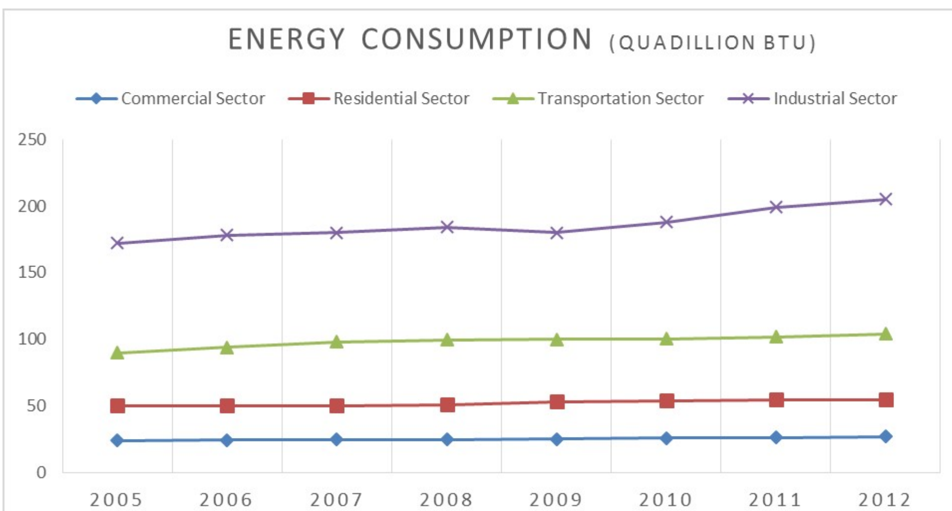

Figure 1.1: The delivered energy consumption based on different end-users [2]

Conventional vehicles using internal combustion engine (ICE) derive their power by combustion of hydrocarbon (HC) fuels. The combustion process releases heat and other combustion products. The engine converts the heat into mechanical power, and the combustion products are released to the atmosphere. A hydrocarbon(HC) is a

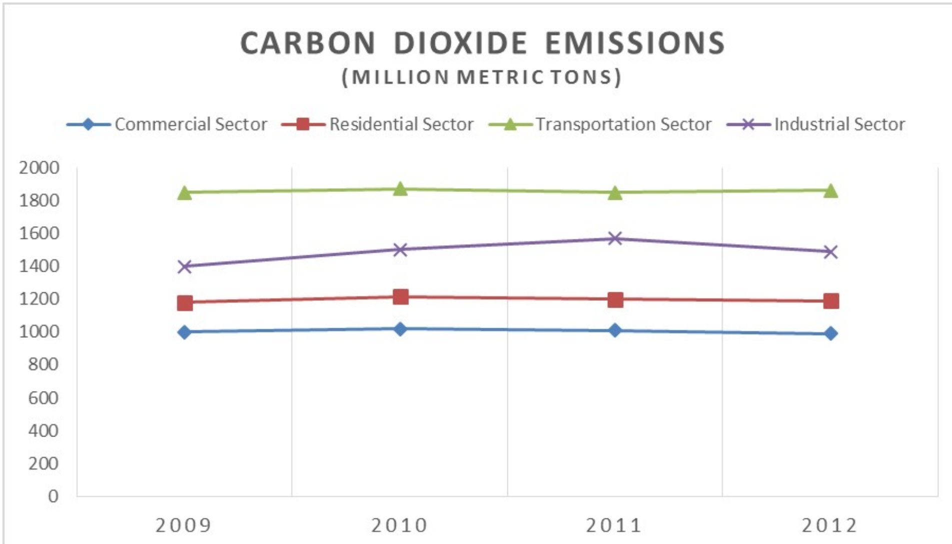

Figure 1.2: The energy-related CO_2 emissions based on different end-users [2]

chemical compound with molecules made up of carbon and hydrogen atoms, which can ideally be converted to CO_2 and water by using a catalyst. The combustion process can never be ideal. Besides CO_2 and water, a certain amount of nitrogen oxides (NO_x), carbon monoxides (CO), and unburned HCs would also be produced, all of which are toxic and harmful to human health [3].

1.1.2 Vehicle Emission Regulation

Given the increasing concern about the environment, public health and the availability of fossil fuels, governments worldwide have started to establish or try to implement more aggressive emissions regulations.

California finalized the third stage of Low Emission Vehicle (LEV) light-duty (LD) emissions standards in January 2012. For heavy-duty (HD) trucks, it also evaluated the feasibility of tightening NOx regulations down to 0.020 grams per brake horsepower-hour ($g/bhp - hr$). Likewise the United States Environmental Protection Agency (US EPA) is calling for a 75% reduction in nonmethane organic gas ($NMOG$) and NO_x, down to 30 $mg/mile$ combined, under Tier 3 regulations. The US EPA is also cooperating with the U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA) to finalize standards for medium and heavy-duty vehicles that will improve fuel efficiency and cut carbon pollution, while bolstering energy security and spurring manufacturing innovation. New standards finalized in 2025 are expected to lower CO_2 emissions by approximately 1.1 billion metric tons, save vehicle owners fuel costs of about $170 billion, and reduce oil consumption by up to two billion barrels over the lifetime of the vehicles sold under the program [4].

Europe is also taking actions to tighten down on LD diesel NO_x and other emissions, by using the Real Driving Emissions (RDE) model that means they put vehicles on the road and measure the real time emissions as part of the certification procedure. Europe is also moving to tighten non-road emissions, by imposing new regulations on smaller and larger engines, and harmonization with HD truck test methods [5].

In some fast growing developing countries, like China and India, they have both severe air quality problems in which vehicular emissions contribute a significant part. China is implementing new emission regulations, requiring all light vehicles to adhere to tougher new "China VI" emission standards by the middle of 2020. India is putting together a fuel and vehicle technology roadmap through to 2025.

1.1.3 Emission Control Technologies

Emission control technologies have result in highly-efficient and clean vehicles. Moving forward, balancing ever-demanding CO_2 and emissions standards with vehicle functionalities that clients will buy would be a big challenge.

Emissions control industry has a stellar record. Future engine developments are focusing on CO_2 reductions, through engine calibration and implementation of emission control systems.

At present, both LD and HD engines are making impressive progress. Gasoline engine fuel consumption reductions of up to 30% versus the multi-port injection (MPI) baseline are in development, and LD diesel might achieve 20% reductions compared to present day. On the HD side, both the government and the private sectors are pursuing a 50% Brake Thermal Efficiency (BTE) (or 10-12% fuel consumption reductions) [6]. Work is also being conducted on advanced engine control methods [7], such as compression ignited natural gas engines, wherein post injections can significantly drop particulate matter (PM) and methane emissions.

1.1.4 Vehicle Electrification

Current trends in energy supply and use are unsustainable; in relation to environment, economy, and society. New technologies and products are now required to enhance fuel efficiency and reduce harmful emissions, without sacrificing performance, cost-efficiency, and safety. Therefore, low-carbon energy technologies and environmentally friendly mobility will play a crucial role for the global automotive industry.

In the search for a sustainable solution to these challenges, electrical energy is a key to success, particularly when it comes to mobility. That is why vehicle electrification and hybridization have been increasingly recognized as the most promising road transportation solutions to both the global energy crisis and the increasingly stringent requirements related to environmental protection [5].

Vehicles using an electrified powertrain, including pure battery electric vehicles, hybrid electric vehicles, fuel cell electric vehicles, etc. (also known as xEVs) can significantly contribute to the protection of the environment by reducing the consumption of petroleum and other high CO_2-emitting transportation fuels. Major trends like connectivity, shared mobility, automated driving, light weight vehicles, digital experience (or more digital devices equipped) and alternative fuels will also have a massive impact on the future of the automotive industry, as illustrated in Fig. 1.3.

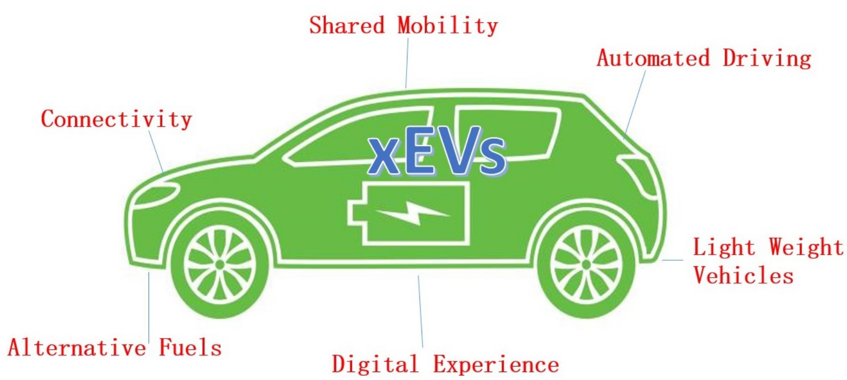

Figure 1.3: Future trends of the automotive industry due to vehicle electrification [1]

1.2 Hybrid Technology

Among all these vehicle electrification measures, hybrid technology plays a crucial role, by bridging the gap between conventional vehicles (using ICE) and pure electric vehicles. From the definition of HEVs, any vehicle that combines two or more sources of power which can directly or indirectly provide propulsion power is a hybrid vehicle. Current HEVs benefit from an efficient combination of at least two power sources to propel the vehicle. One or more electric motors alongside an Internal Combustion Engine (ICE) or a fuel cell as a primary energy source, operate the propulsion system. A battery or a super-capacitor as a bi-directional energy source provides power to the drivetrain and also recuperates parts of the braking energy that is otherwise dissipated in conventional ICE vehicles.

1.2.1 Development History

Surprisingly, the concept of an HEV is almost as old as the automobile itself. The primary purpose, however, was not so much to lower the fuel consumption but rather to assist the ICE in providing an acceptable level of performance. The first hybrid vehicle was introduced at the Paris Salon of 1899. Other hybrid vehicles, both of the parallel and series types, were built during a period ranging from 1899 to 1914. However, the greatest problem that these early designs had, was the difficulty of controlling the electric machine. Regenerative braking system, which is one of the core design concepts of most modern production HEVs, was developed in 1967 by the American Motors Amitron (AMC) and called Energy Regeneration Brake by AMC [8].

In late 1990s, the HEV concept drew much interest as it became clear that EVs could not satisfy the cost and range expectations of users at that time. Toyota released the Prius in Japan in 1997, followed by Honda's Insight in 1999. While initially perceived as unnecessary due to the low cost of gasoline, global increases in the price of petroleum caused many automakers to release hybrid models for sale since the late 2000s; they are now perceived as a core segment of the automotive market [9].

1.2.2 Market Share of HEVs

From data published in January 2017, over 12 million HEVs have been sold worldwide since their commercialization in 1997. As of April 2016, Japan ranked as the market leader with more than 5 million hybrids sold, followed by the United States with cumulative sales of over 4 million units since 1999, and Europe with about 1.5 million hybrids delivered since 2000 [10][11]. Japan also has the world's highest hybrid market penetration. In 2016 the hybrid market share accounted for 38% of new standard passenger car sales, and 25.7% of new passenger vehicle sales including Kei cars (Japanese category of small and light vehicles). Norway ranks second with a hybrid market share of 6.9% of new car sales in 2014, followed by the Netherlands with 3.7%, France and Sweden, both with 2.3% [10]. The following table shows the top national markets for HEVs between 2011 and 2015.

Considering automakers, global HEV sales are led by: the Toyota Motor Company with more than 10 million Lexus and Toyota hybrids sold as of January 2017, followed by Honda Motor Co.. with cumulative global sales of more than 1.35 million hybrids as of June 2014; Ford Motor Corporation with over 424,000 hybrids sold in the United States through to June 2015; and the Hyundai Group with cumulative global sales of 200,000 hybrids as of March 2014, including both Hyundai Motor Company and Kia Motors hybrid models. [10][11][12].

Table 1.1: Top national markets for hybrid electric vehicles between 2011 and 2015[12]

Country	**Number of hybrids sold or registered by year**				
	2015	**2014**	**2013**	**2012**	**2011**
Japan	633,200	Over 1 million	679,100	678,000	316,300
US	384,404	452,152	495,771	434,498	268,752
France	56,030	41,208	46,785	27,730	13,340
UK	44,580	37,215	29,129	24,900	23,391
Italy	25,240	21,154	14,695	5,885	5,244
Germany	22,529	22,908	24,963	21,438	12,622
Spain	18,406	12,083	10,294	10,030	10,350
Netherlands	13,752	10,341	18,356	19,519	14,874
Canada	Not available	∼15,000	∼25,000	Not available	16,167
World	**Over 1.2 million**	**Over 1.6 million**	**Over 1.3 million**	**Over 1.2 million**	**-**

1.2.3 Hybrid Advantages and Current Performance

Modern HEVs make use of efficiency-improving technologies such as regenerative brakes, which convert the vehicle's kinetic energy into electric energy to charge the battery, rather than wasting it as heat energy as conventional brakes do. An HEV produces fewer emissions from its ICE than a comparably sized gasoline car, since an HEV's gasoline engine is usually smaller than a comparably sized pure gasoline-burning vehicle and is not always used to drive the car directly.

The main advantages of the HEV drivetrain can be summarized as follows [13]:

- **ICE downsizing:** since the peak power demand can be provided by a combination of the ICE and the electric motor, the ICE can be sized for the average power demand of the vehicle. This reduces the weight and improves the efficiency of the ICE.

- **Regenerative braking:** the onboard battery or supercapacitor of an HEV can be recharged while the electric motor operates in generator mode, providing braking force instead of the friction brake.

- **Engine on/off functionality:** the engine can be turned off when the vehicle is at a standstill or the vehicle power demand is low. This prevents unnecessary engine idling or its operation at low power, which is inefficient.
- **Control flexibility:** the additional degree of freedom to provide the vehicle power demand from either one of the energy sources gives the flexibility to operate the powertrain components in a more energy-efficient manner. Engine can therefore run close to its peak efficiency while transient effects are absorbed by the electric motor.

1.3 Project Motivation

McMaster University is one of the leading centers and academic institutions in automotive research and has an extensive educational program related to Electric Vehicle (EV) and Hybrid Electric Vehicle (HEV) powertrains. McMaster recently invested over $26 Million in creating the McMaster Automotive Resource Center (MARC) with state-of-the-art laboratories and equipment that specifically support researchers, students and industry professionals working to resolve industrial concerns and promote electrification technologies. MARC not only supports EV and HEV research but also provides facilities and infrastructure for related undergraduate automotive initiatives such as ECO Car and Formula Hybrid. As a leading center for automotive research and education, McMaster needs to develop laboratories that would support training of undergraduate students for the new reality of the auto sector in line with its strategic plan.

The motivation for this project is to create an undergraduate laboratory to expose undergraduate students to the hybrid automotive powertrain. The Hybrid Electric Vehicle Powertrain Teaching Laboratory setup is a flexible teaching tool for the demonstration and simulation of the various forms of hybrid electric vehicle powertrain architectures. This setup will be installed in the Mechanical Engineering Department for the study of hybrid vehicle powertrain architectures, instrumentation, and control. Through the utilization of this laboratory, students will have the opportunity to explore various HEV architectures and their implications on energy usage, also gain valuable insight into the components and control strategies that are integral to a hybrid electric vehicle powertrain system.

1.3.1 Learning Objectives

The laboratory will consider different Hybrid Electric Vehicle powertrain architectures and their operating modes. It will expose students to the key components including the electrical motors and the Internal Combustion Engine (ICE). The objectives of the laboratory will include but not be limited to the following:

1. Demonstration and simulation of the various popular hybrid electric vehicle powertrain architectures, including series, parallel, and power-split.

2. Basic operating characteristics of electric motors, and their application in hybrid vehicles.

3. Consideration of regenerative braking for illustrating efficiency-improvements in HEVs.

4. Evaluation of fuel efficiency and emissions of internal combustion engines in different hybrid modes.

This laboratory is structured to allow for future development and expansion as technologies and techniques evolve within the automotive industry.

1.4 Hybrid Powertrain Laboratory Overview

In this project, to satisfy our vision, an innovative design for the laboratory is developed, which enables experiments with different hybrid architectures. Different forms of hybrid architectures are realized by using various engagements of clutches. Besides, instead of using a planetary gearbox, bevel gearboxes are introduced in this laboratory to simplify its architecture. This consideration makes the whole laboratory much more compact and straightforward for demonstrating the role of the motors and the ICE in different hybrid modes. The design details are described later in Chapter 6.

An important consideration is safety. For added safety, instead of using batteries, three regenerative motor drives are utilized to enable bi-directional paths for electricity and redirection of external power to the grid instead of its storage. This avoids using battery packs for energy storage. That can be a safety concern.

The final target is to complete an undergraduate laboratory on Hybrid Electric Vehicle powertrain to complement the growing educational initiatives related to electrification of transportation systems at McMaster University. A phased development of the laboratory is being pursued. The first phase is to build an electric motor laboratory. The electric motor laboratory has to play two important roles. Firstly, it should be an independent laboratory which would expose mechanical engineering students to electric motors and their characteristics. Additionally, the motor laboratory should fit and be integral to final hybrid powertrain laboratory, and enable physical simulation of various hybrid architectures. The setup of the motor laboratory is discussed later in Chapter 5.

1.5 Thesis Overview

A literature review of hybrid powertrain technologies is provided in Chapter 2. This review considers hybrid vehicle operating patterns, classifications, hybrid powertrain architectures, and their comparisons. Also three hybrid educational labs are reviewed.

As the first phase of the hybrid powertrain lab, more details about the independent electric motor lab are discussed in Chapter3, 4 and 5. The characteristics and working principles of electric motors, modeling based on a simplified equivalent circuit and a speed controller are reported in Chapter 3. In Chapter 4, the three main objectives of the electric motor lab are discussed. motor characterisation testing strategies and the electric motor laboratory procedures are presented. An electric motor laboratory setup is discussed in Chapter 5, both the motor lab's hardware and software realization are presented, including the electrical connections, communication system realization and user interface design based on the LabVIEW software.

In Chapter 6, the development of the hybrid powertrain laboratory architecture design is considered, including its innovative setup combining three different hybrid modes into one laboratory. A combination of a CVT and a bevel gearbox is used to realize three configurations. Component selections and a layout of the lab are made to show the integrated architecture. In Chapter 7, the simulation of the proposed configurations is presented, applying a rule-based energy management strategy in order to run the whole system in different hybrid operating patterns. Conclusions and future research based on the improvement for the proposed design are discussed in Chapter 8.

Chapter 2

Review of Hybrid Technology and Educational Laboratory

2.1 Hybrid Vehicles Concept and Operating Patterns

2.1.1 Hybrid Concept

There are around three primary considerations for improving the performance of vehicles as follows:

- Driving performance and range
- Power efficiency and fuel economy
- Emission reduction

Broadly speaking, any vehicle that combines two or more sources of power which can directly or indirectly provide propulsion power is a hybrid. That means they have more than one energy source or system to be combined or converted, such as having gasoline for a combustion engine, or a fuel cell system with hydrogen, or a battery electrical storage system, and so on [3].

Normally hybrid vehicles are equipped with two kinds of energy sources: a high-capacity storage and a lower capacity rechargeable energy storage system (RESS). The first one typically comes from chemical fuel which serves the ICE. In electrified vehicles, RESS permits bi-directional power flow and recovery of a vehicle's kinetic energy during continuous driving conditions. It also acts as an energy storage system [14].

A Hybrid Electrical Vehicle (HEV), which represents the majority of hybrid vehicles on the road today, is a type of hybrid vehicle that combines a conventional ICE system with an electric motor propulsion system (see Fig. 2.1). The ICE is the primary energy converter with the electrochemical batteries as the RESS.

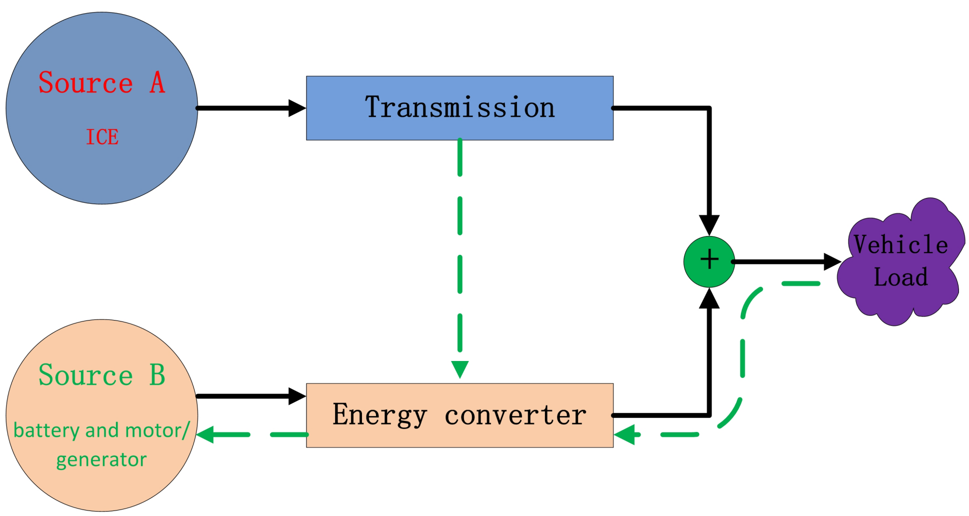

Figure 2.1: Concept of a HEV's power sources

2.1.2 Hybrid Vehicle Operating Patterns

The RESS makes the hybrid vehicle more flexible in its mode of propulsion compared to conventional vehicles. With a proper control method, switching operating modes can be used to optimize the overall performance, efficiency, and emissions of the vehicle according to driving conditions.

To simplify the demonstration of operating modes for HEVs [3], ICE is regarded as source A, while the combined battery and the motor/generator as source B, as shown in Fig. 2.1.

1. **Engine alone propelling mode.** Power source A alone delivers its power to the load. This may be used when the engine can sufficiently supply power to meet the demands of the vehicle, or when the battery needs to be fully charged, or has been completely depleted with no remaining power.

2. **Pure electric propelling mode.** Power source B alone delivers its power to the load. For this pattern, the engine is shut off. The motor provides enough traction power, especially when the engine cannot operate at a high efficiency point such as in low-speed situations, or in areas where emissions are restricted.

3. **Combined hybrid traction mode.** Both A and B deliver their power to the load simultaneously. This pattern may be used when a large power is needed, and when neither of the two sources can provide enough power on their own, such as during sharp acceleration or steep hill climbing.

4. **Regenerative braking mode.** B obtains power from braking. From this pattern, the kinetic or potential energy of the vehicle is recovered and is collected

through the electric motor functioning as a generator. This point is then used to charge the batteries.

5. **Stationary charging mode.** B obtains power from A. In this mode the engine charges the batteries while the vehicle is at a standstill.

6. **Combined charging mode.** B obtains power both from A and the braking operation simultaneously. This pattern makes both regenerating braking and the engine charging modes happen simultaneously.

7. **Power split mode.** A and B deliver power to the load simultaneously.

8. **Series hybrid mode.** A delivers its power to B, and B gives its power to the load. In this mode, the engine charges the batteries, and the batteries supply power to the load.

2.1.3 Advanced Hybrid Technologies

When comparing HEVs with conventional vehicles, the following features should be noted:

- Automatic engine start-stop: this feature automatically shuts off the engine when the car comes to a stop and restarts it when the accelerator pedal is pressed. It prevents energy from being wasted by idling and is being used in all hybrids.

- Regenerative Braking: energy recovery during braking is used to convert braking energy normally wasted into electricity. This recovered energy is stored in a battery pack. The most common way is to employ an electric motor as a generator. This feature not only improves the overall efficiency but also reduces wear of the braking system.

- Electric Motor Drive/Propulsion: this technology allows the vehicle to take full advantage of electrical propulsion in the HEV system. The electric motor provides additional power to assist the engine in acceleration, passing, or climbing, thus allowing a smaller, more efficient engine to be used. At low speeds, the electric motor is often used to power the vehicle while at high speeds the engine would take over. This allows the engine to operate in its most efficient area.

2.2 Hybrid Classification

Further to the above, the electric energy system provides more flexibility to HEVs. The battery in turn plays a critical role in hybridization and electrification.

2.2.1 Hybridization

HEV powertrains can combine two power sources. Typically one component is electric, and the other is ICE for the conversion of fuel into traction energy. Usually, every vehicle with more than two different propulsion concepts can be classified as hybrid according to the technology spectrum shown in Fig.2.2 [15]. According to the figure, there are different rates of hybridization in the car.

The degrees of hybridization refers to the relative division of drivetrain power between the ICE and the electric motor. Full hybrids are characterized by having an electric launch capability [16]. Traditionally there are three types of HEVs based on the different degrees of hybridization as follows [17] [18]:

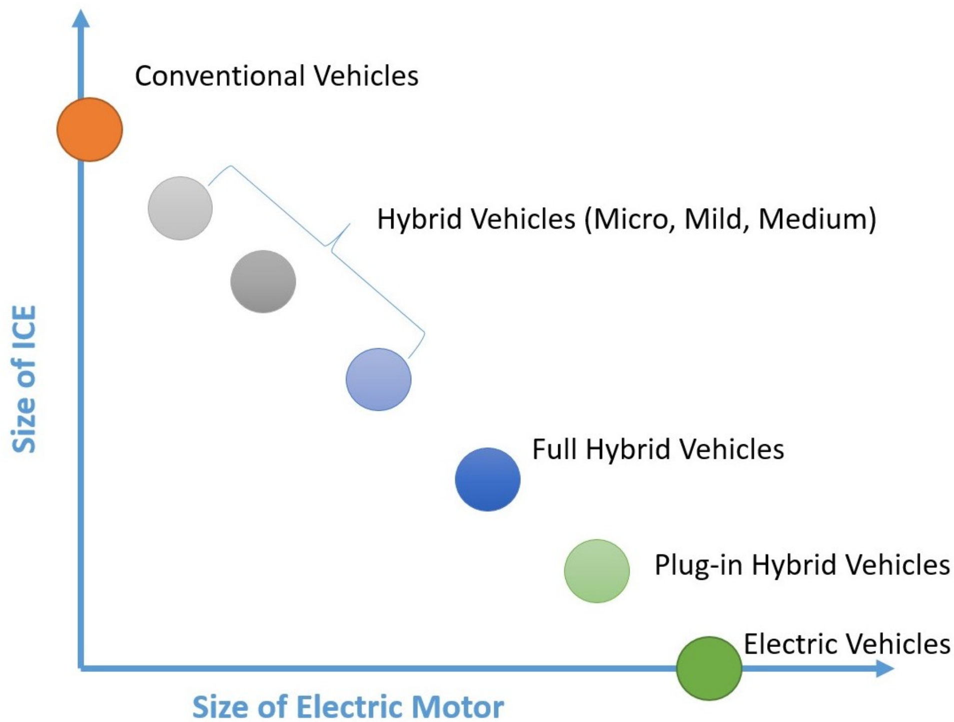

Figure 2.2: Technology spectrum of HEVs [15]

Micro HEVs

A micro HEV is a vehicle equipped with a conventional ICE together with an integrated alternator/starter to enable start-stop functionality. The alternator/starter allows shutting down the ICE during coasting, braking, or stopping and then restarting when the driver releases the brake pedal. But the vehicle is propelled only by the ICE. Typical they provide fuel efficiency increases of around 10% compared to a conventional vehicle.

Mild/Medium HEVs

A mild HEV is very similar to a micro HEV, except that the integrated alternator/starter is larger and has a battery pack that can assist in vehicle propulsion. Compared to a micro HEV, it increases the electric motor assist function. Their typical fuel efficiency is increased to 20% compared to a conventional vehicle.

Full HEVs

A full HEV operates one or more electric motors in combination with a relatively large battery. Full HEVs can be propelled solely by the electric motor. Compared with the mild hybrid, a full HEV typically uses a smaller engine and utilizes a more sophisticated control system to optimize efficiency. Typical fuel efficiency improvements are around 30% compared to a conventional vehicle.

A comparison of three hybrid technologies is provided in table 2.1.

Table 2.1: Hybrid Technology Promotion among Different HEVs

HEV Type	IC Engine Stop/Start	Brake Energy Recovery	Electric Motor Assist	Pure Electric Drive
Micro HEV	√	√		
Mild/Medium HEV	√	√	√	
Full HEV	√	√	√	√

2.2.2 Degree of Hybridization

The bulk degree-of-hybridization is a number between 0 and 1. Vehicles with no electrification (degree-of-hybridization = 0) are conventional vehicles, while those with "1" are electric vehicles. This metric is defined as the amount of power that can be delivered by the electric drive system normalized by the sum of power available from both the electric drive system and the ICE. It is assumed that a PHEV has a degree of hybridization of around 50 %, whereas the extended range electric vehicle (EREV) has an hybridization rate of around 80 % minimum (See Fig. 2.3).

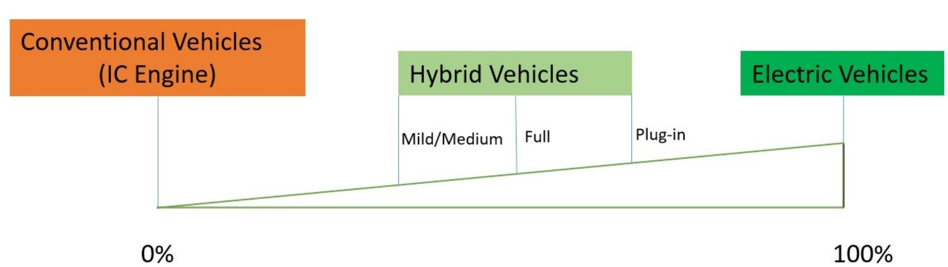

Figure 2.3: Degree of Hybridization - HEVs

Plug-in HEV

As the name suggests, plug-in HEV (PHEV) is a particular type which utilizes a downsized engine to complement an even larger electrical propulsion. The difference between PHEVs and HEVs lies primarily in the size of the battery capacity and the recharging method. A PHEV can recharge its battery pack from the energy of the local power grid through a plug. A large capacity battery allows the PHEV to operate solely by using its battery power for a considerable range without running the ICE. Conversely, the ICE is used only for extended range or during highway driving. Typically, the PHEV is ideal to meet daily commuting requirements, especially in the city and the suburbs, where trips are not too long.

Extended Range Electric Vehicles

Extended range electric vehicle (EREV) contains a plug-in battery pack, an electric motor, as well as an ICE. The difference between the PHEV and the EREV lies on using the ICE: A PHEV may still rely on the ICE to reach its maximum vehicle power, whereas an EREV solely uses the electric motor. The electric motor always drives the vehicle, with the ICE acting as a generator to recharge the battery when its charge level drops down to a pre-specified point. This technology typically extends the whole driving range and can avoid the range limitation of EVs. One example of an EREV is the BMW i3.

Higher degrees of electrification vehicles such as EREVs, PHEVs, and EVs can substantially achieve higher fuel efficiencies. Typically, the external power supply can charge the battery. In both PHEVs and EREVs, dual energy sources are used to improve the fuel economy and to reduce exhausted gas emissions. The ICE extends the driving range, especially for the EREVs [19].

2.3 HEV Configuration

The philosophy of HEVs is to realize '1+1>2', and the spirit behind them is to make reasonable arrangements for improving energy efficiency and reducing emissions. As previously mentioned, HEVs have two propulsion systems, the electric or the ICE. In HEVs, the powertrain's design determines how the electric motor works in conjunction with the ICE.

The components can be connected using different configurations. In general, there are three common design options of hybrid architectures: Series, Parallel, and Series-parallel hybrid. Besides, there are two forms of energy flowing through the drive train: mechanical energy and electrical energy. This section focuses on comparing these different hybrids, as well as introducing other complex configurations [20].

2.3.1 The Series Hybrid

The series configuration is the simplest type of HEV. In a series hybrid, the electric motor is the only means of providing power to the wheels. The ICE has no mechanical connection with the traction load, which means it never directly drives the vehicle. At first, the mechanical power of the ICE which comes from the fuel combustion process is converted into electrical energy by a generator. And then the converted electricity can have two ways to go, either charge the battery or directly supply the electric traction motor for propelling the wheels via the transmission, thus bypassing the battery. Conceptually, it is an ICE-assisted EV that typically can extend the driving range to be comparable to that of conventional vehicles [21]. One example of this kind of hybrid is the Chevrolet Volt. Fig.2.4 shows the architecture of the series hybrid.

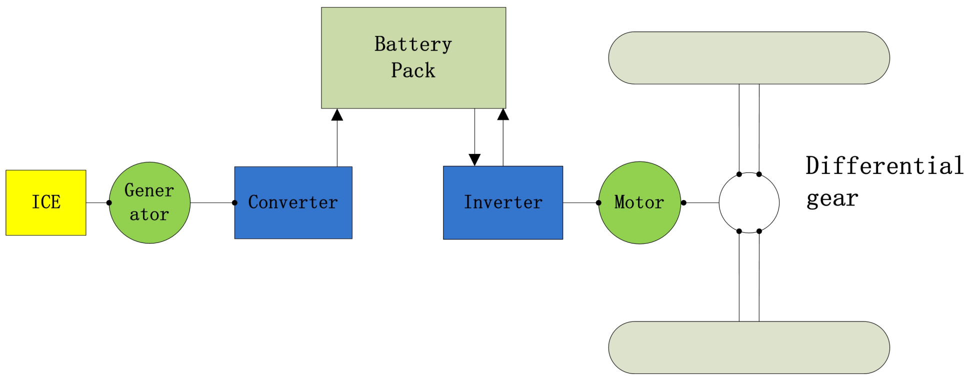

Figure 2.4: Architecture of Series Hybrid

Advantages and Disadvantages

The series hybrid has unique characteristics that offer several advantages:

1. Due to the mechanical decoupling of the ICE and the driving wheels, series HEVs have the distinct advantage of being flexible as to location of the ICE-generator set. Also, the ICE operates always within a very narrow maximum efficiency region, independent of the vehicle speed. These features allow down-sizing of the ICE, and running it in a near steady state form to minimize harmful gas emissions.

2. There is no need for a complicated multi-gear transmission and the clutch is eliminated in series hybrids. Therefore the structure can be greatly simplified and be cheaper. At the same time, this provides more flexibility for having

independent motors for each wheel, resulting in independent speed and torque control of the wheels to enhance the drivability of the vehicle.

3. Compared to other configurations, series HEVs can have simpler control strategies.

Despite their advantages, series hybrids also have some disadvantages as follows:

1. Because the traction motor is the only power source to propel the vehicle, the series hybrid requires a larger, more complicated battery and motor to produce enough power for optimal vehicle performance. The larger battery, motor and the additional generator often make the series hybrid more costly compared to a parallel hybrid.

2. Due to the simplicity of its drivetrain, the series hybrid has to perform energy conversion process twice. Therefore, the efficiency of the series HEV is lower [3].

2.3.2 The Parallel Hybrid

In the parallel configuration, the electric motor is placed in line with the ICE. So the Parallel HEV allows both the engine and the electric motor to independently deliver power in parallel to the transmission for driving the vehicle. The propulsion power may be provided under multiple modes, such as being supplied by the ICE, or the electric motor alone, or by both. Depending on the relative positions of the electric motors and the engine, parallel hybrid powertrains can be categorized into four configurations, which are typically referred as P1 to P4, shown in Fig. 2.5.

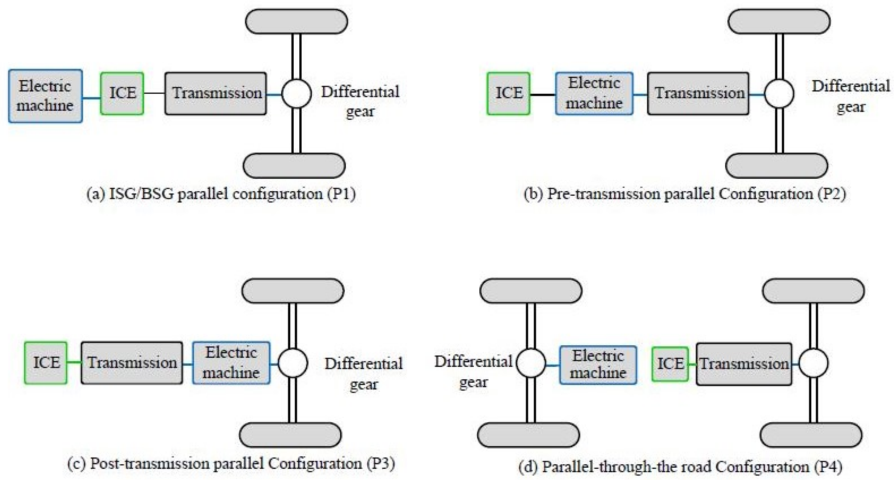

Figure 2.5: Different Architectures of Parallel Hybrids [19]

1. **P1 (ISG/BSG parallel):** The electric machine is located before the ICE. The integrated starter generator (ISG) or belt starter generator (BSG) performs both as a starter motor for the engine and generator for powering vehicle accessories.

2. **P2 (Pre-transmission parallel):** The electric machine is located before the transmission. Here the electric machine can provide assistance to the engine for greater acceleration and performance, or drive the vehicle in electric-only operation depending on the size and power of the battery pack.

3. **P3 (Post-transmission parallel):** P3 is similar to P2 in many ways except that the electric machine is placed after the transmission and thus it connects to the output shaft through the differential gear ratio.

4. **P4 (Parallel through the road):** The electric machine is either placed directly on the wheels or a different axle. The benefit comes from combining the

tractive forces from both the ICE and the motor, and this will enhance the performance of an all-wheel drive (AWD) powertrain.

Advantages and Disadvantages

The following part will focus on the advantages and disadvantages of the parallel hybrid.

Advantages of parallel hybrid includes:

1. Compared with a series hybrid, it can reduce the energy efficiency loss during the process of converting mechanical power to electricity and back. This makes the total efficiency higher, especially during the cruising and long-distance highway driving.

2. Parallel hybrid provides higher flexibility for switching between the ICE and the electric power for the vehicle; this can enhance the drivability.

3. The parallel hybrid tends to use a smaller electric motor and battery pack than series drivetrains, as they are assisting traction. Also, only one electric motor/generator can be used in order to reduce cost.

Weaknesses of parallel hybrid include:

1. The parallel hybrid is rather complicated; this makes the control strategy and energy management more complicated than the series hybrid.

2. Because the engine is mechanically connected to the wheels, the ICE does not operate in a narrow or constant speed range, and its efficiency cannot always be regulated, especially at low rotational speed. Also because of coupling of the ICE, the battery cannot be charged at standstill.

2.3.3 The Series-parallel Hybrid

This hybrid architecture, which is also called the power-split hybrid, combines features of both the series and the parallel HEV. Compared with each, it involves an additional mechanical link with the series hybrid and an additional generator compared with the parallel hybrid. The ICE has a direct mechanical connection to two electric machines. The primary electric machine assists the ICE in providing mechanical drive power for the vehicle and also acts as a generator to recharge the battery during regenerative braking. The other machine usually referred to as the generator is always connected to the ICE. Its function is to act as both a starter motor and also as a generator during vehicle operation.

The power-split system includes an ICE, and two electrical machines (MG1 and MG2), which are integrated with a power splitting planetary gear set to provide various modes of operation. The first configuration based on the planetary gear set architecture is the Toyota hybrid system (THS), which was used in the Toyota Prius before 2004.

It is an input-split hybrid transmission which utilizes the planetary gear set to connect the engine and the electric machine. The planetary gear set splits the engine power into a mechanical path and an electrical path. MG1 is utilized for speed coupling, which is connected to the sun gear. While MG2 is connected with the ring gear, which provides torque coupling with the ICE to supply the required torque to the vehicle and allows the ICE to operate with greater efficient, as shown in Fig. 2.6. Most of the engine power would directly be transferred through the mechanical path to the final drive, while the remaining power would pass through the electric path, transferred to MG1 acting in the generator mode. By adjusting the portions of power transferred through these two paths, the system achieves variable output speed and torque, thus improving vehicle fuel economy and reducing emissions [22] [23] [24].

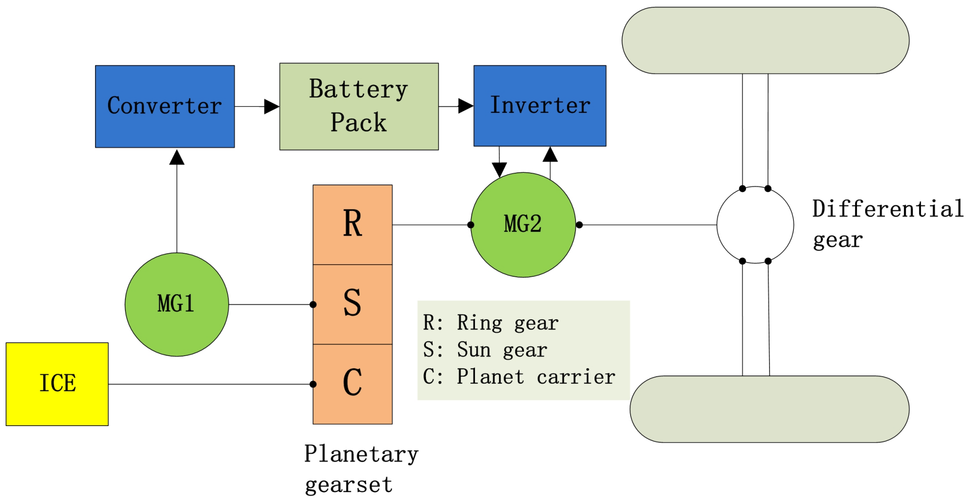

Figure 2.6: Power-split Hybrid Architecture

Advantages and Disadvantages

SPHEV can benefit from both series and parallel advantages. This architecture is the most flexible and gives a higher degree of freedom to control the operating conditions of the parallel architecture. It provides a more efficient way is to reduce the fraction of series mode which requires two processes of energy conversion, thus reducing the overall energy losses. Especially for power split, both engine speed and engine torque are decoupled from the output shaft enabling the engine to work within its optimal operating regions, thus increasing fuel efficiency. Since both electric machines can function as either the motor or the generator, greater system flexibility and performance are achieved.

Although SPHEV possesses the features of both the series and the parallel HEVs, it requires more complex components, such as the planetary gear set, which makes the powertrain somewhat complicated and costly. Additionally, this architecture needs a complex control system and more sophisticated energy management strategy to improve energy efficiency.

2.3.4 Other Specific Hybrids

Apart from the above traditional hybrids, there are other specific hybrids; two of them are introduced in this section.

Complex Hybrid

As reflected by its name, this type of hybrid system involves a more complex configuration which cannot be directly classified into the above three groups. But it is similar to series-parallel hybrid, with the biggest differentiation between the electric flows. The fundamental difference is due to the bi-directional power flow from the electric motor in the complex hybrid and the unidirectional power flow from the generator in the series-parallel hybrid, as the red block in Figure 2.7 shows. This architecture has been adopted by some four-wheel drive systems [20].

General Motors Two-mode Hybrid

Compared to the Toyota hybrid system, General Motors defines another architecture named “two-mode hybrid system.” Rather than using one planetary gear set, it uses 2 or 3 planetary gear sets in an automatic transmission: one on the internal combustion engine side (input split) paired with a second (output split), forming the compound split, and possibly a third additional planetary gear set to multiply the number of fixed gear ratios [25].

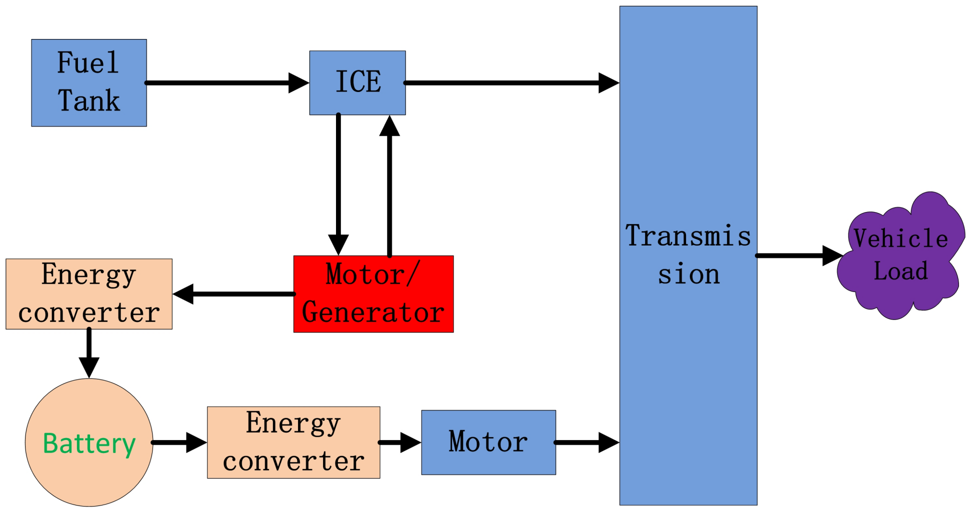

Figure 2.7: Complex Hybrid Architecture [20]

Two-mode hybrid transmissions can operate in the input-split mode and the compound-split mode. The input-split means that the engine power is transmitted to an input member and then split through a differential device into two paths: the mechanical path and the electric path. The compound-split means that, except for the input split differential device, there is another differential device at the output end, which functions to combine the previously split power together. The input-split mode is usually used for low vehicle speeds, while the compound-split mode works better for high speed or high load conditions. More details is shown in Fig. 2.8. The six operating modes are as follows [19]:

1. **Input-split Mode.** Clutch C1 is engaged, the others are released.

2. **Compound-split Mode.** Clutch C2 is engaged, the others are released.

3. **First Fixed Gear Ratio Mode.** Clutches C1 and C4 are engaged, C2 and C3 are released. The gear ratio is 3.76:1.

4. **First Fixed Gear Ratio Mode.** Clutches C1 and C2 are engaged, C3 and C4 are released. The gear ratio is 1.71:1.

5. **First Fixed Gear Ratio Mode.** Clutches C2 and C4 are engaged, C1 and C3 are released. The gear ratio is 1:1.

6. **First Fixed Gear Ratio Mode.** Clutches C2 and C3 are engaged, C1 and C4 are released. The gear ratio is 0.74:1.

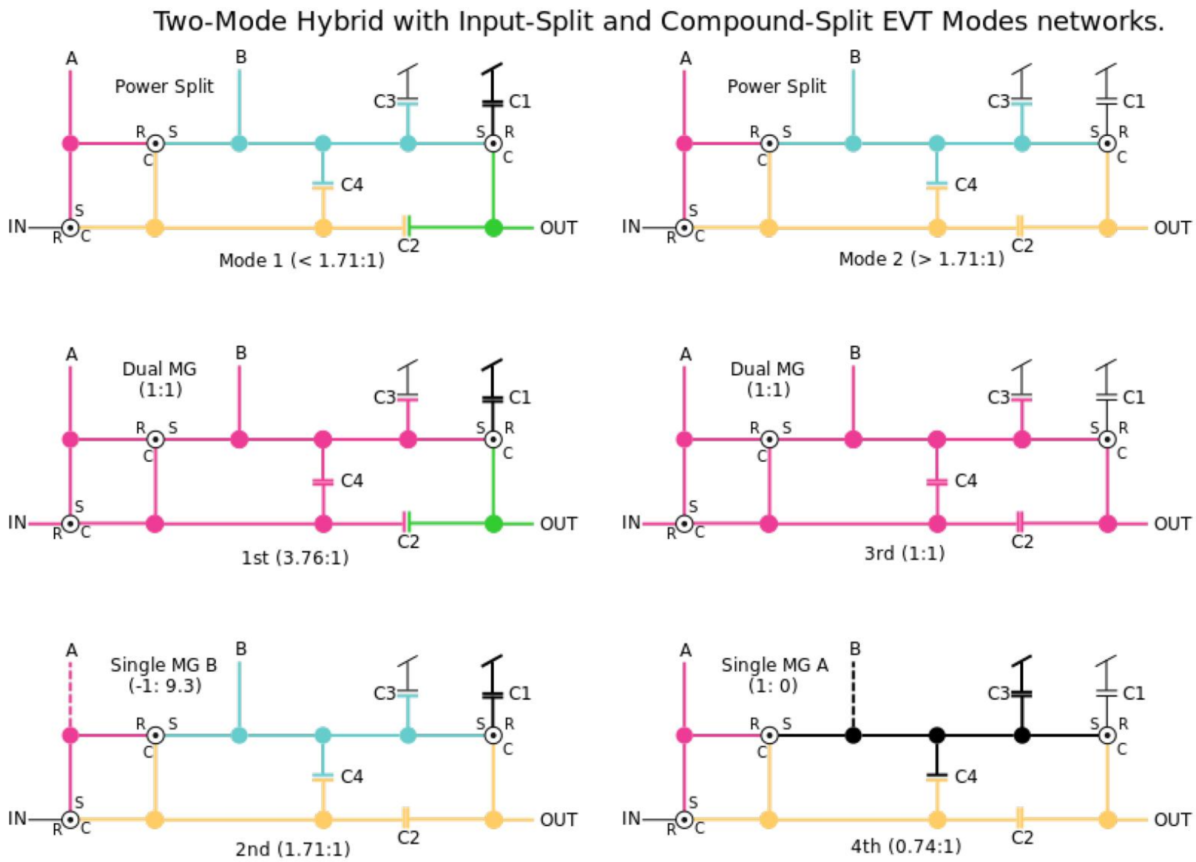

Figure 2.8: Two-mode Hybrid Networks [25]

The technology is referred to as "two-mode" hybrid transmission due to the ability to extend the capabilities of both electrical and mechanical paths of power. By coordinating the two machines, clutches and brakes, this hybrid transmission provides more operating modes when compared to the power-split system. This enables the two-mode hybrid transmission to achieve improved fuel economy and uncompromised performance at both low and high vehicle speed [19].

2.4 Hybrid Educational Laboratory Review

As the above section have explained the importance of HEVs in today's automobile industry, some research institutions around the world focus on developing their research platforms, which not only can provide research resources but also provide analytical and hands-on skills on demonstrating powertrain systems of HEVs to university students. There are different types of solutions to building an educational laboratory. In the following section, three hybrid laboratories at three different universities are discussed.

2.4.1 Engine-in-the-loop from Vienna University of Technology

Using hardware-in-the-loop technology, Institute for Powertrains and Automotive Technology (IFA) at Vienna Technical University has developed an HEV system to simulate different hybrid control strategies and predict the emission and consumption behavior of different possible powertrain configurations. A simulator is a valuable tool in their laboratory [26].

Their research interest is on the ICE. Emission formation process of an ICE is highly complex and still can not be exactly represented in a simulation model. At the same time, the test parameters come from simulation-generated speed and torque profiles which make the results approximated and neglect the non-linear behaviour of the ICE in relation to the input variables. To obtain results close to the real scenarios with little modeling effort, IFA replaces the simulation model of the engine by real hardware. Engine is the hardware operated in the loop and is the remaining elements with a virtual drive train model. In this way, accurate and reliable information on the fuel consumption and emission behaviour of the drive train can be obtained, and the influence of operating strategies for hybrid vehicles can be analyzed. Also, parameter studies of any hybrid vehicle components, such as the capacity of the high-voltage battery, can be examined. Testing of any virtual components using a simulation model is possible or is further complemented by the potential for real-time hardware-in-the-loop augmentation to provide additional flexibility in the studies.

2.4.2 The Michigan Tech Mobile Laboratory

The Michigan Tech Mobile Laboratory partners with government, industry, and non-profit organizations to deliver HEV education, outreach, and research across the United States. Their mobile laboratory features a powertrain test cell, configurable hybrid electric vehicle, three other hybrid test vehicles, a portable chassis dynamometer, and a "smart" interactive micro-grid [27].

The Mobile Laboratory's powertrain "hardware-in-the-loop" test cells are developmental tools that show how HEV components work, namely batteries, engines, electric machines, embedded controls, and power electronics. The powertrain can be operated in steady state, or dynamic modes, while emulating and be used to investigate torque blending between the engine and motor, as well as regenerative braking amongst others [28].

The laboratory content enables powertrain subsystems testing, vehicle dynamic modeling, component sizing, control design and calibration, and study of vehicle performance factors including acceleration and fuel consumption.

2.4.3 Modular Hybrid Test Bench from GESC laboratory

The research team within the GESC laboratory of the University of Technology Belfort-Montbeliard France has developed a modular test bench for simulating an HEV with different energy sources. Their aim is to simulate the real-time behaviour of different subsystems of HEVs. Variable models of energy sources and mechanical loads are applied in their test bench [30].

To achieve their simulation goals, the bench consists of: a diesel engine, a synchronous generator, a synchronous motor, inertial load and electrical brakes, battery packs, super-capacitors, and converters. Both the traction motor and the diesel engine can drive the mechanical load, and the electric energy provided to the traction motor can be supplied by the electric network, battery pack, pack of super-capacitors, or from series hybrid operation which coverts mechanical energy of the engine to electric energy. The modular test bench can be used to test different hybrid configurations from applying different electric energy sources.

2.4.4 Comparison and Innovation in Our Laboratory Design

Our objective is to build an educational laboratory for our undergraduate students and make them exposed to HEV systems. Both engine and motors are considered and used in this laboratory. Rather than using hardware-in-the-loop simulation, the use of the physical hardware is implemented in order to render a more hands-on experience for demonstrating all the concepts and structures of HEVs. Besides, the use and implementation of clutching mechanisms in the design of the laboratory enables switching between different hybrid configurations. The other important consideration is safety. A remote computerized control method is implemented in order to isolate students from the high voltage in the laboratory.

2.5 Summary

A literature review of hybrid powertrain technologies has been presented in this chapter. The first section briefly reviewed the hybrid powertrain architectures and HEV operating modes. This chapter also provided an overview of different HEV configurations, including their advantages, and disadvantages. Finally, three hybrid educational labs were reviewed.

Chapter 3

DC Motors, Modeling and Speed Control

3.1 Traction motor requirements in HEVs

Electric motors convert the electrical energy into mechanical energy in order to provide the required traction force for the vehicle. They must have the following features, in order to satisfy a wide range of driving requirements: a high torque and power density; a sufficient torque for start/stop; a high rate of acceleration and deceleration; a wide speed range with a constant power region; and a high rate of energy recovery in regenerative braking.

Figure 3.1 shows a typical torque-speed envelope for an electric motor used as a traction motor in an HEV application. In different operating regions, there are different priorities: a high torque is required for a quick start of the vehicle and for hill climbing; a high efficiency is needed in the medium-speed range for city driving; and a high-speed high-efficiency operation would benefit highway driving [31].

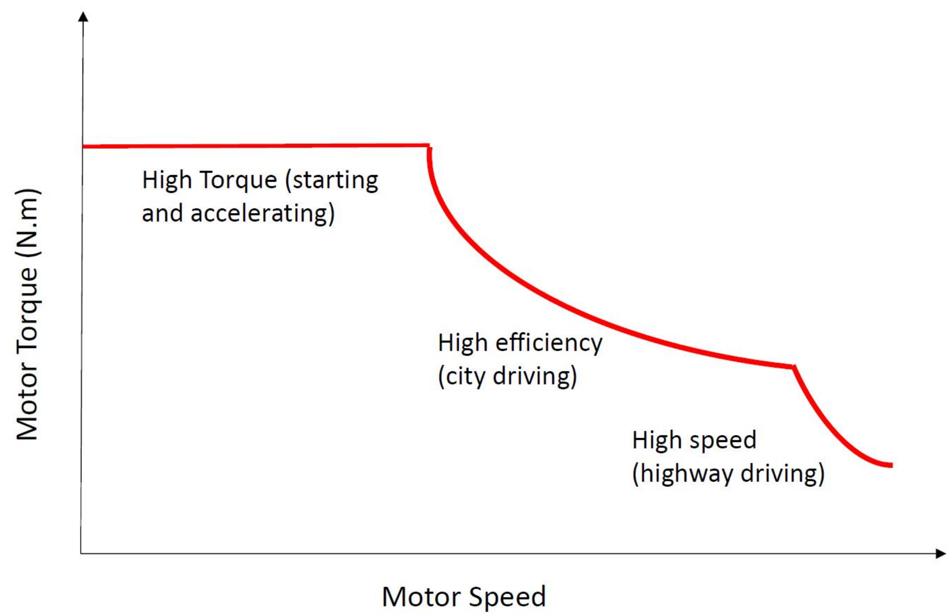

Figure 3.1: Traction motor requirements in HEVs [31]

3.2 DC Motor

DC motors have been widely used in industrial applications. DC motors are easy to control and are used in manufacturing, automation, and other industrial applications. In this HEV powertrain laboratory, DC motors are used for their easy implementation to demonstrate hybrid functionalities.

3.2.1 Principle of DC Motor

The working of DC motor is based on the principle that when a current-carrying conductor is placed in a magnetic field, it experiences a mechanical force. A DC motor converts electrical energy into mechanical energy through the interaction of two magnetic fields. One field is produced by a permanent magnet assembly or its field windings, the other field is produced by an electrical current flowing in the motor armature windings. These two fields result in a torque which tends to rotate the rotor. As the rotor turns, the current in the armature windings is commutated to produce a continuous torque output. The stationary electromagnetic field of the motor can also be wire-wound like the armature (called a wound-field motor) or can be made up of permanent magnets (called a permanent magnet motor) [32] [33].

3.2.2 Types of DC Motors

The wide utilization of DC motors in different industries makes for different functional types being available in the market for specific requirements. The types of DC motor can be listed as follows [34]:

- **Permanent Magnet DC (PMDC) Motor**

  The PMDC motor consists of an armature winding. Instead of using field windings, radially magnetized permanent magnets are mounted on the inner periphery of the stator core to produce the field flux.

- **Separately Excited DC Motor**

  As the name suggests, a separately excited DC motor has separate supplies to its field and armature windings. The armature current does not flow through the field windings, as the field winding is energized from a separate external source of DC current.

- **Self Excited DC Motor**

  For a self excited DC motor, the field winding is connected either in series or in parallel or in a compound way to the armature winding. To be more specific, a shunt wound DC motor connects the armature and field windings in parallel or shunt with a common DC power source. A series DC motor connects the armature and field windings in series, and the entire armature current flows through the field. In order to combine the operational characteristic of both the shunt and series DC motor, a compound wound DC motor essentially contains the field winding connected both in series and in parallel to the armature winding.

Figure 3.2 shows the different types of DC motors:

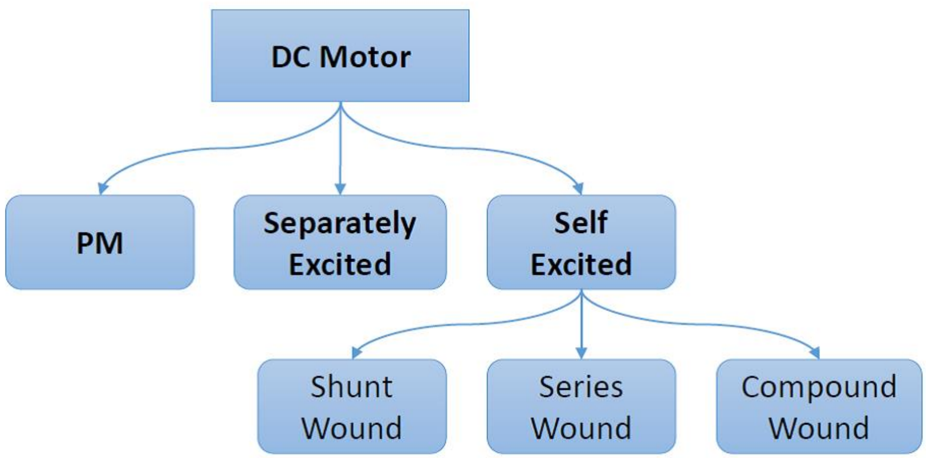

Figure 3.2: Types of DC motors

3.2.3 Four-Quadrant Operation

The four-quadrant operation is another important characteristic of DC motors. Various industrial applications require both driving and braking, i.e., motoring and generating capability. Figure 3.3 illustrates the four quadrant operating region of a DC motor.

The four quadrants can be visualized by plotting the velocity of the motor on the horizontal axis of the graph and the direction of applied torque on the vertical axis. Quadrants I and III represent the motor applying torque in the same direction of motor speed, while quadrants II and IV represent applying torque opposite to the direction of the motor speed. In quadrants 1 and 3 the flow of energy is from electrical to mechanical. The quadrant operations are called forward motoring and reverse motoring. In quadrants 2 and 4, the motor is actually acting as a generator, called forward braking and reverse braking.

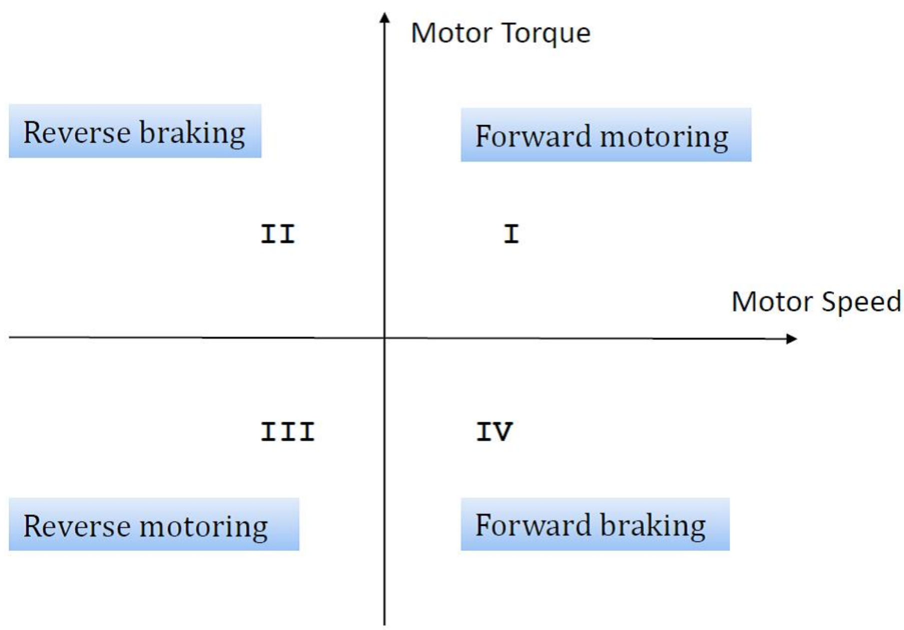

Figure 3.3: Four-Quadrant Operation

3.3 Shunt DC Motor

In our motor lab, two shunt DC motors are selected. Shunt DC motors are widely used in applications with constant speed requirements, since they have good speed regulations, and the drop in the speed from no-load speed is relatively small. In addition, a shunt DC motor provides the lowest starting torque and a much lower no-load speed. Generally, three characteristics are considered important for DC shunt motors which are, 1) Torque - armature current, 2) Speed - armature current and 3) Speed - torque [35].

3.3.1 Torque - Armature Current

As neglecting the change in the flux ϕ of DC shunt motors, the torque is proportional to the armature current. Hence, the Torque - Armature Current characteristic for a DC shunt motor would be a straight line through the origin. Torque increases linearly with the armature current. Now if the shaft torque T_{sh} is plotted against armature current, it is less than the armature torque and the difference between the two is the torque loss T_f as shown in figure 3.4. On no load $T_{sh} = 0$ but the armature torque is present which is just enough to overcome stray losses shown as T_{a0}. The current required is I_{a0} on no load to produce T_{a0} and hence T_{sh} graph has an intercept of I_{a0} on the current axis [36]. The following equation represents the relationship between T_{sh} and I_a(with a constant coefficient K).

$$T_{sh} = K(I_a - I_{a0}) = KI_a - T_{a0} \tag{3.1}$$

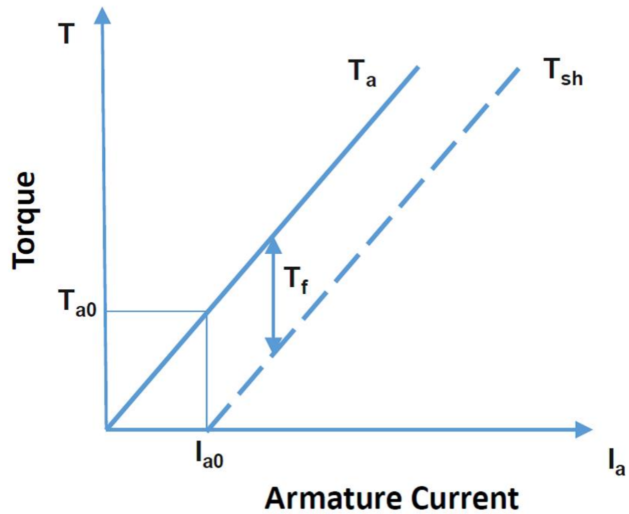

Figure 3.4: Shunt DC motor Torque - Armature Current characteristic

3.3.2 Speed - Armature Current

For the speed with constant supply voltage and field flux, back electromotive force (EMF) is also almost constant, the speed should remain constant. But practically, the flux as well as back EMF decreases with increase in load. Back EMF decreases slightly more than flux, therefore, the speed also decreases slightly. Generally, the drop in speed is not significant from no load to full load, only by 5 to 15% of full load speed. Therefore, a shunt motor can be assumed as a constant speed motor. The following equation represents the relationship between the motor speed N and the armature current I_a.

$$N = K_n(V - I_a R_a) \tag{3.2}$$

Where V is the voltage, R_a is the armature resistance, K_n is a constant coefficient.

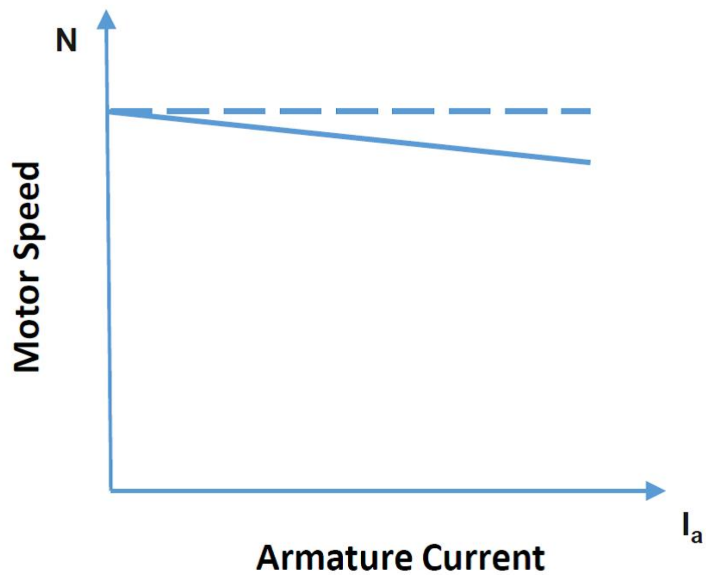

Figure 3.5: Shunt DC motor Speed - Armature Current characteristic

3.3.3 Speed - Torque

From the above two characteristics, the Speed - armature current characteristic can be derived for the condition of constant supply voltage and field flux. The curve in figure 3.6 shows when torque increases, armature current increases, the speed decreases slightly from no load to full load.

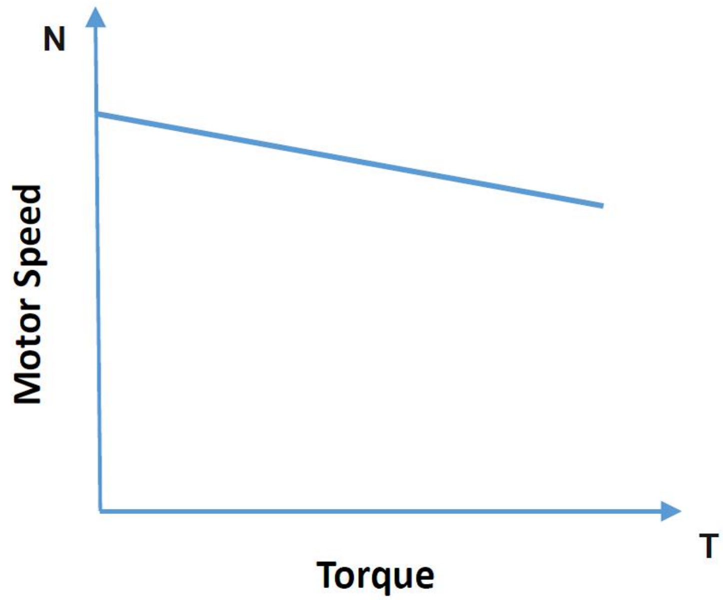

Figure 3.6: Shunt DC motor Speed - Torque characteristic

3.3.4 Motor Speed-torque Operating Characteristic

The speed-torque operating characteristic is shown in figure 3.7. At a low-speed region from 0 to $\pm$ base speed (ω_{base}), the electric motor offers a constant torque (rated torque) over the entire speed range. While passing the base speed (high speed region), the motor provides a constant power. Because the armature currents are limited, the maximum permissible torque also reduces inversely with the speed from ω_{base} to ω_{max} [31]. This region where the torque drops inversely with speed is called the constant power region that entails decreasing the rotor magnetic flux.

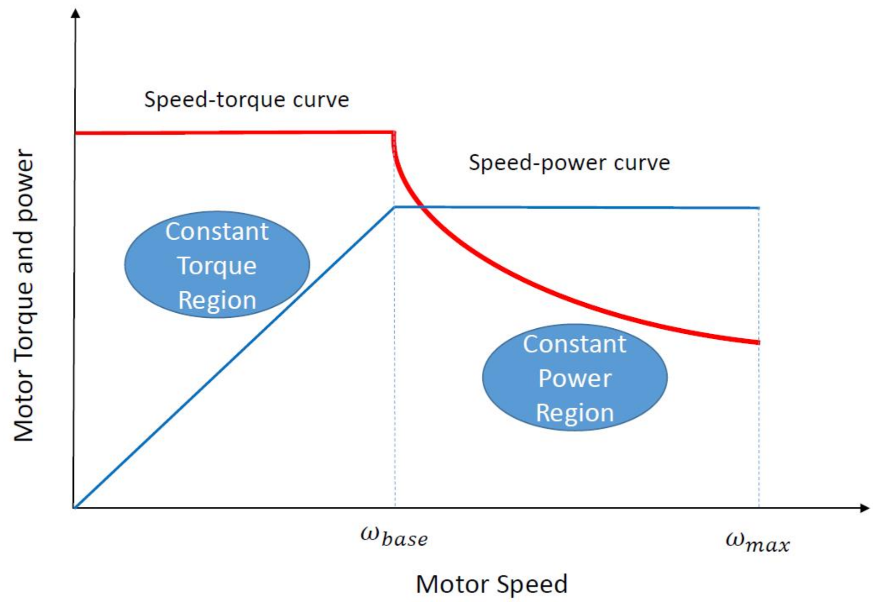

Figure 3.7: Motor speed-torque characteristic

3.4 Modeling and Speed Control

In this section, a model of the shunt DC motor is provided.

3.4.1 Mathematical Model of Shunt DC Motor

The equivalent circuit model of a shunt DC motor is shown in figure 3.8.

The equation describing this electromechanical system is [37]:

$$J\dot{\omega} = T_m - B\omega - T_L \tag{3.3}$$

Where J is the motor inertia, ω is the angular velocity, T_m is the motor electromagnetic torque, B is the system damping, T_L is the load torque. This equation

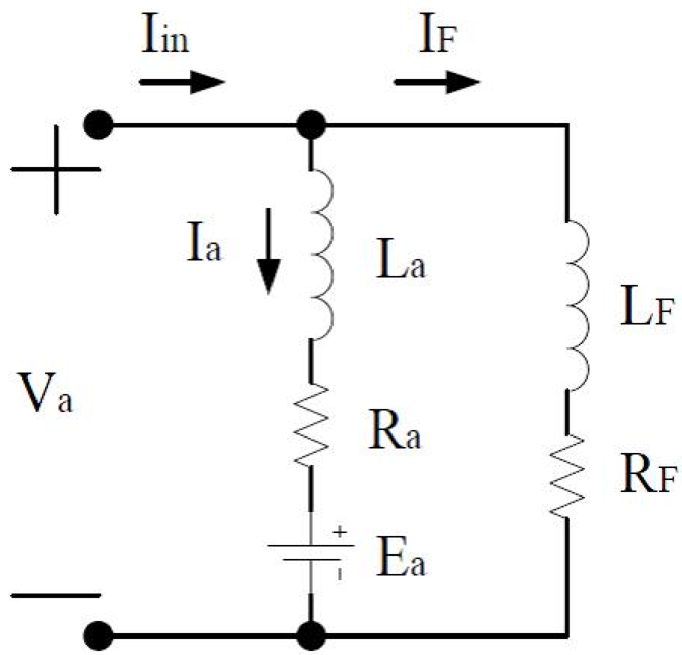

Figure 3.8: Equivalent Circuit Model of Shunt DC motor

describes the mechanical behavior of a shunt DC motor as a first order system.

The magnetic field in the motor induces the following back EMF v_b in the armature:

$$v_b = L_{af} I_f \omega \tag{3.4}$$

L_{af} is a constant of proportionality, I_f is the field current.

The mechanical power is equal to the power reacted by the back EMF:

$$P = v_b I_a = L_{af} I_f i_a \omega \tag{3.5}$$

The motor torque is:

$$T_m = \frac{P}{\omega} = L_{af} I_f I_a \tag{3.6}$$

The voltage equation is as follows:

$$V = I_a R_a + L_{af} I_f \omega = I_f R_f \tag{3.7}$$

Substitute all the other equations to equation 3.3, the following equation represents the relationship of the output toque, the motor angular velocity and the voltage supply:

$$T_L = \frac{L_{af}}{R_a R_f} \left(1 - \frac{L_{af}\omega}{R_f}\right) V^2 - J\dot{\omega} - B\omega \tag{3.8}$$

3.4.2 Modeling and Controller Design

Based on these equations, a shunt DC motor model is developed in Simulink as shown in figure 3.9. For the simulation process, it is assumed that the motor follows a certain speed trajectory, consisting of three parts, starting from 1000 rpm, then stepping down to 750 rpm, and finally returning to 1000 rpm. During the simulation process, a constant load torque 5 N.m is applied to the motor at the time t = 20s.

In this simulation, all the parameters are from a Baldor DC motor chosen for our lab. The following table lists all the parameters:

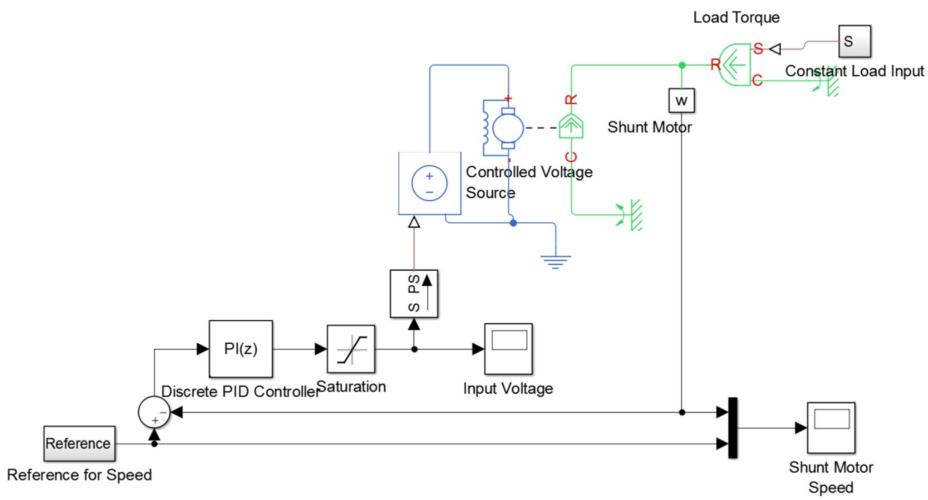

Figure 3.9: PI Speed Controller of Shunt DC motor

Table 3.1: Model Parameters of Shunt DC Motor

Model Parameters		
Armature resistance	0.406	Ohm
Field winding resistance	147	Ohm
Back-EMF constant	0.4	s*V/rad/A
Armature inductance	3.72	mH
Field winding inductance	24.3	H
Rotor inertia	2.329	lbm*ft^2
Rotor damping	0.00001	N*m/(rad/s)
Initial rotor speed	0	rpm

A proportional integral (PI) motor speed controller is designed for our simulation process [38]. The final tuned controller parameters are as follows:

- Proportional gain K_p: 0.48

- Integral gain K_i: 0.043

3.4.3 Simulation Results

The following figures show the speed tracking process and the motor input voltage variation. The results reflects the good performance of speed tracking and disturbance rejection from load torque (5 N.m) at time t = 20s.

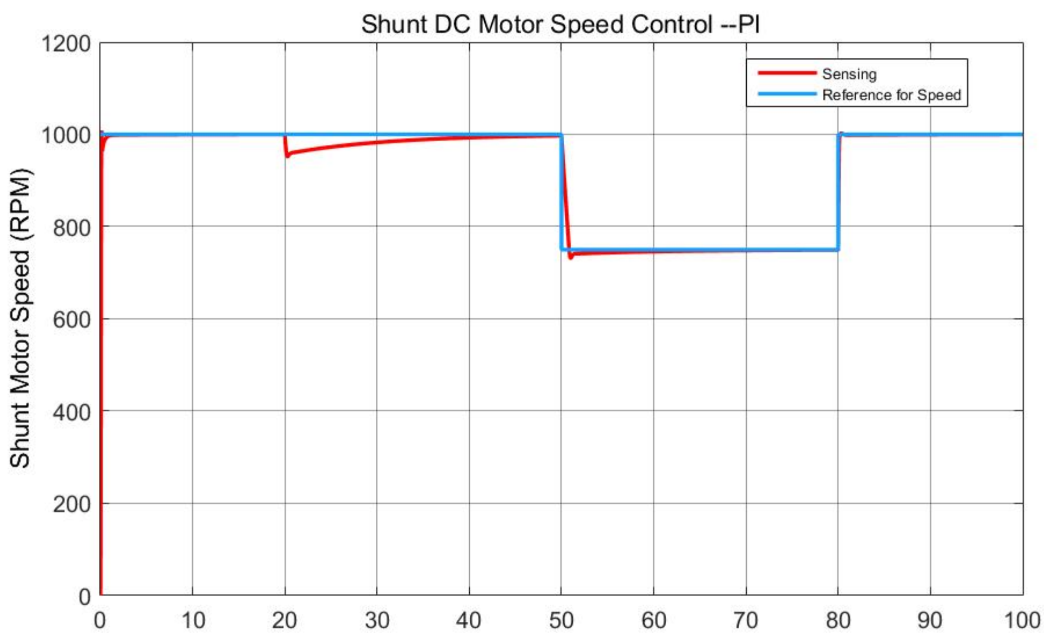

Figure 3.10: Speed of Shunt DC motor

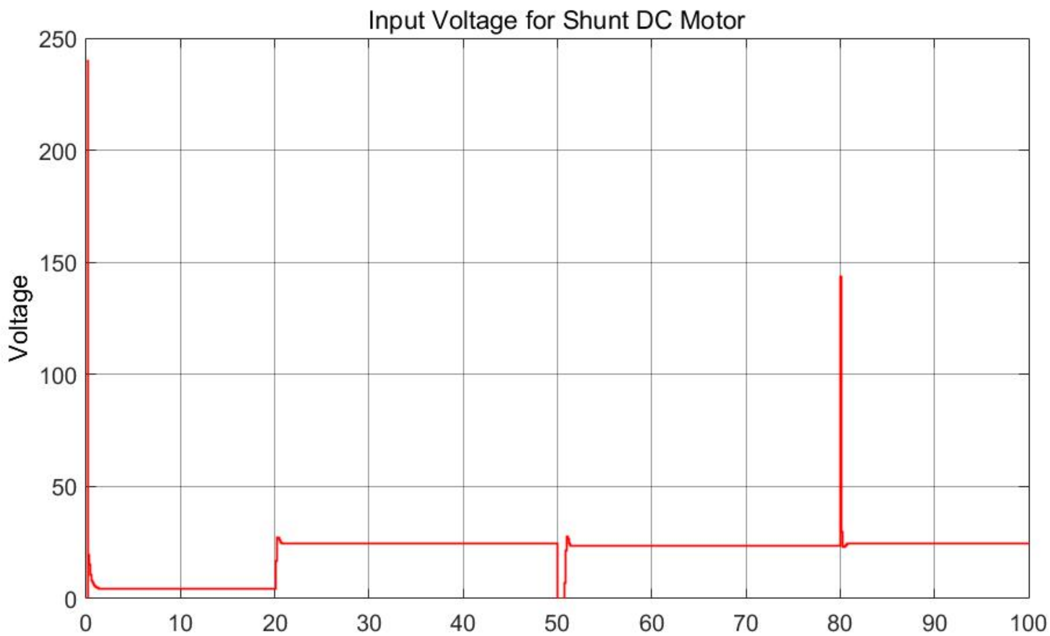

Figure 3.11: Input Voltage of Shunt DC motor

3.5 Summary

In this chapter, a basic model of a DC motor is briefly presented, and its working principles discussed. The mathematical model is based on a simplified equivalent circuit and was useful for designing a speed controller. A PI controller has been tuned and used to regulate the motor speed and the simulation results have been shown.

Chapter 4

Motor Characterisation Testing Strategy and Lab Procedure with User Interface

As an important element of a hybrid laboratory, a stand-alone electric motor lab is initially produced. This chapter presents the educational objectives of the motor lab, its testing procedures based on motor characterisation testing strategies, and the interface design.

4.1 Educational Objectives of the Motor Lab

Our stand-alone motor lab would expose mechanical students to electric motors and their characteristics. The educational objectives of the lab include the following :

1. Demonstration of the motor operating characteristics: the speed-torque curve.

2. Analysis of the motor performance: achieving the motor efficiency map.

3. Simulation of the operation of motors in EV driving application.

4.1.1 Motor Speed-torque Characteristic

The first part of the lab concentrates on the motor operating characteristics, especially the speed-torque characteristic as shown in figure 3.8. Both the constant torque region and the constant power region would be demonstrated in this electric motor laboratory.

In the real HEV and EV driving applications, the relationship between speed and torque determines how the motor can be controlled to meet the driving requirements and affect the vehicle performance.

4.1.2 Motor Efficiency Map

Another important characteristic is the motor operating efficiency. Electric motors have a very wide operating range, but that does not mean they are equally efficient at every speed. There is a 'sweet spot', typically at medium speed and medium to high loads, where the delivery of power is most efficient. Most electric motors are designed to run at 50% to 100% of rated load. Operating efficiency is usually near 75% of rated load. A motor's efficiency tends to decrease dramatically below about 50% load. However, the range of good efficiency varies with individual motors and tends to extend over a broader range for larger motors. The energy efficiency map reflects the motor efficiency at each operating point.

Also, compared with conventional vehicles, EVs or HEVS enhance the total energy efficiency with using electric motors. When these motors run in different operating regions, different energy efficiency will require us to implement various control strategies according to a specific driving scenario.

4.1.3 Driving Cycle Simulation

Not only the motor itself, but also driving scenarios are considered in this lab. Electric motors have their own advantages when they provide traction forces to drive the EVs or HEVs. This motor lab aims to make students understand the impact of motor characteristics on the vehicle driving performance, encouraging them to expand their understanding of HEVs and EVs.

Vehicle dynamics captures the effects of acceleration, braking and steering applied by a driver. The load on the motors can be calculated from the vehicle's model in relation to different driving cycles. This lab can simulate and analyze the motor performance in the highway or urban conditions for educational purposes.

4.2 Characterization Testing Strategies

In the previous section, the operating characteristics of electric motors have been discussed. Another aspect for building a motor lab would be the characterization testing strategies. Some standards, such as "IEEE Standard Test Procedure for Polyphase Induction Motors and Generators" [39], describe the instructions for conducting tests to determine the performance characteristics and machine parameters of electric motors.

The schedule of factory and field tests, which may be required on new equipment, is normally specified by applicable standards or by contract specifications. Building an educational motor lab is different from commercial tests. The key consideration in the educational lab procedure would be the motor characteristics and different operating scenarios. Mainly there are three parts in the lab and three corresponding tests should be implemented in the motor lab:

1. Obtaining the Speed-torque characteristics.
2. Generating the motor efficiency map.
3. Examining motor performance under a typical driving cycle.

4.2.1 Speed-torque Characteristics Test

There are two regions in the motor speed-torque curve, as shown in figure 3.8. When the speed is lower than the base speed, constant torque can be maintained. Over the base speed, constant power can be expected. Based on this specific curve, the testing strategy and characterisation can be divided into two parts.

1. Constant Torque Region

The nameplate provides the base speed and maximum speed of the motor. Several speed levels will be chosen from zero to base speed. On each level, torque will be increased to the maximum. As shown in figure 4.1, the base speed of the Baldor motor is 3000 rpm, and the maximum torque is 20 N.m.

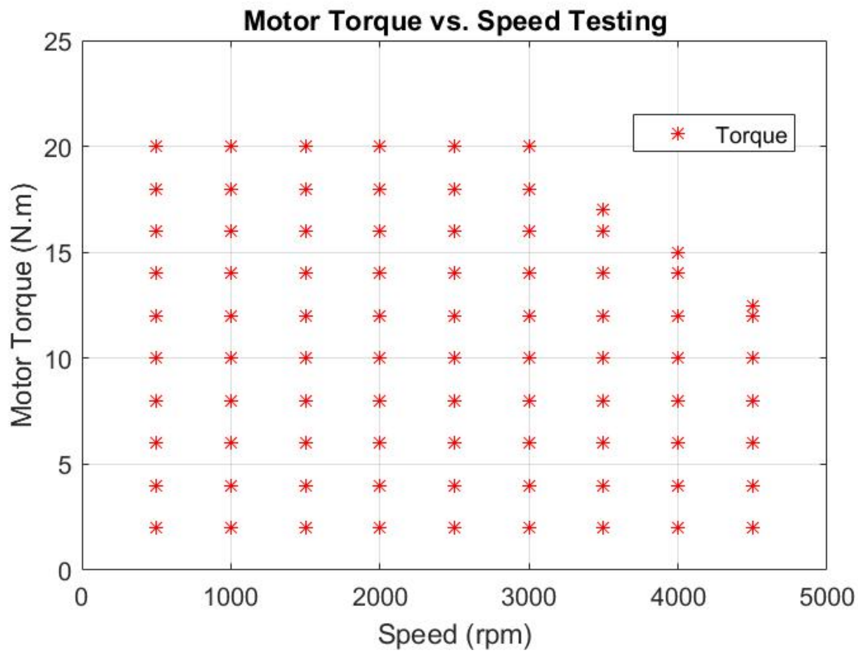

Figure 4.1: Electric Motor Torque vs. Speed Testing

2. Constant Power Region

When the speed is over the base speed, constant torque cannot be maintained. On each speed level, different torque levels will be recorded for the speed beyond the base speed. The critical torque value will be recorded as the maximum torque on the corresponding speed level. Taking the speed level of 4000 rpm as an example, the maximum torque would be around 15 N.m (see figure 4.2).

Following the testing strategies, the two specific regions are tested on several speed levels. The final envelope curve as the figure 4.2 shows the motor speed-torque characteristic that would be derived by students as part of the lab.

4.2.2 Determination of Efficiency Map

Efficiency is the ratio of output power to total input power. Output power is equal to input power minus losses. Therefore, if two of the three variables (output, input, or losses) are known, the efficiency can be determined by the following equations:

$$\text{efficiency} = \frac{output\ power}{input\ power} \tag{4.1}$$

A form commonly used for motors is:

$$\text{efficiency} = \frac{input\ power - losses}{input\ power} \tag{4.2}$$

A form commonly used for generators is:

$$\text{efficiency} = \frac{output\ power}{output\ power + losses} \tag{4.3}$$

Figure 4.2 is a graphical depiction of the process of converting electrical energy to mechanical energy. Motor losses are the difference between the input and output power. The two variables available to the lab that would be used for efficiency calculation are the input electric power and output mechanical power as follows.

Motor Input Electric Power

At each operating point, the consumed electrical power (P_{in}) of the motor is defined by the following equation from the measured current (I_{in}) and voltage (V_a):

$$P_{in} = V_a I_{in} \tag{4.4}$$

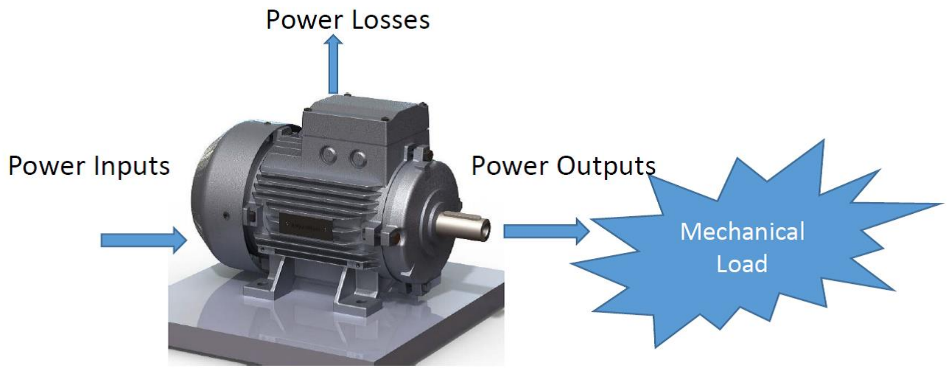

Figure 4.2: Depiction of Motor Losses

Where

P_{in} is the input electric power, measured in watts (W);

$I_{in}$is the input DC current, measured in amperes (A);

V_a is the applied armature voltage of the motor, measured in volts (V).

Motor Output Mechanical Power

Normally, the mechanical power will be regarded as the output power of the motors. The shaft power (P_{out}), of the machine under test at each load point is obtained from the following equation using the test values of torque (T) and speed (n).

$$P_{out} = \frac{2\pi nT}{60} = \frac{nT}{K} \tag{4.5}$$

Where

P_{out} is shaft power, in watts (W);

n is the measured speed in r/min;

T is the torque in N.m;

$K = \frac{60}{2\pi}$, which is a constant equal to 9.55.

Loss Components

The losses affecting the efficiency of an electric motor are as follows:

- **Core losses.** They are also called iron losses. As iron core of the armature is rotating in magnetic field, some losses occur in the core which are called core losses, such as the hysteresis losses due to reversal of magnetization of the core. Normally, motors are operated with a constant speed, so these losses are almost constant.

- **Friction and wind-age losses.** These losses are due to friction in bearings and commutator. Air friction loss of rotating armature due to the resistance offered by air to the rotational shaft also contributes to these.

- **Copper losses.** The copper losses are the winding losses taking place during the current flowing through the winding. These losses occur due to the resistance in the armature and field windings, resulting in heat produced by resistance to the flow of electrical currents.

- **Stray-load losses.** These miscellaneous losses are due to the short-circuit current in the coil undergoing commutation, distortion of flux due to armature and other losses which are difficult to determine. They are generally taken as 1% of the whole load power output.

On each speed and torque level, the efficiency (η) can be calculated from the following equation, enabling the construction of an efficiency map.

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% \tag{4.6}$$

4.3 Motor Lab Interface Design

To build a teaching lab, a user-friendly interface is necessary to achieve our educational objectives.

4.3.1 Interface Design Logic

In our lab, LabVIEW is used to build the user interface. It is a system-design platform and development environment for a visual programming language from National Instruments. LabVIEW includes extensive support for interfacing to devices, instruments, cameras, and other devices. Users interface to hardware by either writing direct bus commands or using high-level, device-specific, drivers that provide native LabVIEW function nodes for controlling devices [40].

The objectives of this motor lab include motor characterization tests and simulation of vehicle driving scenarios. In this interface design, the logic behind the lab procedure should be clear and straightforward.

Motor Characterization Tests

Motor speed-torque curve and efficiency map are the outputs of these tests. Given the testing strategies described in the previous section, the procedures are demonstrated in the following figure 4.3. What is important in the procedure is to define the inputs, acquire all the relevant parameters, and calculate the outputs on each testing level.

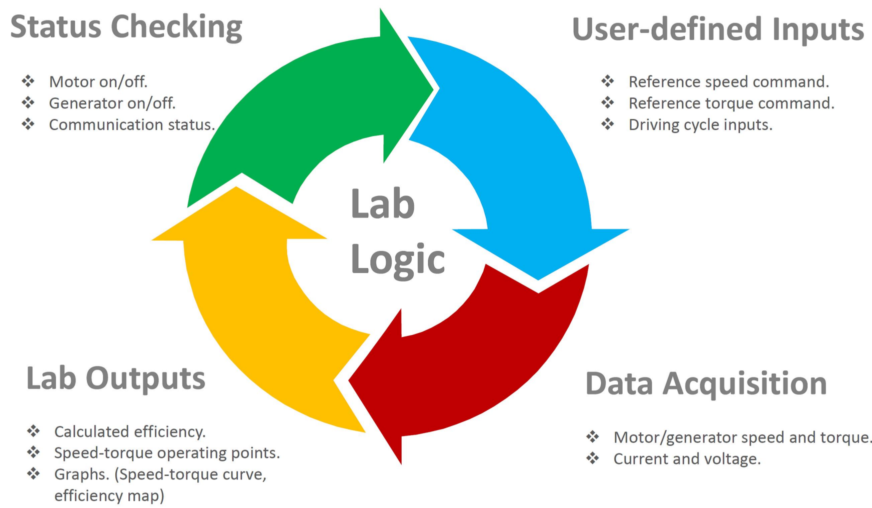

Figure 4.3: Motor lab logic and testing procedures

Simulation of Vehicle Driving Scenarios

A driving scenario is the combination of different operating points of the motor. After obtaining the speed-torque curve and efficiency map, this continuous simulation process can make the students aware of the change of motor performance in real applications, and analyze the motor efficiency for different driving cycles.

4.3.2 User Interface

After analyzing the lab logic, the final version of our user interface is formed as shown in figure 4.4. In this interface, the motor works under speed control, and the generator works under torque control. Other relevant parameters, such as the armature current and voltage can be acquired from the communication network.

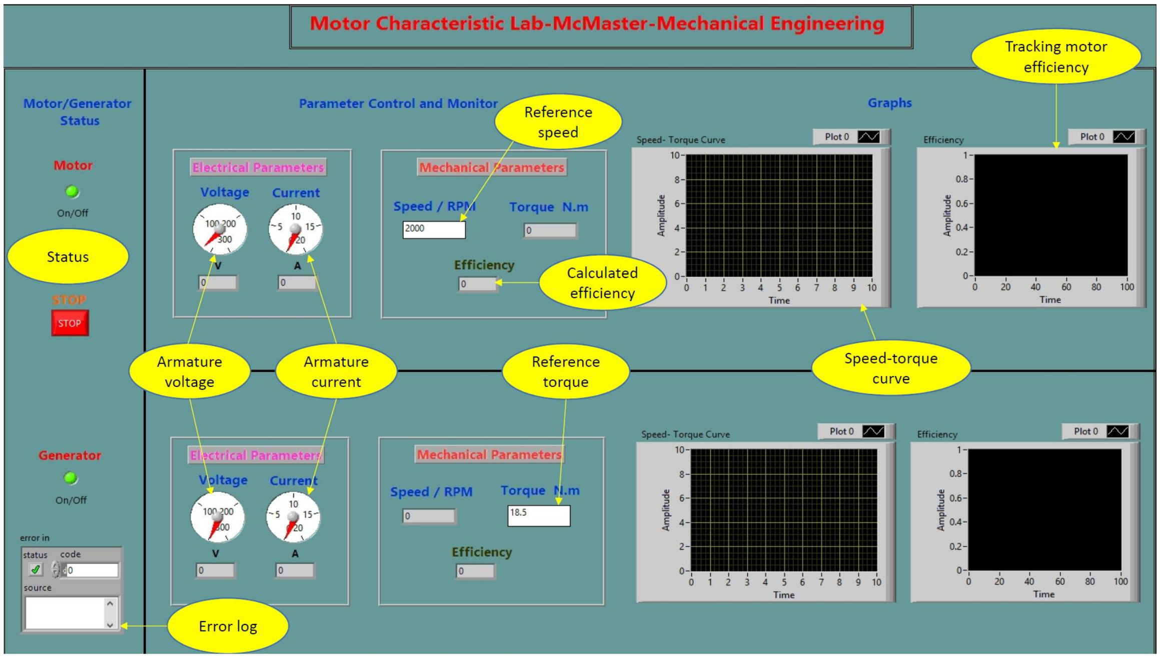

Figure 4.4: Motor lab user interface

Interface Descriptions

Following the design logic described in previous section, the lab's user interface provides three important parts:

1. **Motor and generator status checking.** In this motor lab, the motor acts as the traction motor, while the generator mimics the load requirement, as shown in figure 4.5. On the left side of the interface, the real-time on/off statuses of both the motor and generator are shown. Additionally, the emergent stop button is also applied just in case. On the bottom of the left side, any communication errors would be monitored to confirm the lab procedures would run well.

Figure 4.5: Motor lab mechanical installation

2. **Parameters control and monitoring.** In the middle part, relevant parameters for characterization tests are monitored. For both the motor and generator, input current and voltage are essential electric parameters, speed and torque are the two important mechanical parameters. Because the motor and generator are coupled together, the control methods for them are different. As suggested in the manual of the motor drive, the motor would be under speed control while there would be torque control for the generator. Furthermore, the efficiency would be calculated automatically and shown in the interface.

3. **Graphs for the lab.** On the right side, two graphs are shown for each of the electric machine. One is for monitoring the efficiency variation in real time. The other is used for demonstrating the motor speed-torque operating curve.

All these three compositions are utilized for implementing the pre-designed lab procedures which would be demonstrated in the next section.

4.4 Motor Lab Procedures

As described at the beginning of this chapter, three objectives need to be achieved in this motor lab. This section demonstrates the motor procedures, especially the main steps for each part. More details would be demonstrated in the Appendix.

4.4.1 Motor Speed-torque Characteristic

In order to achieve the motor speed-torque characteristic curve, several speed and torque levels would be tested. Seven steps should be implemented as follows:

(1) Check the status of power supply from the motor drives, confirm there is no error. If there is any fault or alarm, contact with the instructor and the lab technician.

(2) Open the lab interface in LabVIEW, make sure the motor and generator are ready to operate.

(3) Set a reference for the motor speed, for example, 500rpm at the beginning.

(4) After running the motor in this constant speed level, vary the reference torque for the generator from 2 to 20 N.m. At each torque level, run the system until reaching a stable status. To be noticed, when increasing the torque of the generator, the maximum torque for this speed level would be the critical value, for which the reference speed of the motor cannot be maintained.

(5) Change the generator torque to zero, and change the speed of the motor to the next level, such as 1000rpm.

(6) Repeat step 4 until the maximum torque value is reached at this speed level.

(7) Record all the maximum torque values for each speed level and draw the motor Torque-Speed characteristic curve shown in figure 4.2.

4.4.2 Motor Efficiency Map

Motor efficiency describes the relationship of mechanical power delivered and electrical power consumed. In this lab, the efficiency map can be achieved based on different speed and torque profiles. Six steps would be implemented as follows:

(1) Check the status of the system, confirm there is no error. If there is any fault or alarm, contact with the instructor and the lab technician.

(2) Run the operating points of the system at each paired speed-torque level.

(3) Record the input voltage and current of the motor.

(4) Calculate the motor efficiency based on equations(4.4) to (4.6).

(5) Record all the efficiency points.

(6) Draw the motor efficiency map as figure 4.6.

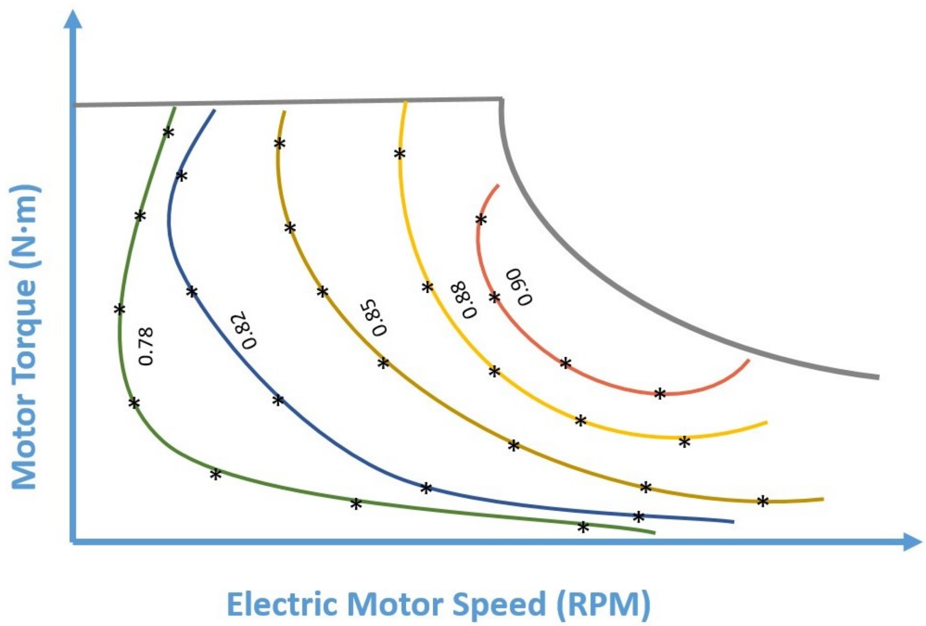

Figure 4.6: Electric motor efficiency map

4.4.3 Driving Cycle Simulation

After finishing the first two parts of the characterization tests, an analysis of motor performance would be done in the final part of the lab by simulating different driving cycles. The eight steps would be as follows:

(1) Choose a driving cycle for this experiment, such as US06.

(2) Calculate the load requirement with the above driving cycle.

(3) Run the system at the each paired speed-torque level for two seconds (the speed reference is from the motor, and the torque reference is from the generator which reflects the load requirement), and record the voltage and current of the motor, write down the efficiency from the interface.

(4) Draw the efficiency points of the motor in the map in the lab report.

(5) Calculate the electric power at each point.

(6) Sum up the consumed electric energy (E) using the following equation:

$$E = \sum \frac{2\pi n T}{60\eta} \frac{\Delta t}{1000 * 3600} \tag{4.7}$$

Where n is the motor speed in rpm; T is the output torque in N.m; η is the motor efficiency; $\Delta t = 2$ seconds; E is the electric energy in kWh.

(7) Calculate the final state of energy (SOE) which would automatically be shown in the updated interface, assume the initial value is 2 kWh:

$$SOE = \left(1 - \frac{E}{2}\right) * 100\% \tag{4.8}$$

(8) Change to another driving cycle and repeat step 1 to 7.

4.5 Summary

In this chapter, the three main objectives of the electric motor lab were discussed. The final version of user interface was presented and designed to satisfy the requirements for these tests. The motor lab procedures were listed.

Chapter 5

Motor Lab Hardware and Software Realization

The realization of the motor lab would be demonstrated in this chapter, both in terms of hardware and software. Not only the hardware integration, but also the communication method would be discussed in the following sections.

5.1 Motor Lab Architecture

5.1.1 Motor Lab Integration

The motor lab is an integral platform for the analysis and testing of electric motors. In addition to the mechanical components, the lab consists of electric connections, sensors, a communication system and a user interface, as shown in figure 5.1. Students are exposed to a multi-disciplinary concept, from which they can explore different disciplines apart from the traditional mechanical engineering.

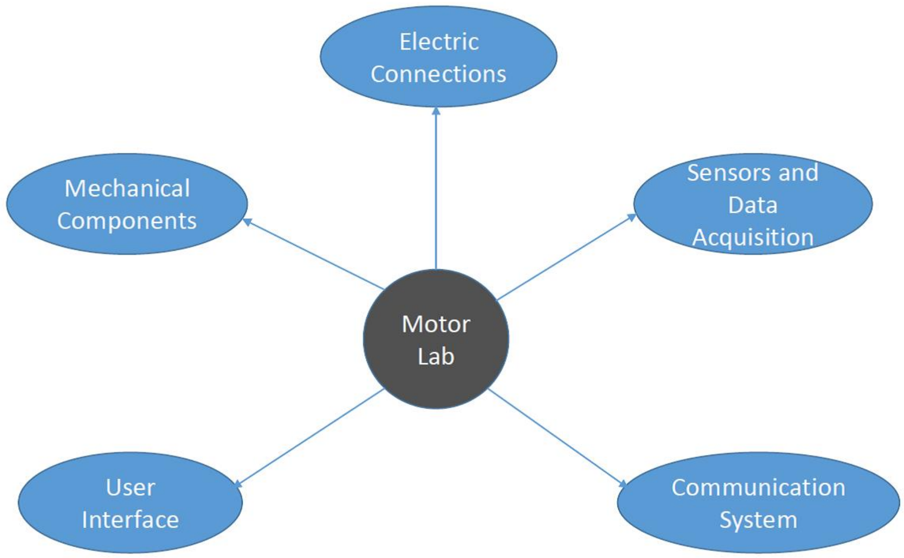

Figure 5.1: Motor lab integration

5.1.2 Motor Lab Architecture

Figure 5.2 shows the architecture of the motor lab, and how the motor and the generator operate by connecting the motor drives with the user interface.

When different elements are organized to obtain the objectives of the motor lab, both hardware and software are important. Installation and alignments of the motor and the generator, electric power supply, sensors for parameters feedback, and how to communicate with the user interface would be decided to confirm how this multi-disciplinary concept could work.

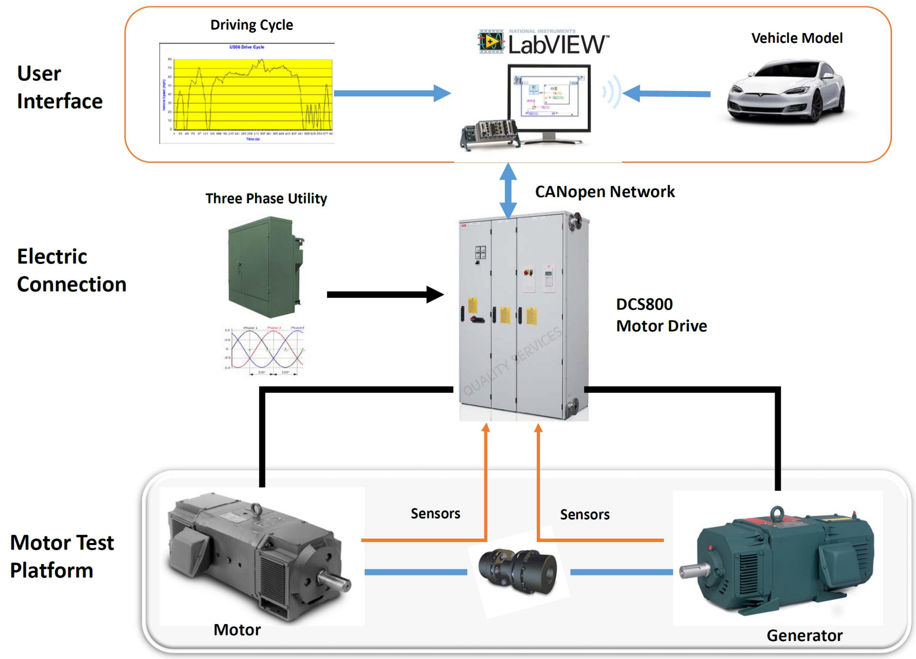

Figure 5.2: The architecture of the motor lab

5.2 Motor Lab Hardware Realization

In this section, the hardware realization that consists of four parts are described, namely: Mechanical installation of the motor and the generator, the electric connection in this lab, the sensors, and the communication network.

The Mechanical Installation

As shown in figure 4.6, the motor and the generator are coupled together with a pair of flexible couplings in our design. Because they are fastened on the floor, an important consideration is their alignment. The shaft axial height difference of them is 19.05 mm as shown in table 5.1, a metal gasket would be used to adjust the gap.

Table 5.1: Shaft axial height of the Baldor motor and generator

Component	**MOTOR**	**GENERATOR**	**Height difference**
Brand & SERIES/OEM	BALDOR RELIANCE SC2113ATZ	BALDOR RELIANCE C1812ATZ	**19.05mm**
Height of shaft center	**133.35mm(5.25”)**	**114.3mm(4.5”)**	

Electric Connection

The motor drives used for this lab are from ASEA Brown Boveri (ABB), and they are in line with the Electromagnetic Compatibility (EMC) guideline. Figure 5.3 provides details of the configuration for this power drive system. In this drive system, the input voltage should be around 400 Volts, the output voltage for the DC motor and generator is 230 Volts. The fuses are used for protecting the system from those over-current conditions, the current ratings are 125 A for AC lines and 80 A for DC lines. The line reactors are used for reducing most of the electrical harmonic, as they are inductors wired between a power source and a load. They can be used to filter out spikes of current and may also reduce injection of harmonic currents into the power supply. This is important as the converters used in ABB DCS800 drives provide for the four quadrant operation of these motors, the harmonic created by the regenerative braking process should be controlled.

Sensors

In the motor drive controller, feedback signals are provided. An encoder is embedded in the motor, which can be connected with the motor drive. The accuracy of

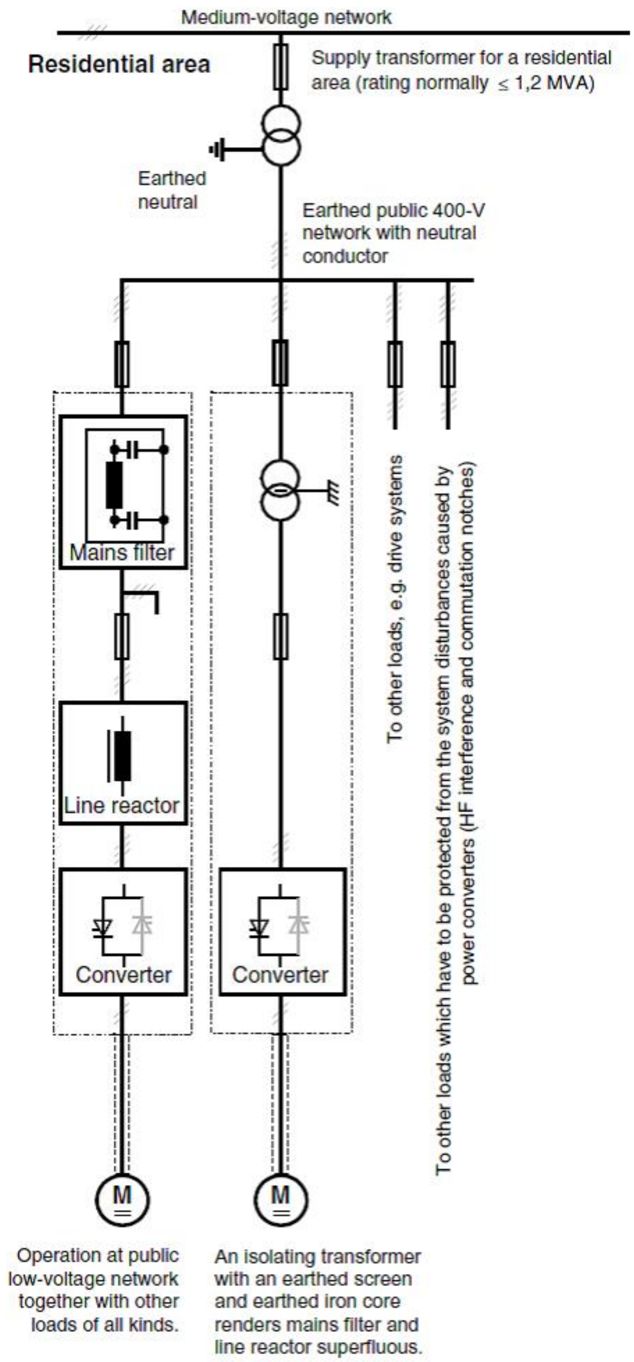

Figure 5.3: Configuration for ABB motor drive system [43]

speed resolution with the encoder is 0.005% of nominal Speed; for our system, this is translated to an average of around 0.15 rpm. The generator is under torque control, to avoid using expensive torque sensors, the torque signal would be provided by the motor drives directly. Other critical parameters, such as the current and voltage would be read from the drives.

Hardware for the Communication System

Another aspect of this lab would be the hardware for the communication system. Figure 5.4 presents the components used, which are also listed in table 5.2. National Instruments (NI) provides easy configuration solutions with their integral modules. In our system, CANopen network is chosen for communication. cRIO-9063 and NI 9881 are from NI, which can be connected with one ABB RCAN-01 module via a CAN cable. The breakout box is used for multi-nodes communication.

Table 5.2: Hardware used for communication system

Manufacturer	Description	Function	Quantity
National Instruments	cRIO-9063, 4-Slot Integrated Dual-Core Controller, Artix-7 FPGA	Embedded controller	**1**
	NI 9881, C Series CANopen Interface, 1 Port	Master port	**1**
	NI CAN Single Termination, High-Speed/FD Cable, 2m	Connection cable	**3**
	NI CAN Breakout Box 7-Port for CAN, DeviceNet, and CANOpen	Breakout Box for multi-nodes communication	**1**
ABB	RCAN-01 Module	Slave port	**2**

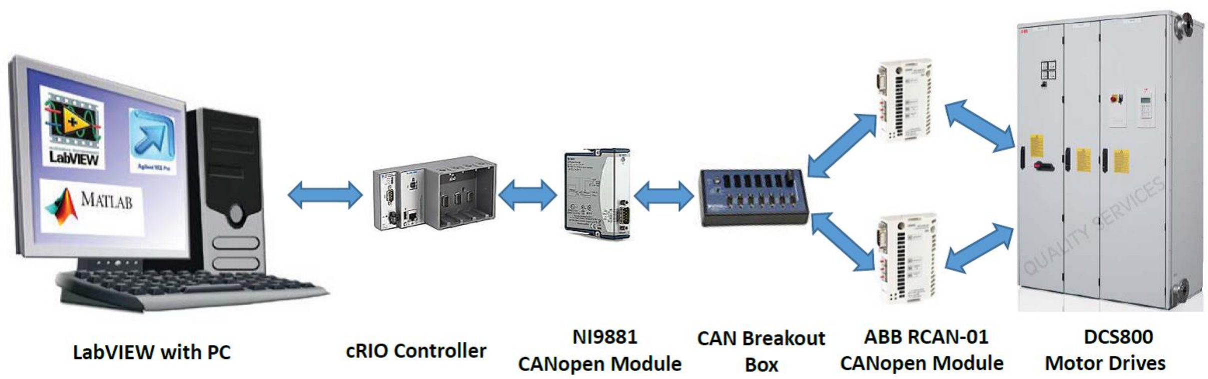

Figure 5.4: Motor lab communication system

5.3 Motor Lab Software Realization

Communication with LabVIEW is another important aspect of this lab. According to the firmware manual of ABB DCS800 motor drives, different communication methods can be used in this system, such as CANopen, Ethernet, DeviceNet, ControlNet, etc. In our lab, CANopen network is selected for its simple integration capability, RCAN-01 module is integrated with DCS800 motor drives.

CANopen is a CAN-based communication system. It comprises higher-layer protocols and device profile specifications. CANopen has been developed as a standardized embedded network with highly flexible configuration capabilities. The CANopen umbrella covers a network programming framework, device descriptions, interface definitions and application profiles. Today it has been used in a wide range of industries, including automation and motion applications [41]. CANopen provides a protocol which standardizes communication between devices and applications from different manufacturers. In our application, the Compact-RIO 9063 and NI 9881 CANopen interface from National Instruments are used to connect with DCS800 via RCAN-01 module.

Inside the CANopen data frame, different types of Communication Objects are used to convey the data. Process Data Objects (PDO) are used for transmitting time critical process data (references, control commands, status information); Service Data Objects (SDO) are used for less time critical data, e.g. parameters. In addition, there are Special Function Objects and Network Management Objects (NMT) [42]. Figure 5.5 shows the protocol stack flowchart of CANopen. Each new message is executed based on the message type and priority.

Service Data Objects (SDO)

The SDO protocol is used for setting and for reading values from the object dictionary of a remote device. The device whose object dictionary is accessed is the SDO server and the device accessing the remote device is the SDO client. The communication is always initiated by the SDO client. A SDO parameter set contains two communication object identifiers (COB-IDs) and the node-ID of the related communication partner. The COB-ID entries cover the CAN-Identifiers of the CAN frames used to transmit information in the direction "server to client" and vice versa [44].

Process Data Objects (PDO)

Process data represents data that can be changing in time, such as the inputs (i.e. sensors) and outputs (i.e. motor drives) of the node controller. Process data is also

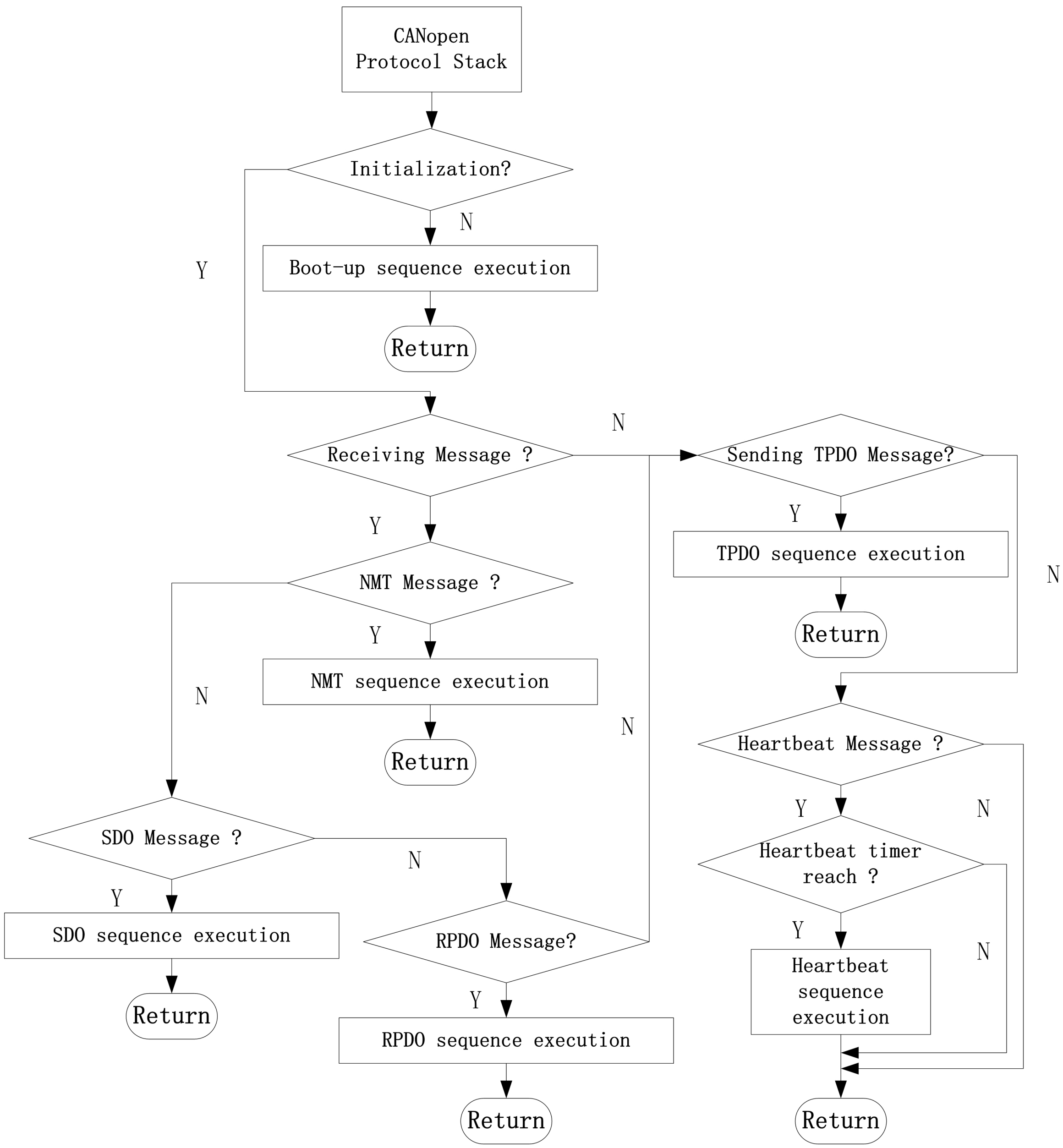

Figure 5.5: Protocol stack flowchart of CANopen

stored in the object dictionary. PDOs are used in CANopen for broadcasting high-priority control and status information. There are two kinds of PDOs: transmit and receive PDOs (TPDO and RPDO). The former is for data coming from the device (data producer) and the latter is for data going to the device (data consumer) [44].

Boot-up Sequence

The RCAN-01 supports the boot-up sequence of a “Minimum Capability Device”, as defined by the CANopen Communication Profile. The boot-up state diagram of the RCAN-01 is shown as figure 5.6 [44]. Four main states are initialisation, pre-operational, prepared and operational. After being successfully initialized, the other three states can be switched to from one another. The pre-operational state is primarily used for the configuration of CANopen devices. In operational state, the transmission of PDOs is possible. The prepared state (also known as stopped state), is only active for NMT services, a node cannot transmit or receive any other messages in this state.

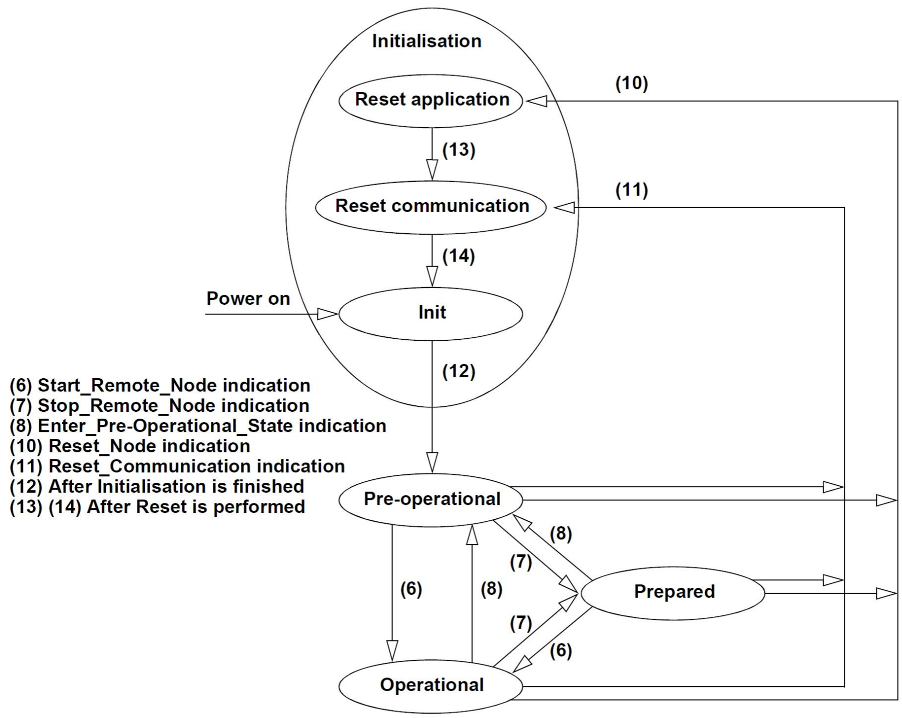

Figure 5.6: Boot-up Sequence [45]

5.3.1 Communication Realization

From LabVIEW, the integrated CANopen library provides basic tools that can be used to build CANopen network with DCS800. After configuring all the parameters of DCS800, some parameters need to be set regarding to CANopen network guides, such as baud rate, node address. Then status of DCS800 will be confirmed, and SDOs and PDOs are ready to communicate with LabVIEW. The user defined parameters are sent to the motor drives to operate the motor and generator, and parameters can be received from PDOs. The details of the communication realization are shown in figure 5.7.

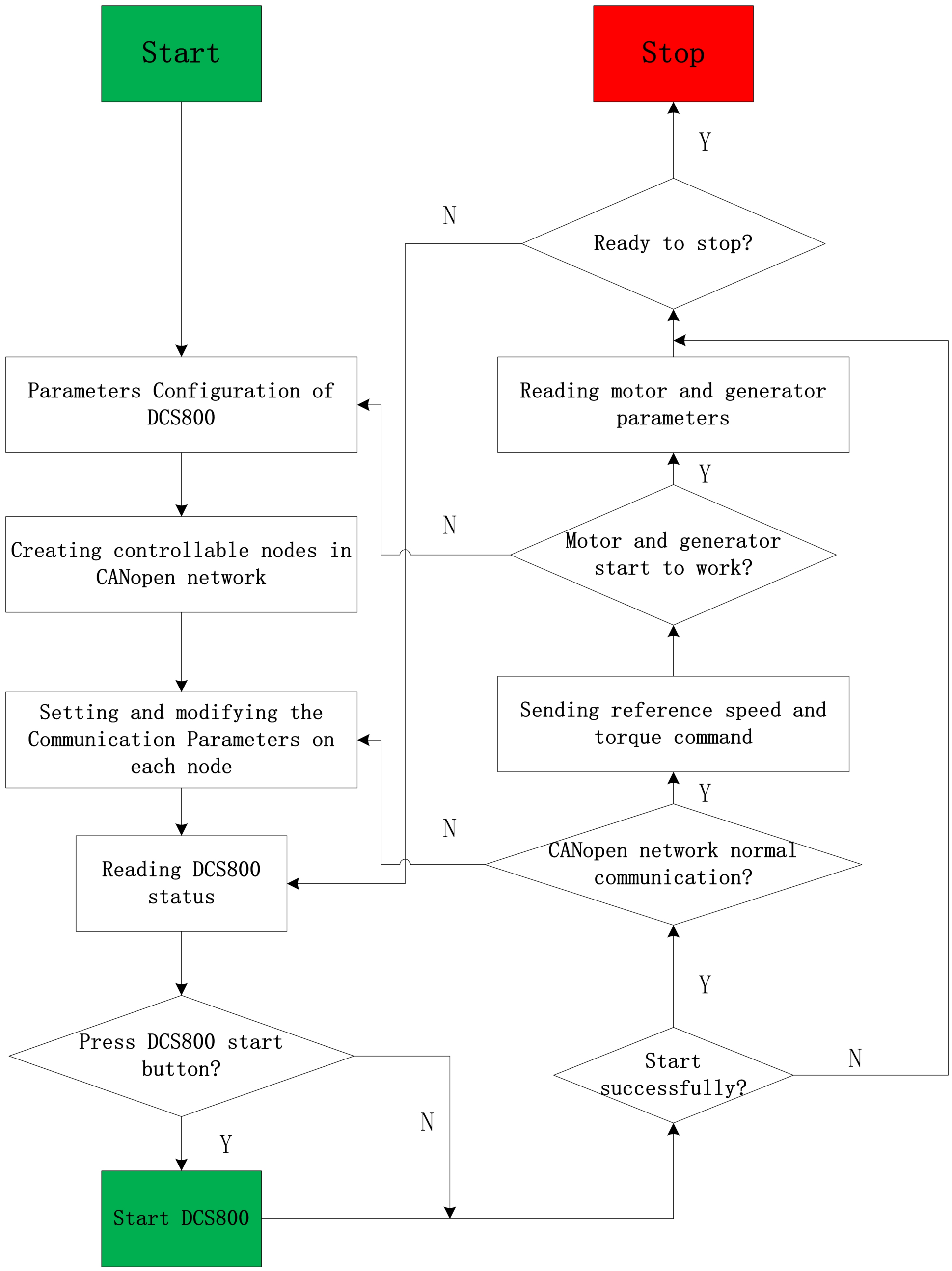

Figure 5.7: Software realization diagram

5.4 Summary

Both the motor lab's hardware and software realization were presented in this chapter. The motor lab architecture was briefly introduced at first, then the components used for configuring the motor lab were demonstrated. Finally the communication realization based on CANopen network was carefully explained. Understanding the motor lab will provide us a big step to approach the final hybrid lab.

Chapter 6

Hybrid Powertrain Lab Design

The electric motor lab is an integrated element of a broader Hybrid Electric Vehicle (HEV) teaching lab. This chapter presents the design details of the HEV teaching lab, including the components selection. The layout of the entire HEV teaching lab is presented in this chapter.

6.1 Design Considerations

Based on our objectives for this educational lab, specific requirements from stakeholders and associated constraints should be taken into account. This section will consider: definition, constraints, benefits, and advantages related to the lab.

Definition

This is an undergraduate lab that can be used for teaching mechanical engineering students the concepts and ideas of HEVs, making them aware of the integrated architecture of different hybrid powertrain realizations and operating modes.

It is important to consider the users' background, and the benefits they would gain from the lab. This lab is intended for mechanical students who have little knowledge of hybrid vehicles. Our lab would be a tool to guide them in this area and expand their knowledge of hybrid powertrains. At the same time, it needs to be practical and hands-on.

The lab needs to consider the various forms of hybrid architectures. Students would need to have the opportunity to simulate the functions of different hybrid architectures and explore concepts related to the vehicle system modeling, optimization, and control. The lab would be a platform for demonstrating the basic operating principals and energy conversion processes of hybrid vehicles.

The operation and maintenance of the lab are other important considerations in our design.

Constraints

The scope, cost and other relevant constraints need to be considered for a successful project. It should be noted that this lab uses existing equipment purchased before the start of this project as follows (Figure 6.1):

- Kubota Internal Combustion Engine.
- Electric generator and drive. (As described in Chapter 5)
- Two electric traction motors and drive systems. (As described in Chapter 5)

All the equipment have to be used in our design due to cost considerations.

Safety is always of primary concern. To educate undergraduate students, safety

Figure 6.1: Equipment Purchased

needs to be guaranteed. Given the compositions and components in a hybrid powertrain, energy storage devices would present a potential risk and are bypassed in this lab. This is because of the potential instability of chemical reactions in batteries.

Benefits and Advantages

The benefits and advantages brought by this project are discussed here, as follows.

- **Reliability.** This hybrid lab assists teaching of mechanical students. The lab uses reliable components to enable long term usability and minimize maintenance activities.

- **Flexibility.** Based on the current design, there is flexibility in lab functionality and future expansion. The lab can be split into an electrical motor test lab, an engine lab, or a complete hybrid powertrain lab in an integrated form.

- **Safety.** Safety is critical. Without the use of batteries, the risk of monitoring unstable conditions of battery management system can be eliminated. Furthermore, the user interface allows the students to remotely control the motors and monitor the system.

- **Simplicity.** Using bevel gearboxes and a continuously variable transmission (CVT) rather than other components can make the whole system more compact and straightforward. Our focus is on the hybrid functions; this lab is also an ideal platform to allow students to quickly acquire basic knowledge of different hybrid configurations and control strategies.

Our design benefits from these considerations as shown in the following sections.

6.2 Comparison of Potential Design Options and Different Configuration Solutions

The lab would enable the demonstration of the three most popular architectures. The control strategy can realize switching from different architectures. In this section, three proposed design solutions are considered and their advantages and disadvantages discussed.

6.2.1 Solution 1 - Using Planetary Gear Sets

Toyota Prius is well known and is the first mass-produced hybrid vehicle model, sold all around the world. It is famous for using the unique electronically controlled continuously variable transmission (eCVT), in which the power split device is the central part. So in this solution, Prius is used as a reference model.

The hybrid powertrain of Toyota Prius uses the series-parallel architecture as discussed in Chapter 2.The Prius hybrid system components include the following:

- A hybrid transaxle, consisting of two Motor/Generators (MG1 and MG2), and a planetary gear set.
- 1NZ-FXE engine (1.5L version).
- Inverter and converter assemblies.
- High-voltage Battery pack.
- Regenerative braking system.
- Hybrid vehicle electronic control system.

Generally, in hybrid vehicles, mechanical coupling consists of torque coupling and speed coupling. In torque coupling, the mechanical coupler adds the torques of the engine and the motors together and delivers the total torques to the driven wheels. The engine and motor torque can be independently controlled. But the speeds of the engine, the motors, and the vehicle are linked together and cannot be independently controlled. Similarly, in speed coupling the speeds of the engine and the motors can be added together and all the torques are linked together, and cannot be independently controlled. By combining torque and speed coupling, one may establish a hybrid drive train in which both torque- and speed-coupling states can be alternately chosen [3].

This drive train is schematically illustrated in Figure 6.2. The drive train uses a planetary gear unit as the speed-coupling device and a set of fixed axle gears as the torque-coupling device. The ICE is connected to the planetary carrier, and MG1 is connected to the sun gear to constitute the speed-coupling configuration. The ring gear and MG2 constitute the torque-coupling configuration through the axle-fixed gear.

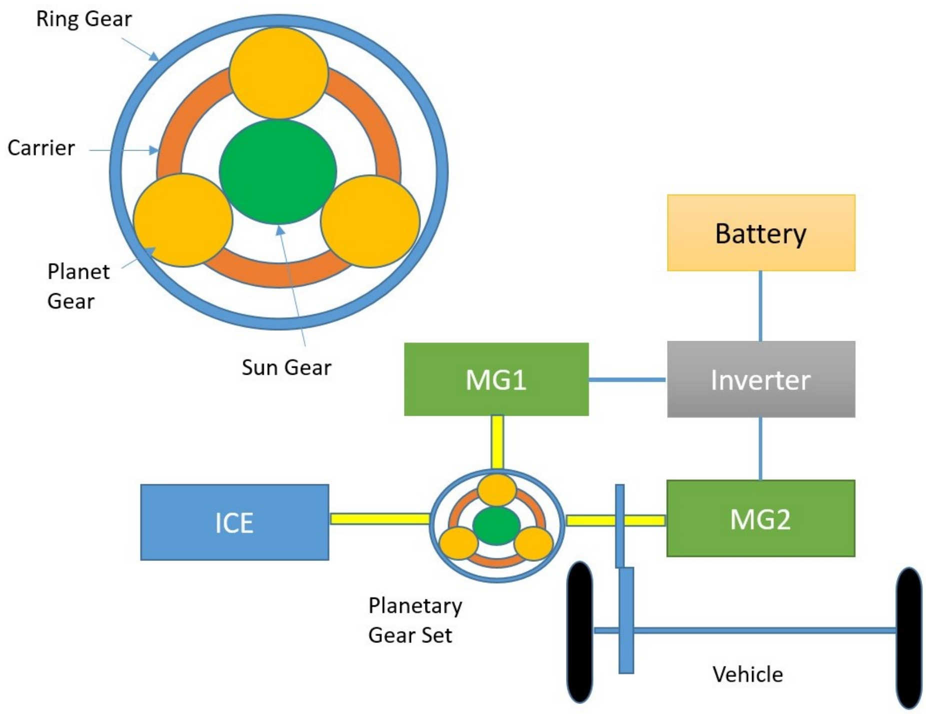

Figure 6.2: Toyota Prius Drive train

Proposed Solution

Further to the above details, the structure can be simplified by using a planetary gear set as the primary transmission for the whole system. The set-up is designed to allow maximum operational flexibility by utilizing three clutches, which can also realize multi-modes switching. Figure 6.3 shows the whole architecture that would be capable to include a physical simulation of the Prius powertrain functionality.

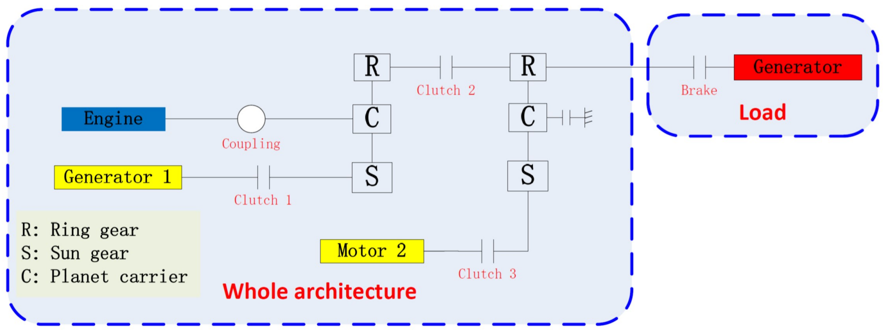

Figure 6.3: Solution 1 architecture

Hybrid Mode Realizations

This solution is designed to enable demonstration of either pure series, pure parallel, or a power-split architecture by using a different combination of clutch engagements. The different configurations are as follows:

1. ***Pure series hybrid:*** With the clutch 1 and 3 (C1 and C3) engaged and clutch 2 (C2) disengaged, the internal combustion engine (ICE) can drive the motor 1 (M1) to generate electricity. At the same time, motor 2 (M2) can be used as the traction motor which will match the requirement of the load from the generator (G).

2. ***Pure parallel hybrid:*** With C2 and C3 engaged and C1 disengaged, both ICE and M2 can be combined to drive the load G.

3. ***Power split hybrid:*** With all the clutches (C1, C2 and C3) engaged, the planetary gear set splits ICE power into a mechanical path and an electric path. Partial power can be used by M1 to generate electricity; the other part

can transmit to the output and be combined with M2 to drive the required load from G.

Advantages VS. Disadvantages

This architecture can satisfy most of the expected educational objectives as expected. The associated benefits are as follows:

1. **Similarity.** This architecture is similar to the commercial hybrid vehicle powertrains. It intuitively shows the key components of HEVs. This makes it easily understandable to students while demonstrating advancements in hybrid technology.

2. **Flexibility.** Two planetary gear sets can provide more freedom to configure different hybrids. The speed and torque control can be decoupled from both of these planetary gear sets.

The disadvantages are:

1. **Redesign of the planetary system.** Because almost all commercial planetary gear sets are designed as reducers with the ring gears fixed, it is impossible to introduce a standardized planetary gear set which can be purchased and utilized directly in our design. Besides, when redesigning the non-standardized components, the lubrication system, bearings and support should also be taken into consideration.

2. **System Complexity.** The Prius powertrain is designed to be compact, this would make our educational lab more complex to mimic its hybrid functionality, especially when three motors and one ICE need to be integrated.

3. **Cost.** Designing and manufacturing non-standardized components increases the total cost. For our project, this design is not an optimal choice.

6.2.2 Solution 2 - Using Continuously Variable Transmission (CVT) and Belt Drive

To avoid the problems associated with the first solution, the main idea of using belt drives along with a CVT is to simplify the whole system without changing the expected functionalities.

CVTs have aroused lots of interest in the automotive sector due to the potential for lower emissions and better performance. A CVT is a transmission that operates on an ingenious pulley system that automatically varies the transmission ratio, allowing an infinite variability between highest and lowest gears with no discrete steps or shifts. Today, CVTs are aggressively competing with automatic transmissions and several different models are in production vehicles. A continuously variable transmission is also a promising powertrain technology for hybrid vehicles.

Principle Elements of a CVT includes [46]:

Primary clutch. It is an advanced form of centrifugal clutch and is typically mounted to the output end of the engine crankshaft. The clutch has two sheave faces; one that is laterally fixed (stationary sheave), and one that can move in and out to engage the belt (moveable sheave).

Secondary clutch. It is mounted to the input shaft of the transmission, transaxle, or the like. In modern CVT systems such as those used in recreational vehicles, the secondary clutch has two functions; as a "slave" to the primary clutch and to provide a torque sensing element.

Belt. The belt in most CVT systems is a heavy duty "V-belt" which is V-shaped in cross section. They are made of rubber components reinforced with Kevlar and other materials to enhance durability.

Figure 6.4 shows how a CVT works. The drive clutch (1) is activated by centrifugal forces from the input. The moveable sheave of the clutch is forced in with increased speed. This contacts the drive belt (2). The drive belt will then be forced to a larger diameter within the clutch sheaves, thus pulling it to a smaller diameter within the driven unit (3) sheaves. The moveable sheave of the driven unit is (3) forced out, as shown, allowing the belt to seek its smaller, high-speed ratio diameter. As this happens, the speed from the input transferred to the final drive is increased. The system is infinitely variable between low and high ends [47].

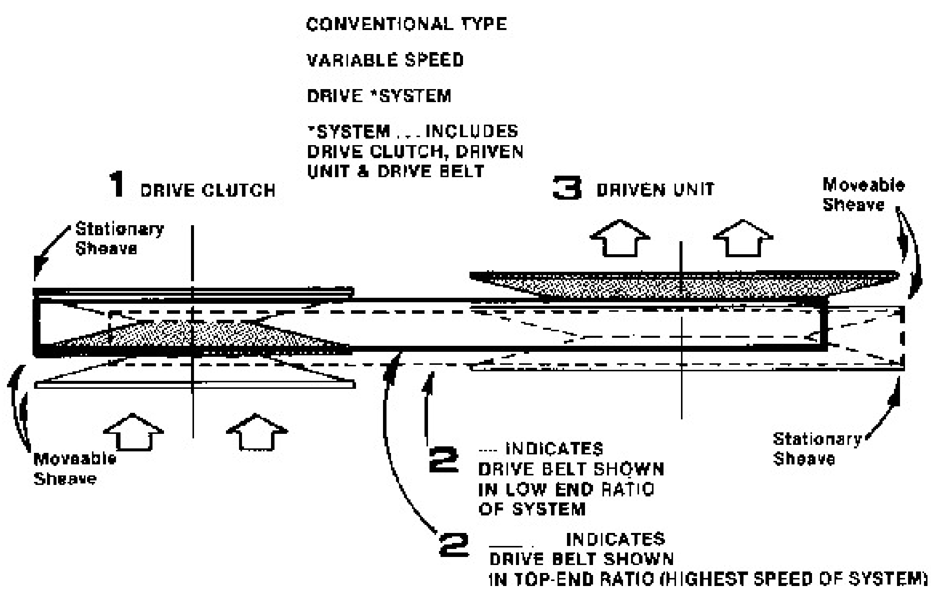

Figure 6.4: How a CVT works [47]

Proposed Solution

In a hybrid system, total energy efficiency can be improved by decoupling the ICE with the final drive which allows the engine to run in a narrow and more efficient range. The performance can be enhanced by coupling the energy efficient motors which can provide the additional power source. These principles motivate another solution. The key concept is that the CVT makes the engine speed free from the final drive, the belt drive forms a torque coupler. The set-up configuration is presented as shown in Figure 6.5.

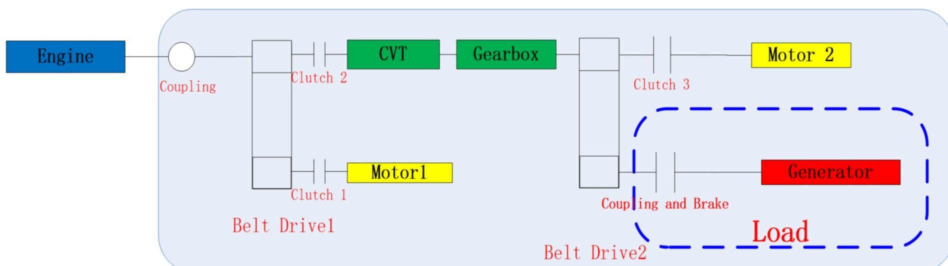

Figure 6.5: Solution 2 architecture

Hybrid Mode Realizations

All the three hybrid modes can still be simulated through this architecture. All the three clutches can be made to function as switches for different modes.

1. ***Pure series hybrid:*** With the clutch 1 and 3(C1 and C3) engaged and clutch 2(C2) disengaged.

2. ***Pure parallel hybrid:*** With C2 and C3 engaged and C1 disengaged.

3. ***Power split hybrid:*** With all the clutches (C1, C2 and C3) engaged, the last belt drive tries to imitate the 1:1 gear ratio, so the output can be connected directly via CVT with M2.

Advantages VS. Disadvantages

This design can still provide all the three hybrid modes, but the structure is much simpler. Also based on the system requirements, direct selections of all the components from suppliers are possible. Additionally, upgrading the engine for the lab can be accommodated by simply coupling the new engine in the loop. On the other hand, this architecture relies on two belt drives, which will increase periodic maintenance activities. Furthermore, the belt drives require larger space.

6.2.3 Solution 3 - Using CVT and a Bevel Gearbox

Keeping the advantages brought by CVT and avoiding the problems with belt drives, our final architecture design contains the CVT and two bevel gearboxes. The whole configuration is shown in Figure 6.6. All the three hybrid modes can be switched in this solution by engaging different clutches.

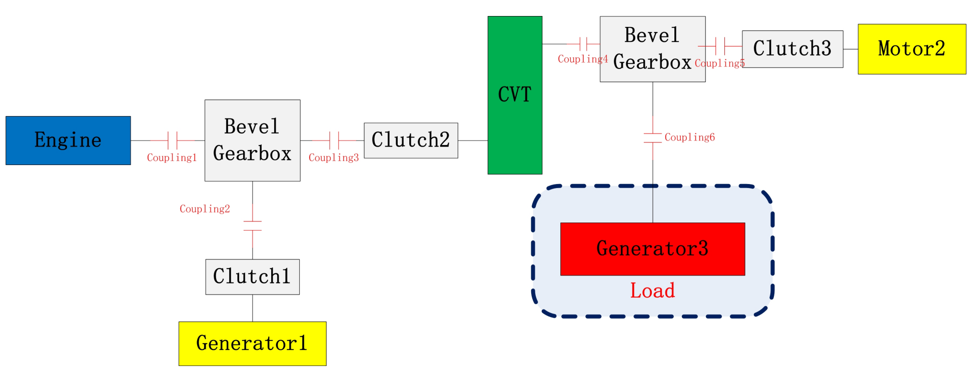

Figure 6.6: Solution 3 architecture

Hybrid Mode Realizations

This architecture can still achieve the three hybrid modes. These configurations are as follows:

1. ***Pure series hybrid:*** With the clutch 1 and 3(C1 and C3) engaged and clutch 2(C2) disengaged. The ICE drives generator 1, and motor 2 works as the traction motor to drive the load.

2. ***Pure parallel hybrid:*** With C2 and C3 engaged and C1 disengaged. Both the ICE and motor 2 provide traction torque to the final load.

3. ***Power-split hybrid:*** With all the clutches (C1, C2 and C3) engaged, partial power of the ICE can be used for generator 1, the other portion would drive the load with motor 2.

Improvement

Compared with solution 2, the novelty of the design and the major improvements are as follows:

- In this design, the additional generator provides the ability of input power-split, which can allow the engine to operate at a narrow high-efficiency region, thus higher energy efficiency and lower vehicle emission can be achieved.

- Instead of using a belt drive, the bevel gearbox acts as the torque coupler. It is more durable and reliable than a traditional belt drive. Fewer adjustments and periodic maintenance are needed for daily operation.

- The whole system should be more compact. This can also improve safety as it allows more enclosures to prevent exposure of students to rotational components.
- After looking over the speed range of the ICE and the motors, there is no need to keep the fixed ratio gearbox.

This design is chosen for the laboratory. Component selections of this design are provided next.

6.3 Component Selections

Selection of components is one of the most critical activities in the design cycle for any system. Different aspects should be taken into consideration during the selection process. Current approaches for addressing component selection are mainly driven by system requirements that depend directly on the attributes of the individual components. The goal is to select every component satisfying a set of given system requirements.

The parameters to be considered for component selection can be broadly classified as technical parameters and non-technical parameters. Here non-technical parameters involve the total cost of these components, reliability, and delivery time requirements.

At the beginning understanding and prioritizing the requirements is an essential step. For most types of components, there are scores of choices from different vendors that could potentially be used. The designer has the responsibility to go through all the options and choose the one that is right for the system. Once the components are selected, it is important to list all their features and check the interfacing requirements for each of them.

The review process is important since the project has many different stakeholders who may claim different concerns. If necessary, a more thorough evaluation can be done to check most of the technical parameters and non-technical parameters match the operating conditions of the system, and other factors, such as the total cost, also meet the stakeholders' requirements.

In our lab design, the components selection is confined to match the operating conditions of pre-existing equipment (one ICE, and three DC motors). The CVT, bevel gearbox and the clutches should be chosen accordingly. Tables 6.1 and 6.2 below list the parameters of the engine and motors which are critical for other components.

Table 6.1: Engine Parameters

Model		**EA330-E4-NB1**
Type		Horizontal 4-cycle liquid cooled Diesel
Maximum Speed	rpm	3000
Maximum Torque	N.m	17.7
Output:	kW	5.15
Net Intermittent	hp	6.9
Shaft diameter	in	1.875

Table 6.2: Motor Parameters

Model Frame		**C1812ATZ**	**SC2113ATZ**
Type		STRAIGHT SHUNT	STRAIGHT SHUNT
Base Speed	rpm	3000	3000
Maximum Safe Speed		3500	4500
Maximum Toruqe Output	N.m	48.13	26.98
Rating	kW	10	5
	hp	13.4	7.5
Shaft Diameter	in	1.375	1.875

6.3.1 CVT

The CVT in this system connects the ICE and motors; the variable transmission ratio can automatically match the speed of the engine properly with the final load without shifts.

For CVT, there are two factors which are essential:

- Speed range. The Kubota engine has a maximum speed of 3000 rpm, and the motors have the same base speed, 3000rpm.
- Horse power. Hybrid output relies on the input power of the engine and the motor; the CVT is connected with the 5 kW engine.

Selection Result

Further to review of components from different vendors, the final choice is a Comet 700 Series CVT. The table and figure below provide more details.

Comet 700 Series CVT		
Specifications	**Features**	**Applications**
Diameter: 7-1/4"	Adjustable	Go-Karts
Actuation: 3-roller Cams	Tunable	Industrial Equipment
Calibration: Spring Ramp	Reliable	Light Utility Vehicle
Bore: 1"	Wide Ratio	
Power: 2 cycle 4 cycle	18.64 kW 11.93 kW	
Engagement speed (RPM):	800 - 4000	

Table 6.3: Comet CVT Parameters

Figure 6.7: Comet CVT

6.3.2 Bevel Gearbox

Bevel gearbox acts as the torque coupler, both from the input and output side in our hybrid architecture. For the bevel gearbox, there are three factors which are critical:

- Speed range and ratio. The Kubota engine has a maximum speed of 3000 rpm, and the motors have the same base speed, 3000rpm. Obviously, the gear ratio should be a 1:1 to match each component. The maximum speed should not be under 3000 rpm.

- Power Rating. The minimum requirement should be 10 kW, which is the maximum power of the motor used in our design.

- Torque. According to the operating conditions, such as the daily operation time and the start-up numbers, a conservative operation safety factor would be considered. In our design, 2.0 can be chosen as the safety factor, and the minimum rating torque should be 96.26 N.m, which is twice that of the load motor.

Selection Result

The 100 Series gearbox from SUPERIOR GEARBOX COMPANY is a good choice; the specific details are shown in the table 6.4 and the figure 6.8 below.

6.3.3 Clutches

The procedure for choosing clutches are as follows:

1. Determine the frame size, horsepower, and speed at the module.

Model 100Series		**SUPERIOR GEARBOX**
Gear Design		21,21 Forged Straight Bevel
Gear Ratio		1:1
Maximum Speed	rpm	3000
Output Torque	N.m	129
	inch-lbs	1140
Input Power	kW	40.48
	hp	54.28
Shaft diameter	in	1

Table 6.4: Bevel Gearbox Parameters

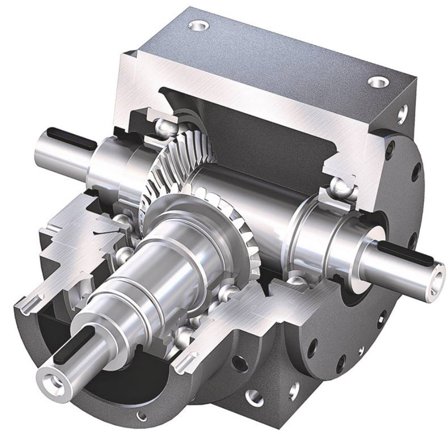

Figure 6.8: Bevel Gearbox

2. Choose proper module size based on motor frame size or motor power and operating speed.

3. Check to ensure the max allowable cycles per minute rating is not exceeded by consulting charts in the engineering/technical section.

To totally isolate each of the energy source components during the experiment, five clutches are involved in the final architecture. There are two types as listed in table 6.5.

Table 6.5: Clutches Types

NO.	**Brand**	**Type**	**Bore/shaft size (inch)**	**Static Torque**	**Quantity**
1	**BALDOR DODGE**	BSL-42	1	28.25 N.m	2
2	**WARNER ELECTRIC**	EP-825	1.125	169.48 N.m	3

6.3.4 Whole Architecture

After integrating all the components, Figure 6.9 presents the final architecture. The novelty of this design is that a range of functionalities related to existing hybrid powertrain can be simulated with this architecture, enabling both torque and speed enhancement to the internal combustion engine. This enable the ICE to be operated in its peak efficiency region. The lab architecture also ensures safety by simulating energy storage, rather than implementing batteries in the system.

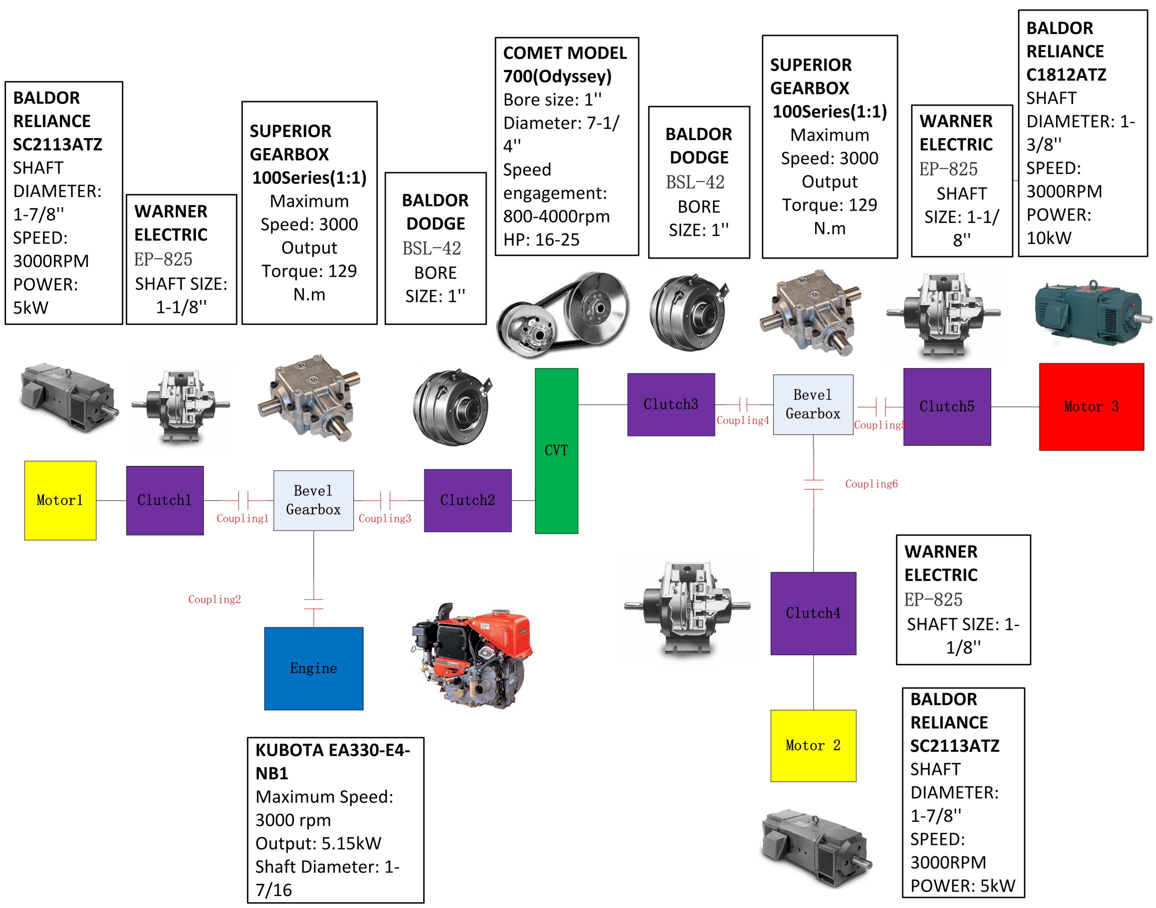

Figure 6.9: Whole Architecture of the Lab

6.4 Layout Consideration

The layout of the lab is expected to be designed before the actual installation of machinery. Before any specific considerations and decisions can be made a general appreciation should be obtained by conducting a thorough investigation and examination of the equipment specification, and space requirements for each item. The basic theme behind the layout arrangement is to minimize the space, and to provide a safe and proper physical environment for students equipped with enclosures to prevent exposure to rotational components.

6.4.1 Layout Principles

There are several principles to follow for getting a good system layout [48]. These are:

Integration and minimum movement. A good layout is to integrate all the equipment in a better way which requires less movement in the future. All the specifications, such as the operating marginal space and shaft arrangements should be carefully taken into account.

Efficient use of available space. Comparison between different layout arrangements should be made to confirm utilizing less space in three dimensions, horizontal, vertical and height.

Maximum visibility and accessibility. The hybrid lab is a platform to show all the components of the hybrid system. The equipment should be placed in a visible and accessible way to make students quickly understand the operating mechanism of the system. Also, maintenance activity could be performed easily.

Safety. As explained in the first section, safety is always the primary concern. Risk must be eliminated for educating undergraduate students. A good layout is an important element for ensuring safety and security.

Maximum flexibility. A proper layout that is a good spatial system should be one that is adaptable or flexible enough to take care of likely future changes.

6.4.2 Layout of the Lab

Motors, engines, and gearboxes are all rotational equipment. The alignments of each component would significantly affect the vibration and operating performance of the whole system. The axial heights of all the components are listed in Table 6.6. The integrated system requires a minimum space - height of 133.35mm, and then requires the adjustment of all components to match this axial reference height (133.35mm).

Table 6.6: Shaft Axial Height of each Component

Item NO.	**1**	**2**	**3**	**4**
Component	**ICE**	**Bevel gearbox**	**Clutch**	**CVT**
Series/OEM	KUBOTA EA330-E4-NB1	SUPERIOR GEARBOX 100Series	DODGE BSL-42	COMET MODEL 700
Shaft/Bore Size	Shaft Diameter: 1-7/16	Shaft Diameter: 1	Bore Size: 1	Bore Size: 1
Height of shaft center	**125mm**	**45.97mm (1.81")**	**50.99mm (4.015"/2)**	**91.75mm (3.6125")**
Item NO.	**5**	**6**	**7**	**8**
Component	**Bevel gearbox**	**Clutch**	**Motor**	**Motor**
Brand & SERIES/OEM	SUPERIOR GEARBOX 100Series	WARNER ELECTRIC EP825	BALDOR RELIANCE SC2113ATZ	BALDOR RELIANCE C1812ATZ
Parameters (inch)	Shaft Diameter: 1	Bore Size: 1-1/8	Shaft Diameter: 1-7/8	Shaft Diameter: 1-3/8
Height of shaft center	**45.97mm (1.81")**	**133.35mm (5.25")**	**133.35mm (5.25")**	**114.3mm (4.5")**

The top view of the lab in the figure shows the integration logic of all the components.

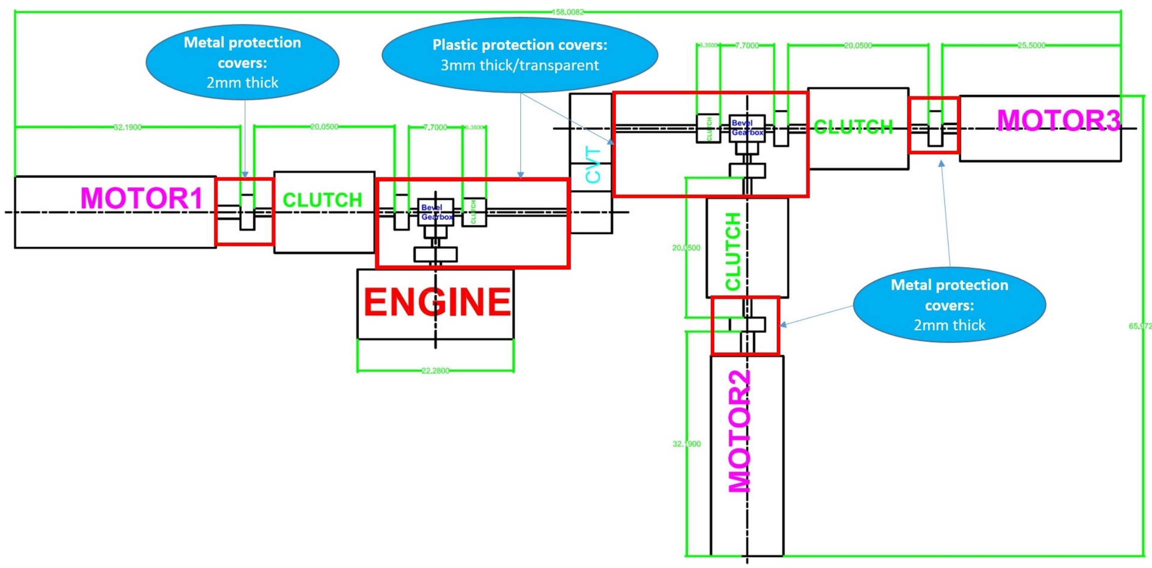

Figure 6.10: Layout of the lab

This layout prevents students being exposed to rotational components in this lab, 2 mm metal protection covers are installed for the motors' couplings, and 3 mm plastic and transparent covers are utilized for the gearboxes. Most of the components are arranged on one side near the wall, this can avoid less risk exposures to the students and ensure safer operations. In addition, it is helpful for the installation of pipes and wires, such as the path for engine exhausts.

6.5 Summary

In this chapter, system design considerations, such as the definition of the lab, constraints, benefits, and advantages have been discussed for three lab configurations. A lab architecture that uses a combination of a CVT and a bevel gearbox has been proposed. Component selections have been made to show the integrated architecture of our hybrid lab. Finally, a layout for the lab has been proposed.

Chapter 7

Hybrid Lab Modeling and Simulation

The hybrid lab has been explained in the previous chapter. Before operating our physical lab, the safe and efficient way is to build a simplified simulation model, analyze the system capability, and implement energy management and control strategies to the proposed architecture. Details of all these topics will be discussed in this chapter, complemented by some simulation results.

7.1 Energy Management Strategies for HEVs

Energy analysis is essential to understanding why HEVs are beneficial from the efficiency point of view and to design and assess energy management strategies appropriately. In HEVs, the total power demand is satisfied by summing together the outputs of the engine and the electric paths. The ratio between the paths provides the freedom which permits optimization strategies to improve the total efficiency and fuel economy. Additionally, the regenerative braking system can replace the conventional mechanical brakes, and capture some of the mechanical energy to store in batteries. This characteristic of HEVs can substantially increase the overall efficiency over a long running period.

Energy management in hybrid vehicles pertains to deciding the amount of power delivered at each instant by the energy sources present in the vehicle while meeting several constraints. The power management strategy can implement braking energy recovery, energy storage and thereby impact the total fuel economy benefits over a long term.

7.1.1 Objective of Energy Management in HEVs

The objective of energy management is to satisfy the performance requirements (acceleration, deceleration, start, stop, etc.), achieve high overall efficiency whenever possible by minimizing the vehicle fuel consumption and recovering brake energy, while maintaining the battery state of charge around the desired value.

The energy management control strategy is the strategy for the vehicle controller, which is used to distribute the desire drive power to make each component work in their most efficient ranges with different operating patterns. The overall control strategy consists of the vehicle controller, engine controller, electric motor controller, and mechanical brake controller. Only the vehicle controller is at the top level (see Figure 7.1), which plays a critical role in the operation of HEVs. It collects data from all subsystems, such as the desired torque, speed of the vehicle, engine and motor speed, state of charge (SOC) of the battery pack, and so on. Based on these data, along with the component efficiency characteristics, an optimized control strategy can be realized, giving control signals to the subsystem controllers. Each subsystem controller then regulates the operation of its corresponding components to meet the performance requirement of the total vehicle. The energy management strategy in HEVs is the key to the success of the drive train operation [3].

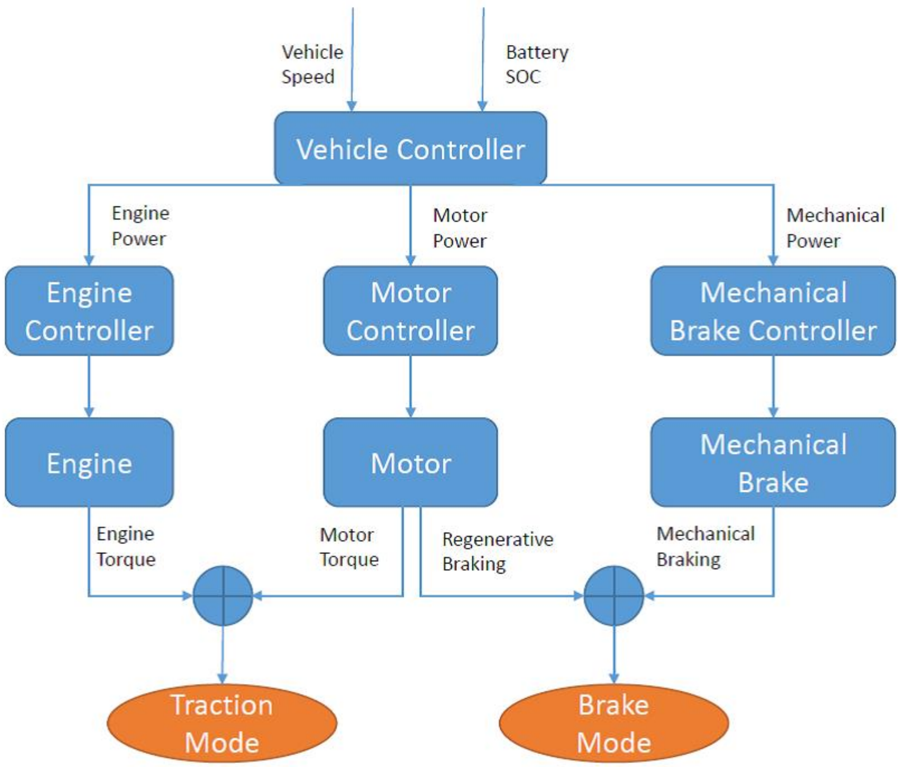

Figure 7.1: Overall Control Scheme of HEVs

7.1.2 Classification of Energy Management Strategies

Several energy management strategies have been proposed in literature [51–53, 56, 59, 60, 62].Two general trends can be identified, namely rule-based and model-based optimization methods [49].

The main characteristic of rule-based approaches is their effectiveness in real time implementation without high computation times for explicit minimization and optimization. The strategies rely on a set of Boolean rules translated from expert knowledge or from optimal global solution generated with mathematical models through optimization algorithms, and then providing the control input at each time. They are easy to implement and make the power sources work in their most efficient regions [50].

In model-based optimization strategies, the optimal values are calculated by optimization approaches which rely on analytical or numerical algorithms. Optimization methods can be sorted into two main groups: offline optimization and online optimization. Dynamic programming (DP) is widely used for offline optimization, and DP method is typically used as a benchmark for evaluating other algorithms. [51–55]. Other online implementable optimization approaches involve the equivalent consumption minimization strategy (ECMS) [56–58], stochastic DP (SDP) strategies [59–61], and model predictive control (MPC) strategies [62, 63]. Figure 7.2 presents the classification of energy management strategies in HEVs [50].

7.1.3 Our Lab Strategy

According to our lab design, different clutches are used to switch between different hybrid modes. Implementing the control strategy needs to choose different vehicle modes depending on the speed range and different SOC levels. Furthermore, the engine operating efficiency characteristics impact the applications of different control strategies (on/off, high efficient range) to improve the total efficiency.

The educational lab is a simplified hybrid platform. By demonstrating the hybrid patterns in our power-split architecture, a rule based control method on the vehicle

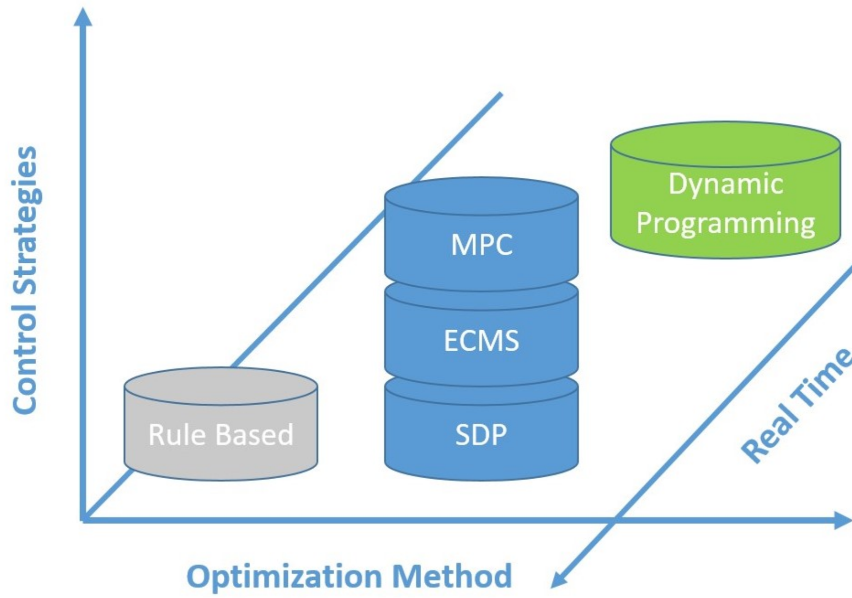

Figure 7.2: Classification of Energy Management Strategy in HEV [50]

level is applied in our lab. More details about the modeling process and strategy implementation is provided in the following sections.

7.2 Vehicle Modeling and Torque Requirement

By vehicle-level energy analysis and modeling, the vehicle can be considered as a point mass interacting with the external environment, then the amount of power and energy needed to move it with specific speed can be calculated. The energy management strategy informs the distribution of energy flows within each component in HEVs. Based on the control inputs and different driving conditions, an accurate estimation of SOC can be obtained. In this section, vehicle motion characteristics and driving cycles will be considered and discussed.

7.2.1 Vehicle Motion Characteristics

Optimizing the performance of each subsystem and evaluating the strategy of energy source control and management, require us to analyze the characteristics of the vehicle motion. The linear motion of the vehicle along the x-axis is longitudinal motion, and the vehicle dynamics in this direction is longitudinal dynamic. Longitudinal dynamic variables are the basis for expressing and judging a vehicle's performance during acceleration and braking.

In principle, assuming that the vehicle runs on a flat road, the traction force can be expressed as follows:

$$F_{\mathrm{trac}} = F_{initial} + F_{roll} + F_{aero} \tag{7.1}$$

Here, the inertial force $F_{initial}$ is positive when the vehicle is accelerating, and negative during deceleration; the rolling F_{roll} and aerodynamic F_{aero} resistances are always positive.

Multiplying all terms of (7.1) by the vehicle speed v_{veh} , the following balance of power equation is obtained:

$$P_{\mathrm{trac}} = P_{initial} + P_{roll} + P_{aero} \tag{7.2}$$

Each term is obtained as follows:

The inertial force is expressed as

$$F_{initial} = M_{veh}\frac{dv_{veh}}{dt} \tag{7.3}$$

The aerodynamic resistance is expressed as

$$F_{\text{aero}} = \frac{1}{2}\rho_{air}A_f C_d v_{veh}^2 \tag{7.4}$$

The rolling resistance force is usually modeled as

$$F_{roll} = c_{roll}M_{veh}g \tag{7.5}$$

Where M_{veh} is the mass of the vehicle, ρ_{air} the air density, A_f the vehicle frontal area, C_d the aerodynamic drag coefficient, c_{roll} the rolling resistance coefficient, and g is the gravity acceleration.

7.2.2 Driving Cycle

A driving cycle represents both the way the vehicle is driven during a trip and the road characteristics. In the simplest case, it is defined as a time history of the vehicle speed. Driving cycles are produced by different countries and organizations to assess the performance of vehicles in various ways. An essential use of driving cycles is in vehicle simulations. In our simulation, US06 cycle is taken as an example (see Figure 7.3).

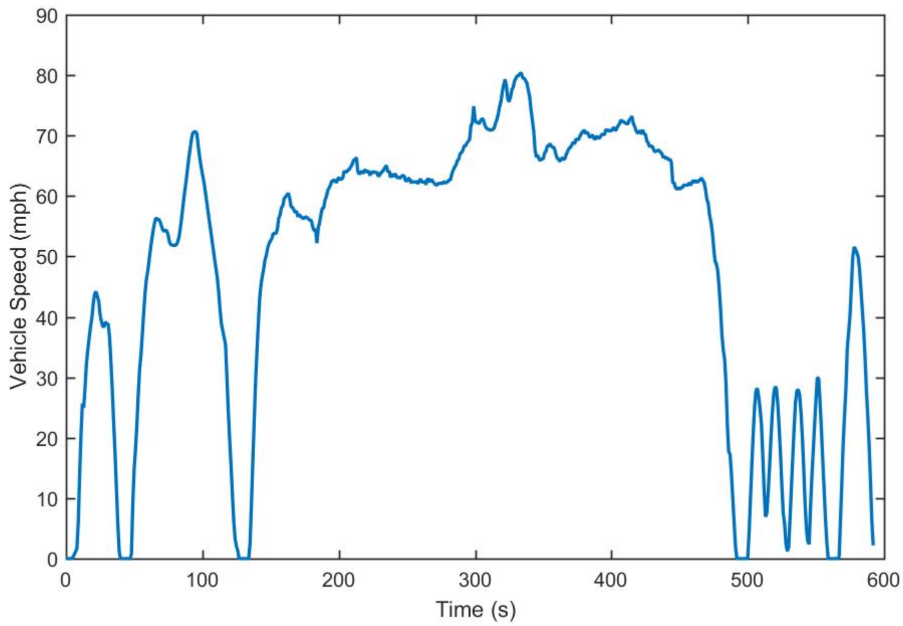

Figure 7.3: US06 Driving Cycle

7.2.3 Parameters and Model Output

According to equations (7.1) to (7.5), the following table lists the parameters used in our vehicle model. The total torque and speed requirements, are used as inputs to our control strategy.

Table 7.1: Vehicle-dependent Parameters for Longitudinal Vehicle Model

Parameter	**Compact car**	**Full-size car**
M_{veh}	1200 - 1500 kg	1700 - 2000 kg
C_d	0.3 - 0.35	0.28 - 0.33
A_f	1.3 - 1.7 m^2	1.8 - 2.2 m^2
c_{roll}	0.01 - 0.03	0.01 - 0.03

M_{veh} is chosen to be 1500 kg, $C_d = 0.35$, $A_f = 1.7m^2$,$c_{roll} = 0.03$, the calculated torque and motor speed curves for our vehicle are shown in Figures 7.4 and 7.5.

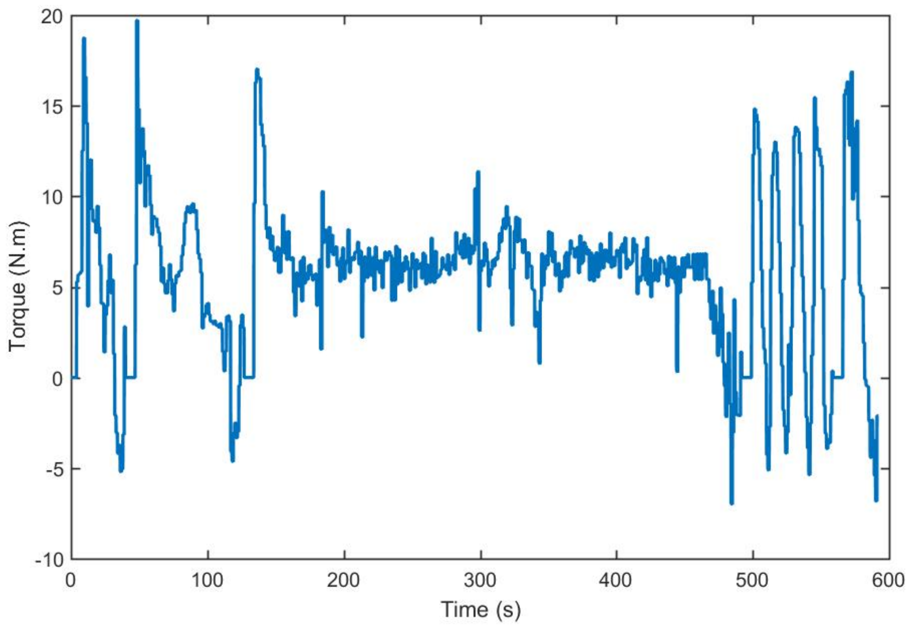

Figure 7.4: Torque Requirement Based on Vehicle Model

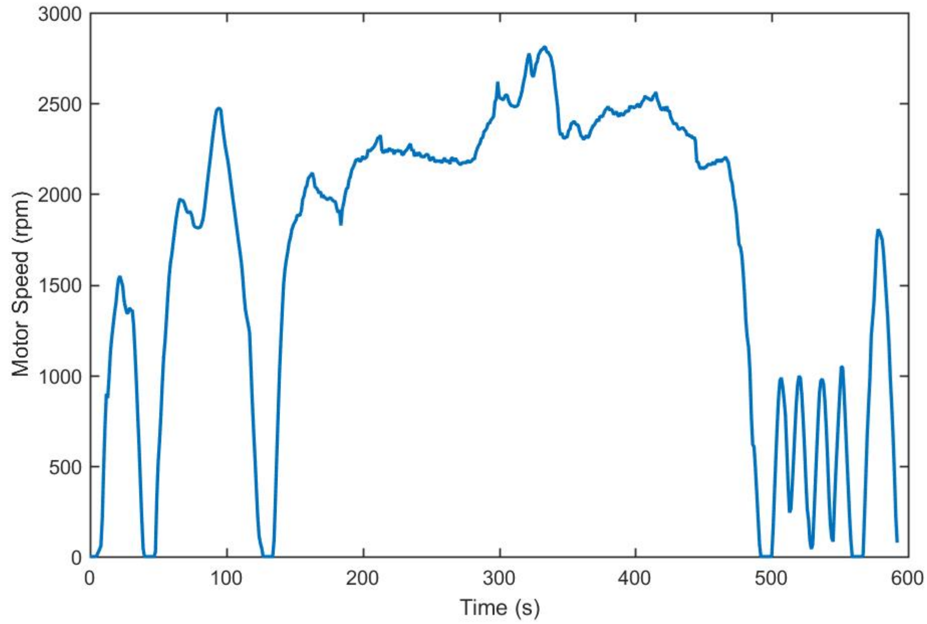

Figure 7.5: Motor Speed Based on Vehicle Model

7.3 System Modeling

The performance analysis of the vehicle leads to the requirement and modeling of each component. The mathematical models of the components are considered next, and then these models are combined to form the overall powertrain model.

7.3.1 Engine Performance Map

Some researchers have built complex physics-based engine models for the design and optimization of powertrain systems. However, these are overly complicated for developing the vehicle level control strategy. Alternatively, output power and torque of a powertrain system can be calculated from characteristic curves or look up tables instead of complex physics-based equations.

In our control strategy, the engine performance curves are used. Figure 7.6 shows the torque performance and fuel consumptions of the Kubota engine versus speed.

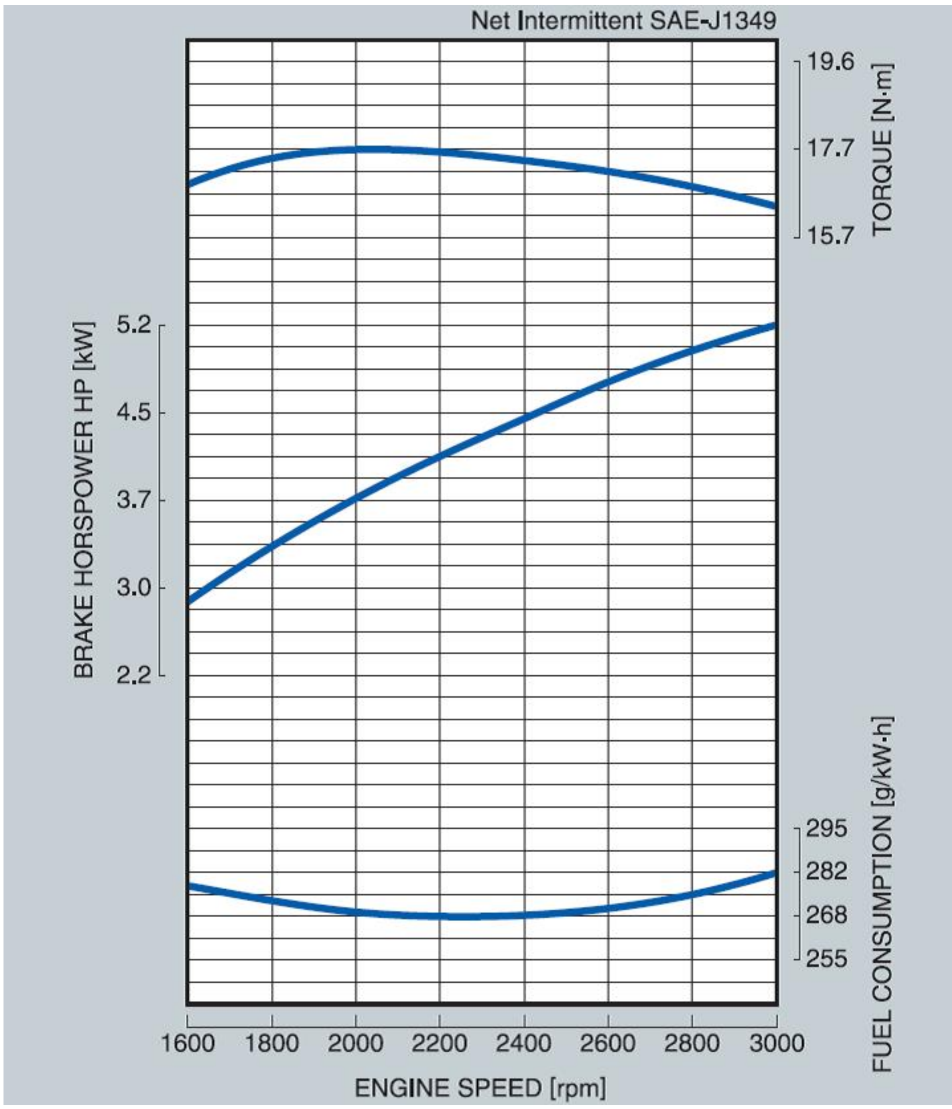

Figure 7.6: Kubota Engine Performance Curve [66]

7.3.2 Electrical Motor Performance

The other energy source in our traction system is the electric motor. Typically in industrial applications, it is easy for electric motors to operate at predefined distinct modes and achieve optimized performance. While for HEV applications, the motors need to satisfy different driving conditions such as frequent stop-start and high acceleration/deceleration rates. These conditions require the motors operate at all operating ranges. As shown in Figure 7.7, the output curve of electric motors used in our simulations includes a constant torque/constant power characteristic. Constant power is the ideal characteristic of automotive powertrains because it provides high traction at low speeds and low traction in high speeds which exactly match the vehicle's needs to overcome inertial and resistance forces. Table 7.2 shows the efficiency data of the motor at each operating point, this can be used to analyze the motor's performance and calculate state of charge (SOC) of the battery in our simulation.

Table 7.2: Motor efficiency data table

Motor	**Motor Speed**									
Torque	**0**	**350**	**700**	**1050**	**1400**	**1750**	**2100**	**2450**	**2800**	**3150**
0	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
2	0.7	0.77	0.82	0.87	0.88	0.89	0.9	0.91	0.92	0.92
4	0.7	0.81	0.85	0.89	0.91	0.91	0.91	0.91	0.9	0.88
6	0.7	0.82	0.86	0.9	0.91	0.91	0.9	0.88	0.8	0.78
8	0.7	0.82	0.87	0.9	0.91	0.9	0.86	0.8	0.78	0.78
10	0.7	0.82	0.88	0.9	0.9	0.87	0.82	0.78	0.78	0.78
12	0.7	0.81	0.87	0.9	0.88	0.85	0.79	0.78	0.78	0.78
14	0.7	0.8	0.86	0.89	0.87	0.82	0.78	0.78	0.78	0.78
16	0.7	0.79	0.86	0.88	0.85	0.82	0.79	0.78	0.78	0.78
18	0.7	0.78	0.86	0.87	0.82	0.82	0.79	0.78	0.78	0.78
20	0.7	0.78	0.85	0.86	0.81	0.82	0.79	0.78	0.78	0.78

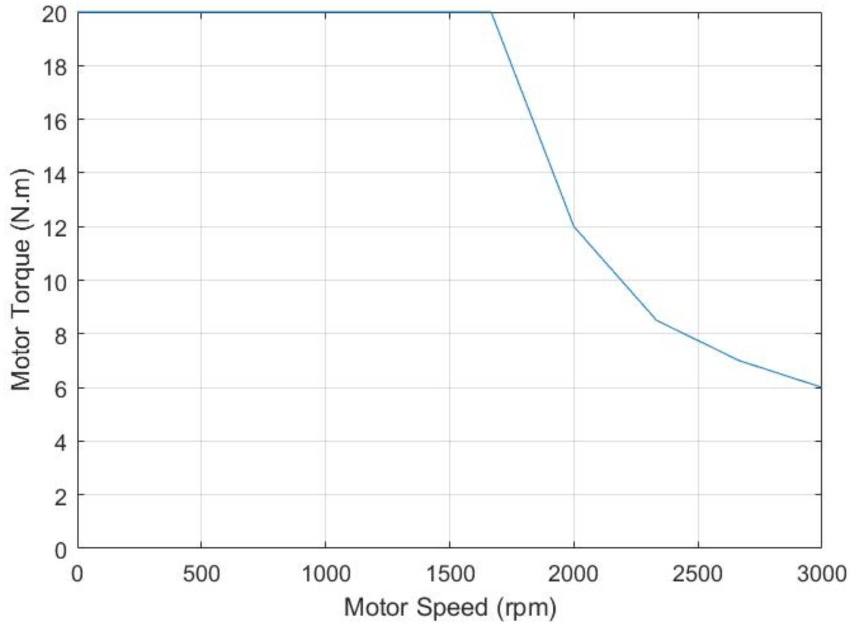

Figure 7.7: DC Motor Performance Curve

7.3.3 CVT

The CVT consists of two pulleys, a primary and secondary pulley connected with a belt drive. There are two speed ratios, low end ratio and high end ratio. Low end ratio is the ratio between the drive clutch and the driven unit when the drive clutch is at its smallest pitch diameter and the driven unit is at its largest. The high end ratio refers to the opposite pitch diameters of the drive clutch and driven unit. Most Comet torque converter systems range in a ratio from approximately 3:1 initially through to about 1:1 when “fully shifted”.

At speeds below the belt slipping RPM, the belt slips between the pulleys, operating effectively as a clutch. As the speed of the primary increases, the belt begins to slip against the pulleys up to the engagement RPM, where they become locked. For a short period, the CVT holds the low end ratio (3:1) as the engine speeds up. Once the engine reaches the shift RPM, the CVT begins to change ratios. Ideally, if tuned correctly, the CVT will keep the engine at the shift RPM, until the high end ratio (1:1) is reached. A curve of CVT ratios to intermediate shaft speeds can be seen in the figure 7.8. The specific shift speed ratio is listed in table 7.3. Linear interpolation method is used for calculating the speed ratio at each time of the control strategy.

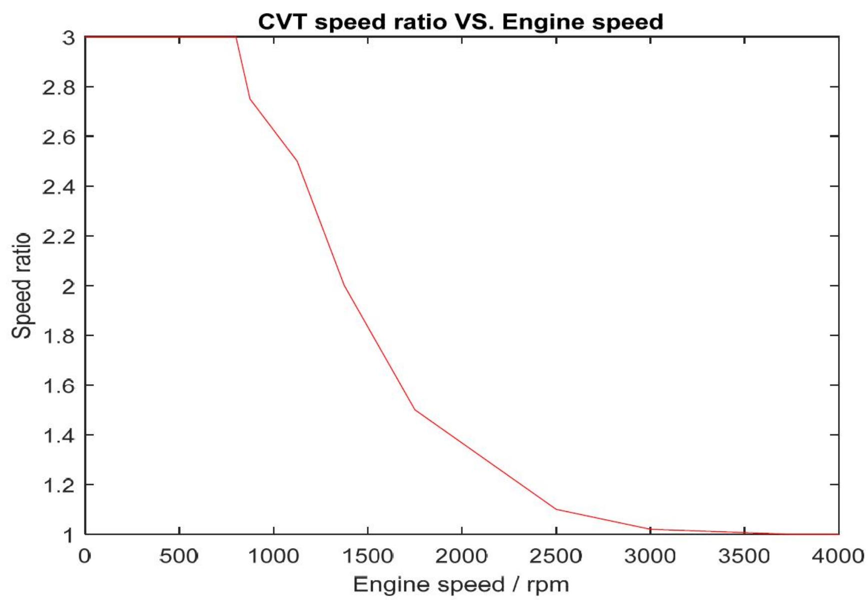

Figure 7.8: CVT Speed Ratio Curve

Table 7.3: Gear Ratio in relation to engine speed

Engine Speed	0	800	875	1125	1375	1750	2500	3000	3750	4000
Speed Ratio	3	3	2.8	2.5	2	1.5	1.1	1.02	1	1

7.3.4 Bevel Gearbox and Clutches

When simplifying the control strategy with the assumption of ideal components, the mechanical efficiency loss of the gearbox transmission and clutch engagement should be ignored (with around 99% transmission efficiency). The bevel gearbox acts as the torque coupler with a gear ratio 1:1, from this point of view, the output torque of the bevel gearbox is regarded as the sum of the input. The clutches operate as the mode switches without energy losses.

$$T_{out} = T_{CVT} + T_{Motor} \tag{7.6}$$

Where T_{out} is the total output torque, T_{CVT} is the torque from the CVT, and T_{Motor} represents the torque provided by the traction motor.

7.4 Control Strategy for Our Lab Architecture

A control strategy plays a crucial role, determining the driving performance. Pre-set rules would send commands to each component and receive feedback from them, and then make decisions on operating patterns in this power-split architecture. Based on our architecture, a rule based strategy is developed. There are three considerations in our control strategy as follows.

1. **SOC stable range control**

   To mimic the real vehicle driving scenarios, limiting the SOC of the battery pack in a stable range is necessary. When SOC reaches its upper limit, electric power should be used to drive the vehicle. On the other hand, when the SOC reaches its lower limit, charging the battery would be a priority without sacrificing driving requirements.

2. **Engine on/off control**

The clutches used in our system also improve the control flexibility. Based on different driving conditions, the status of the engine and engagement of the clutches can be changed to realize different hybrid modes. This strategy is not applied directly in our lab, only one independent configuration would be tested at a time according to the engine status.

3. **Efficiency improvement control**

   Efficiency improvement is the core expectation from the hybrid powertrain. The engine should be controlled to operate in its optimal range and avoiding low efficiency regions such as under a low vehicle speed. Motors are used at low vehicle speeds for improving overall efficiency. At high speeds, operation is supported by both the engine and the motor.

Figure 7.9 provides the control flowchart for the power-split architecture which makes all the three clutches engaged. In this flowchart, certain thresholds are set to control the directions of each decision point. Take SOC as an example, it is maintained in the range of 60% to 80% as expected which would be beneficial for a higher efficiency [64]. Based on the SOC levels, this power-split hybrid architecture switches between different hybrid operating patterns. The logic behind mode switching is as follows:

1. Braking mode or traction mode would be determined by the sign of torque requirement. If it is minus, hybrid braking or regenerative braking would be activated; otherwise traction mode would be applied.

2. If the required speed is below 800 rpm, the electric motor would drive the load; the engine would change the status from “off” to work in a series hybrid only if SOC value is below its lower limit of 60%.

3. When the speed is over 800 rpm, "engine first" or "motor first" would be obtained based on whether SOC value is above the upper limit of 80%.

4. Parallel hybrid is applied when the engine cannot provide enough torque in "engine first" conditions, the electric motor would provide additional torque.

5. Power-split mode would be applied when the engine provides its maximum torque, but just a portion is used to drive the load, the rest is used to drive the generator.

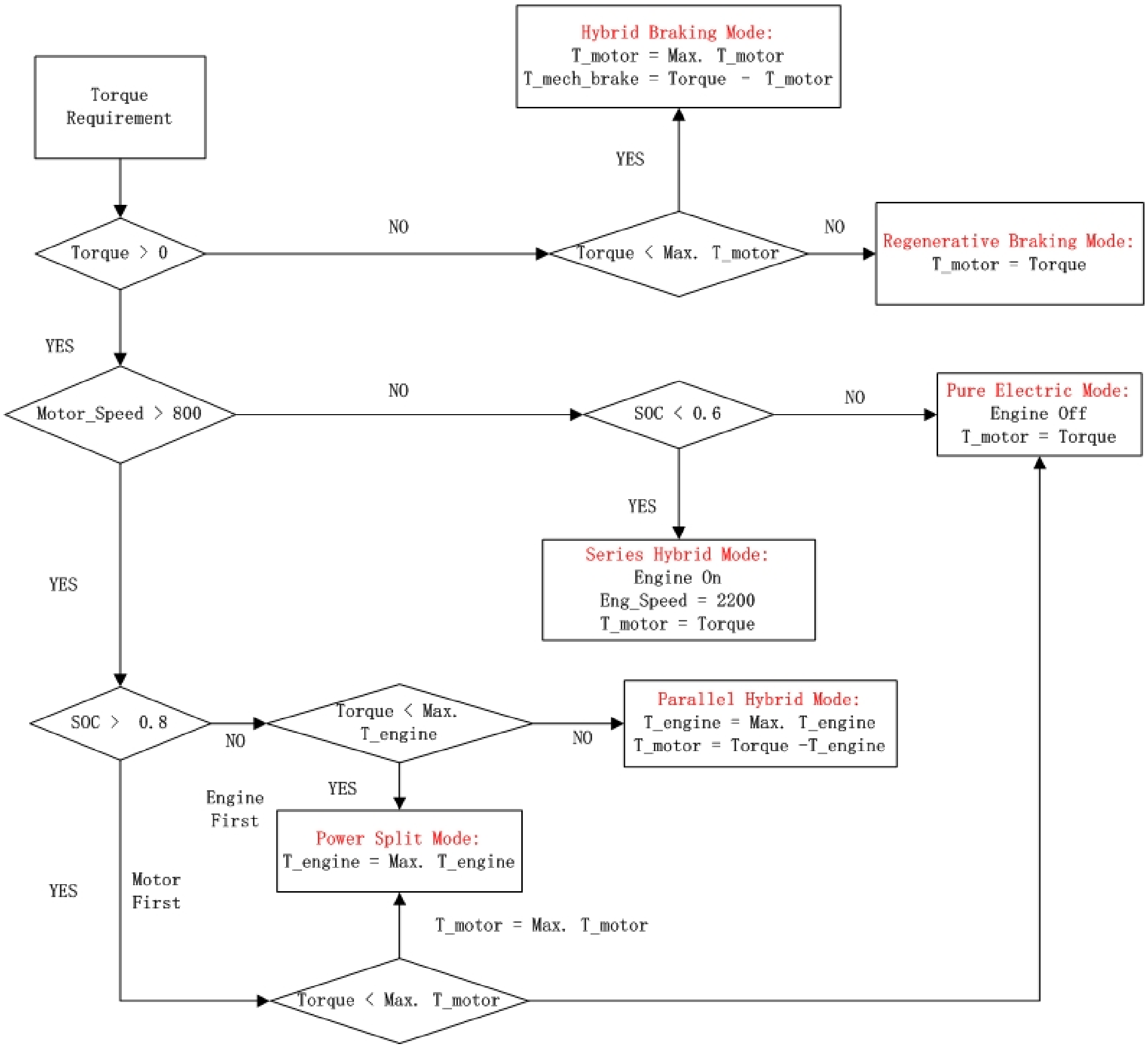

Figure 7.9: Control Flowchart of Hybrid Educational Lab

7.5 Results and Discussion

According to the control strategy presented in section 7.4, the driving condition with 80% of SOC is simulated for the power-split architecuture under the US06 driving cycle. After implementing the proposed control strategy for this scenario, the ON/OFF conditions and torque output of the engine in the whole cycle can be acquired; and the motor output and the generator input can also be recorded.

Assumptions made for implementing the control strategy are as follows.

- The battery pack has a predefined energy capacity to be 2kWh, and a storage efficiency changes according to the motor efficiency table (See Table 7.2), both for charging and discharging.

- To simplify the analysis, the mechanical efficiency of transmission is mainly affected by the CVT. From some researchers' experimental study on transmission efficiency of CVT, the efficiency of CVT can be assumed to be 80% [65].

The following figures show more details of the simulation results. Figure 7.10, 7.11 and 7.12 show the scenario of 80% SOC.

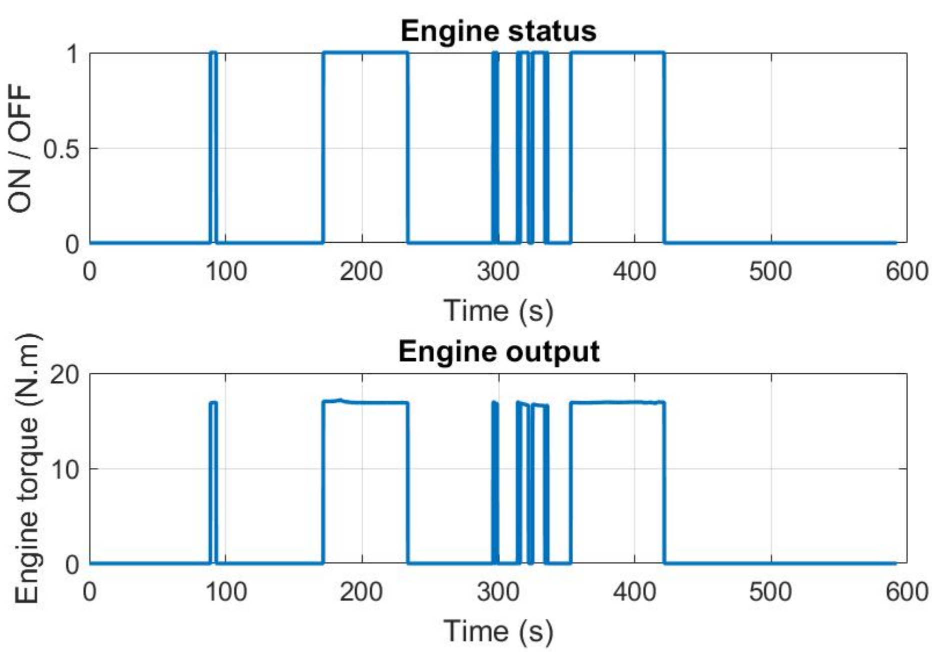

Figure 7.10: Engine Status and Torque Output - 80% SOC

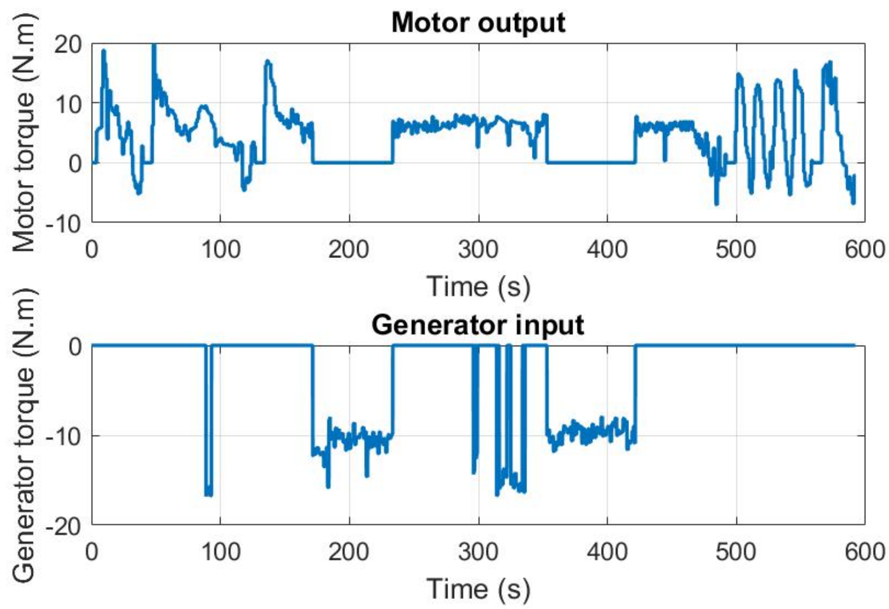

Figure 7.11: Motor Output and Generator Input Torque - 80% SOC

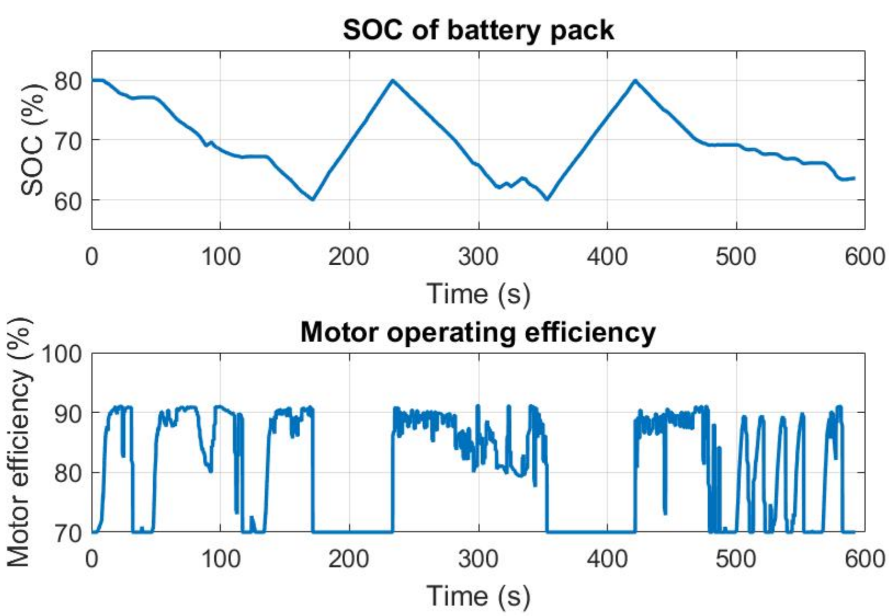

Figure 7.12: SOC Trend of Battery and Motor Efficiency - 80% SOC

Discussions

Analyzing this simulation scenario of the power-split architecture, some features can be observed as following:

1. When running in low vehicle speed range, the engine is isolated from the load and the electric motor provides the whole traction force. This is because the critical engagement speed of CVT in our system is 800 rpm, the other reason is that at low speeds and electric motors have a higher efficiencies.

2. When operating under highway driving cycles and when the motor runs in the high speed range with a lower torque output, the engine should be the main power source.

3. When considering the total efficiency, the ICE should be regarded as the dominant power supplier in "engine first" condition, because of reducing the conversion loss. When the SOC is higher than the upper limit, the system prefers utilizing more electrical energy and running in "motor first" condition.

In summary, in this chapter our simulation models are built based on the chosen components for the power-split architecture. A realistic control strategy has been applied in order to demonstrate the utility of different hybrid operating patterns with this power-split architecture. The results and discussions have been presented as above.

Chapter 8

Conclusion

8.1 Conclusion

The advantages of HEVs include improved energy efficiency and reduced emissions. It is necessary to develop laboratories that would support training of undergraduate students for automotive research and education. The objective of this work is to develop a novel undergraduate laboratory for educating students on hybrid automotive powertrain.

The development of the hybrid powertrain lab is divided into two phases. In the first phase, a motor lab, is designed as an independent platform for demonstrating motor characteristics. Moreover, the motor lab should serve as an important element of the final hybrid powertrain lab, simulating traction motor functions in hybrid or electric vehicles. Characterization testing strategies for electric motors were reviewed in chapter 4, and LabVIEW based interface has been designed to implement specific electric motor characterization tests. CANopen network has been chosen to realize the communication strategy between the motor drives and our interface.

For the HEV powertrain teaching laboratory, an innovative design architecture has been proposed to realize different hybrid architectures. Instead of using a planetary gearbox, a bevel gearbox with a CVT are combined for making the lab much more compact and flexible for demonstrating hybrid functionalities. A number of clutches have been used to allow the reconfiguration of the lab powertrain architecture. The three most common HEV architectures, namely series, parallel, and power-split can be configured by using various combinations of clutch engagements. The additional generator provides the ability of input power-split for allowing the engine to operate at a narrow high-efficiency region. The components have been selected based on system requirements. The integrated architecture and the layout of this hybrid lab has been presented.

After designing the hybrid lab, a simplified simulation model based on the chosen components has been produced for analyzing the system capabilities, and for implementing novel energy management and control strategies. A rule-based energy management strategy has been applied in order to run the whole system in different hybrid operating patterns. An initial SOC conditions (80%) was simulated with this proposed control strategy. The results effectively reflected the three main principles: SOC stable range, engine on/off, efficiency improvements.

8.2 Future Works

Further to the proposed hybrid lab, two future research works are proposed:

1. **Updating the hybrid lab with a controllable CVT.** In order to increase system flexibility, an advanced controllable CVT can be used rather than a

passive CVT. This update can provide an additional freedom for system control.

2. **Modeling from experiments.** In order to improve the performance of our control strategies, a more accurate model obtained from real experiments should be applied rather than a simplified simulation model under some assumptions.

3. **Laboratory procedures revision.** The electric motor and hybrid lab are currently being constructed and the actual laboratory procedures may need revision upon the completion of the lab's physical set up.

Appendix A

DC Motor Lab Instruction

A.1 DC Motor Lab Objectives

As an important element of a hybrid laboratory, a stand-alone electric motor lab is initially produced. Our stand-alone motor lab would expose mechanical students to electric motors their characteristics. The educational objectives of the lab will include the following:

1. Demonstration of the motor operating characteristics: the speed-torque curve.
2. Analysis of the motor performance: achieving the motor efficiency map through the whole operating regions.
3. Simulation of the operation of motors in EV driving application.

A.2 Important Safety Procedures to Follow

- Please be very careful with high voltage sources and equipment in the lab.

- Do not touch any of the wiring terminals or open the wiring cabinet. If any of the wires are exposed or a cabinet is left open, immediately notify the lab instructor.
- Follow instructor's instructions carefully, such as the safety requirements.
- Always turn off the power before leaving, and making any changes in the connections is not allowed.
- Checking with the instructor for any changes before turning on power.
- Power on the Control Unit first, and then power on the Power Supply unit.
- Power off the Power Supply unit first, and then power off the Control Unit.

A.3 Motor Lab Procedures

After checking the lab is under safe condition and ready for operation, the three objectives of the motor lab would be achieved with the following experiment procedures.

A.3.1 Speed-Torque characteristics

Two shunt DC motors play different roles in the lab. The one with 5 kW power capacity is the traction motor, and the other with 10 kW acts as the dynamometer (generator) and provides the load, as shown in figure A.1.

Different control methods are applied to them. **The traction motor is under speed control, and the generator is with torque control.** The motors drives have been embedded with pre-set PID controllers, the reference speed and torque should be provided at each step as shown in figure A.2.

Figure A.1: Motor lab mechanical installation

The base speed of the motor is 3000 rpm provided by the nameplate, and the maximum safety speed is 4500 rpm. With full load on base speed, the torque is around 20 N.m. Several torque and speed levers are made to test the motor's characteristics.

Table A.1: Speed and torque levels

Speed level	500	1000	1500	2000	2500	3000	3200	3400	3600	3800	4000	4200
Torque lever	2	4	6	8	10	12	14	16	18	20		

Seven steps should be implemented as follows:

(1) Check the power supply status from the motor drives, make sure the light is green, confirm there is no error. If there is any fault or alarm, contact with the instructor and the lab technician.

(2) Open the lab interface in LabVIEW, make sure the motor and generator are ready to operate with the lights of ON/OFF status being green, as shown in figure A.2.

(3) As demonstrated in the previous page, set a reference for the motor speed, for example, 500 rpm at the beginning.

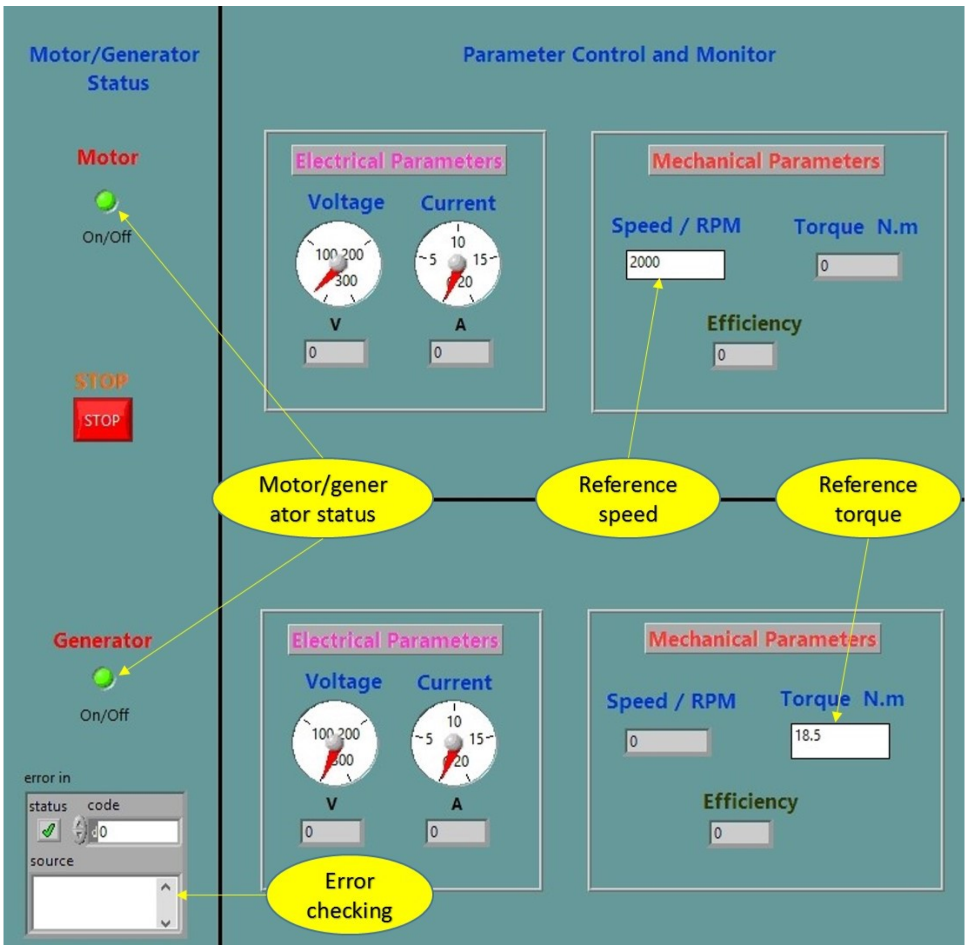

Figure A.2: Interface for setting parameters

(4) After running the motor in this constant speed level, set the reference torque for the generator from 2 to 20 N.m according to table 1. At each torque level, running the system until reaching a steady state. To be noticed, when increasing the torque of the generator, the maximum torque for this speed level would be the critical value, for which the reference speed of the motor cannot be maintained.

(5) Change the generator torque to zero, and change the speed of the motor to the next level, such as 1000 rpm.

(6) Repeat step 4 until the maximum torque value is reached at this speed level.

(7) Recording all the maximum torque values for each speed level and draw the motor Torque-Speed Curve as in Figure A.3.

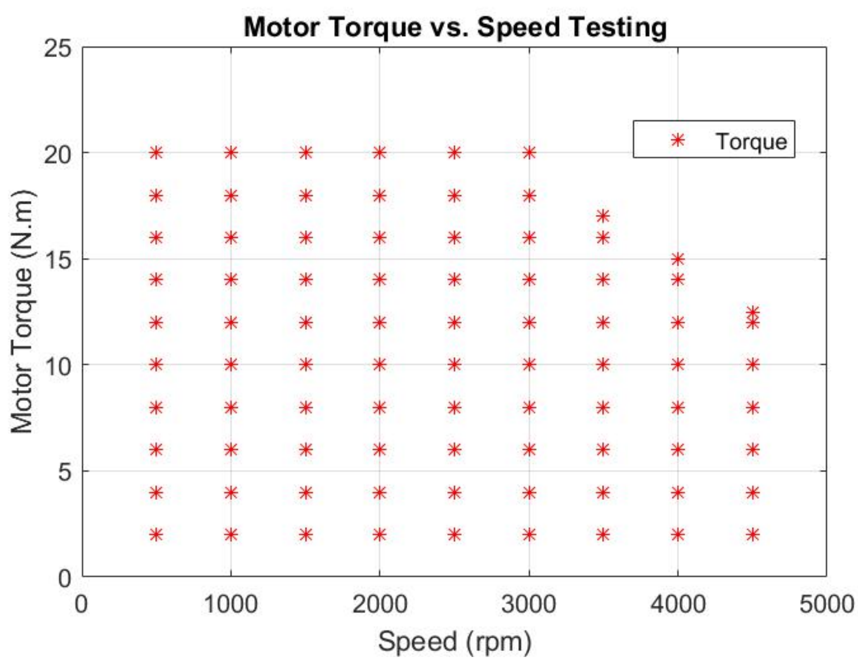

Figure A.3: Motor Torque-Speed Curve

A.3.2 Motor Efficiency Curve

The efficiency η describes the relationship of mechanical power delivered and electrical power consumed. In this lab, the efficiency map can be obtained from different speed and torque settings.

- **Electrical power**

$$P1 = V_a I_{in} \tag{A.1}$$

Where V_a is the armature voltage in volts (V). I_{in} is the input current in amperes (A).

- **Mechanical power**

$$P2 = \frac{2\pi n T}{60} \tag{A.2}$$

Where n is the motor speed. T is the motor torque in N.m.

- **Efficiency**

$$\eta = \frac{P2}{P1} \times 100\% \tag{A.3}$$

Six steps should be implemented as follows:

(1) Check the status of the system, confirm there is no error from our user interface, as shown in Figure A.2. If there is any fault or alarm, contact with the instructor and the lab technician.

(2) Running each operating point of the system in a steady state at each paired speed-torque level.

(3) Record the input voltage and current of the motor from the user interface.

(4) Calculate the motor efficiency based on the above equations.

(5) Record all the efficiency points in Table A.2.

(6) Draw the motor efficiency map, such as Figure A.4.

Table A.2: Motor efficiency at each paired speed-torque level

Speed	**Torque**									
	2	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**
500										
1000										
1500										
2000										
2500										
3000										
3200										
3400										
3600										
3800										
4000										
4200										

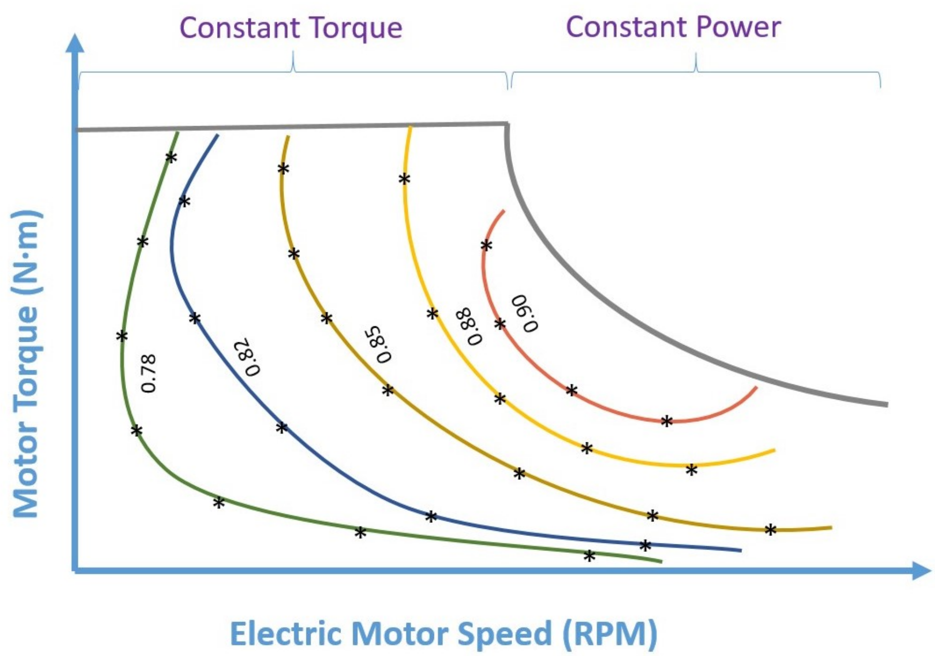

Figure A.4: Electric motor efficiency map

A.3.3 Driving Cycle Simulation

Not only the motor itself, but also driving scenarios are considered in this lab. Electric motors have their own advantages when they provide traction forces to drive the EVs or HEVs. This motor lab enable students to understand the impact of motor characteristics on the vehicle's driving performance, encouraging them to expand their understanding of HEVs and EVs. Vehicle dynamics captures the effects of acceleration, braking and steering applied by a driver. The load on the motors can be calculated from the vehicle's model in relation to different driving cycles. This lab can simulate and analyze the electric motor's performance in highway or urban conditions for educational purposes.

A vehicle model is used to calculate the motor speed and torque requirements at each operating point of the driving cycle.

Eight steps should be implemented for simulating the motor's performance in a driving cycle as follows:

(1) Choose a driving cycle from the excel files saved in the computer for this experiment, such as US06. The vehicle speed is shown in figure A.5.

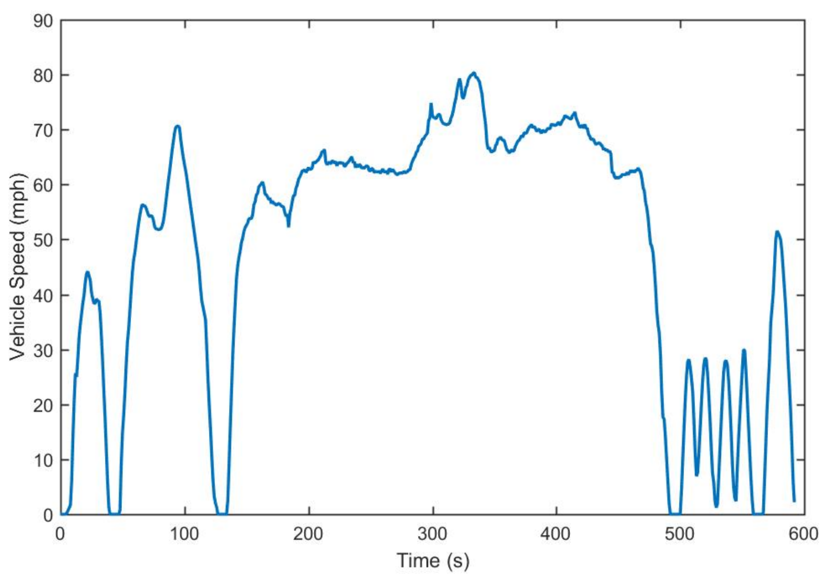

Figure A.5: US06 driving cycle

(2) Calculate the load requirement with the above driving cycle, more details are described in Chapter 7. Figure A.6 and A.7 show the motor torque and speed requirements in US06 driving cycle.

(3) Run the system at the each paired speed-torque level for two seconds (the speed reference is from the motor, and the torque reference is from the generator which

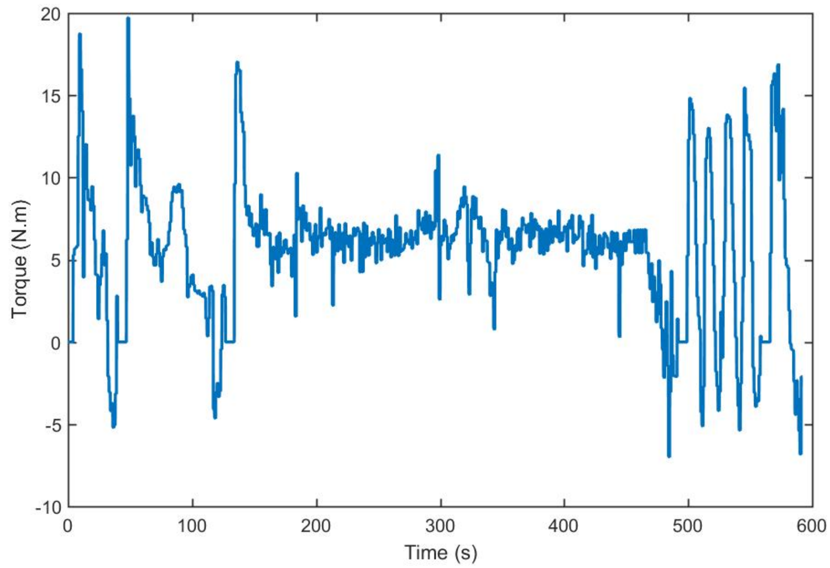

Figure A.6: Torque requirement

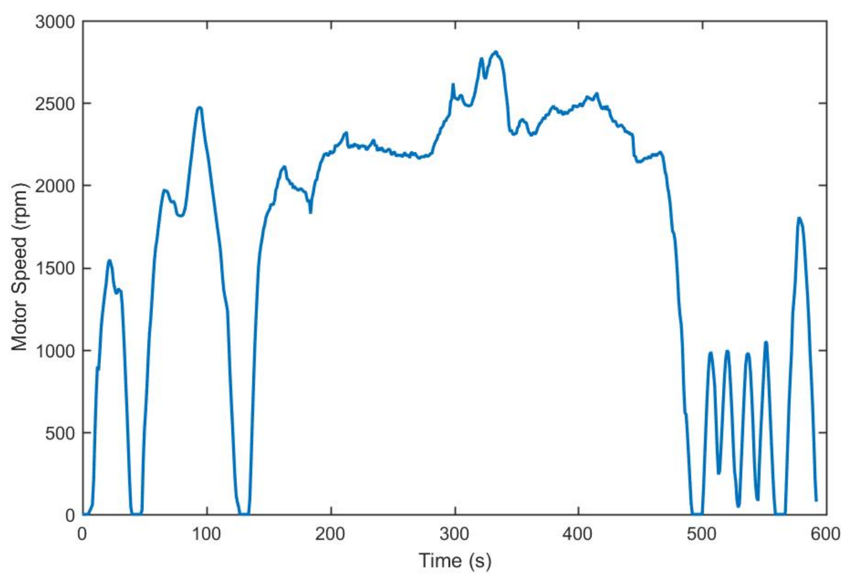

Figure A.7: Speed requirement

reflects the load requirement), and record the voltage and current of the motor, write down the efficiency from the interface.

(4) Use the stored voltage, current, and efficiency points to plot and analyze the motor's operating performance (figure A.4).

(5) Calculate the power consumed at each point according the variable efficiency:

$$P = \frac{2\pi n T}{60\eta} \tag{A.4}$$

Where n is the motor speed in rpm. T is the output torque in N.m, η is the motor efficiency.

(6) Sum up the consumed electric energy (E) using the following equation:

$$E = \sum \frac{2\pi n T}{60\eta} \frac{\Delta t}{1000 * 3600} \tag{A.5}$$

Where $\Delta t = 2$ seconds; E is the electric energy in kWh.

(7) Calculate the final state of energy (SOE), assume the initial value is 2 kWh:

$$SOE = \left(1 - \frac{E}{2}\right) * 100\% \tag{A.6}$$

(8) Change to another driving cycle and repeat step 1 to 7.

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