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DEPARTMENT OF AUTOMOTIVE, COMBUSTION ENGINE AND RAILWAY ENGINEERING

Master Thesis

OPTIMAL CONTROL STRATEGY OF HEV SCADA SYSTEM

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Program: Master of Automotive Engineering

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MASTER'S THESIS ASSIGNMENT

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Algoritmus řízení hybridního pohonu

Guidelines:

On the basis of SCADA control system creates functional analysis of electric hybrid drive system based on electro-mechanical power splitter.
Steps of the work:
1. Analyse of single operational elements of the drive
2. Determination operational elements working range.
3. Design of control algorithm structure.
4. Compare your simulation results with experimental data for testing bench at the CTU FEE laboratory H 26..

Bibliography / sources:

1) Dobri Cundev, Pavel Mindl, "European Driving Schedule of Hybrid Electric Vehicle with Electric Power Splitter and Super-capacitor
2) 'CONTROL STRATEGY OF CAR HYBRID SYSTEM AND ITS EXPERIMENTAL CONFIRMATION' Doctoral Thesis Dobri Čundev
3) MODELING, SIMUL MODELING, SIMULATION AND CONTROL OF HYBRID ELECTRIC VEHICLE DRIVE WHILE MINIMIZING ENERGY INPUT REQUIREMENTS USING OPTIMIZED GEAR RATIOS by Sanjai Massey
4) European Driving Schedule of Hybrid Electric Vehicle with Electric Power Splitter and Supercapacitor as Electric Storage Unit Dobri Cundev, Pavel Mindl
5) Modeling of the Hybrid Electric Drive with an Electric Power Splitter and Simulation of the Fuel Efficiency Dobri CUNDEV, Zdenek CEROVSKY, Pavel MINDL

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Date of master's thesis assignment: **15.02.2022** Deadline for master's thesis submission: **12.08.2022**

Assignment valid until: ______________

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III. Assignment receipt

The student acknowledges that the master's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master's thesis, the author must state the names of consultants and include a list of references.

Date of assignment receipt	Student's signature

Acknowledgment

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Declaration

I, Rahul Jaiswal, declare that this thesis and the work presented in it, titled "Hybrid Drive Control Algorithm", are my own and have been generated by me as the result of my original research. I confirm that the thesis work was done entirely or primarily while pursuing the master's degree in Automotive Engineering at Czech Technical University, in Prague. This thesis it has been mentioned where any element of it has previously been submitted for a degree or other qualification at this University or any other institution. I declare that I worked out this thesis independently and I quoted all used sources of information in accord with Methodical instructions about ethical principles for writing an academic thesis. When I refer to someone's published work, I ensure their work credit. I have given the source when I quote from other people's work. This thesis is the result of my work, except for quoted texts. I've acknowledged all major sources of assistance. The work shown here has never been published before the submission of this thesis.

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Abstract

The thesis deals with the design of a drive control Algorithm for Hybrid vehicle drive systems. Based on the SCADA (Supervisory control and data acquisition) control system of an Electro-mechanical power splitter unit which controls the power split between the Internal combustion engine and Electrical motor drive resulting in higher efficiency and increased range. The E.P.S. consists of a double rotor synchronous permanent magnet generator. This consists of two separate rotating parts, a traditional permanent magnet rotor and, a rotating stator. The rotor is permanently coupled to the drive shaft of the vehicle ICE. The rotating stator, which is a structurally typical AC machine stator, is linked with the vehicle's transmission, which connects to the wheel output. This technical solution allows the ICE to operate at an optimum RPM throughout the driving cycle. This system uses Supercapacitors instead of the traditional battery packs used in passenger cars to store the energy during recuperation. The analysis of the drive algorithm method and its linked elements is the main goal of this thesis. The model was created in MATLAB Simulink for the whole drive system and its related algorithms. The results of the Simulink model analyzing the WLTC driving cycle were then compared with the driving cycle made by a physical test bench in CTU FEE laboratory H.26. The ICE and traction load are simulated with a tuned AC induction motor. The entire workbench provides a complex machine, measurement, and control system for implementing this task.

Keywords: Hybrid electric vehicle (HEV), Simulation, Modelling, Efficiency, Optimisation, Power converter control, EPS, Test bench, Power transmission, Supercapacitor, Energy recuperation

ABSTRAKT

Práce se zabývá návrhem algoritmu řízení pohonu pro hybridní systémy pohonu vozidel. Založeno na řídicím systému SCADA (Supervisory control and data processing) elektromechanické jednotky rozdělovače výkonu, která řídí rozdělení výkonu mezi spalovací motor a pohon elektromotoru, což vede k vyšší účinnosti a většímu dojezdu. E.P.S. je založen na dvourotorovém synchronním generátoru s permanentními magnety. Skládá se ze dvou samostatných rotujících částí, tradičního rotoru s permanentním magnetem a rotujícího statoru. Rotor je trvale spojen s hnací hřídelí vozidla ICE. Rotační stator, který je konstrukčně typickým statorem střídavého stroje, je spojen s převodovkou vozidla, která je připojena k výstupu kola. Toto technické řešení umožňuje ICE pracovat při optimálních otáčkách během celého jízdního cyklu. Tento systém využívá superkondenzátory namísto tradičních bateriových sad používaných v osobních automobilech k ukládání energie během rekuperace. Hlavním cílem této práce je analýza metody algoritmu pohonu a jejích souvisejících prvků. Model byl vytvořen v MATLABu Simulink pro celý systém pohonu a jeho související algoritmy. Výsledky modelu Simulink analyzujícího jízdní cyklus WLTC byly následně porovnány s jízdním cyklem provedeným na fyzickém zkušebním pracovišti v laboratoři FEL ČVUT H.26. ICE a trakční zatížení jsou simulovány vyladěným střídavým indukčním motorem. Celý pracovní stůl poskytuje komplexní strojní, měřicí a řídicí systém pro realizaci tohoto úkolu.

Klíčová slova Hybridní elektromobil (HEV), Simulace, Modelování, Efektivita, Optimalizace, Řízení měniče výkonu, EPS, Testovací stolice, Přenos výkonu, Superkondenzátor, Rekuperace energie

ABBREVIATIONS

ICE – internal combustion engine
HEV – hybrid electric vehicle
HEV-CVUT – Hybrid-Electric Vehicle - České Vysoké Učení Technické
EV – electric vehicle
HPS – hybrid propulsion system
CTU – Czech Technical University
FEE – Faculty for Electrical engineering
SC – super-capacitor
EPS – electric power splitter
TM – traction motor
RPS – re-fuelable power source
PZEV – partially zero emission vehicle
TB – traction battery
EG – electric generator
BSFC- Brake specific fuel consumption
PCG – planetary changing gear
WLTC- Worldwide Harmonized Light Vehicles Test Cycle
KM – kinematical model
CPU – central processing unit
SCADA – supervisory control and data acquisition
HEV-SCADA – SCADA system for HEV-CVUT
RTU – remote terminal unit
FC – frequency converter
FC 1 – VLT5011 Danfoss frequency converter for control of "ICE motor"
FC 2 – VLT5011 Danfoss frequency converter for control of "brake motor "
HEV-RTCS – HEV Remote Terminal Control Set
EMI – electromagnetic interference
GUI – graphic user interface
HMI – human machine interface
DSP – digital signal processing
DAQ – data acquisition
ADC – analogue-digital converter
DAC – digital-analogue converter
AI – analogue input
AO – analogue output
COG- Centre of gravity
TTL – square-wave pulse signal (Transistor–transistor logic)
CCT – control cable terminals

PWM – pulse wide modulation
mpg – miles per gallon

SYMBOLS

P_{eg} – electric generator power
P_{ice} – mechanical ICE output power on the drive-shaft
P_{epsmh} – mechanical power on the stator shaft of the EPS
P_{epsel} – electrical EPS output power to the DC circuit
P_{sc} – electrical charging (discharging) power to the SC
P_{el} – electrical power from the DC circuit that powers TM
P_{tm} – mechanical output power produced by TM
P_{veh} – mechanical power of the car wheels that propels the vehicle
F_{air} – aerodynamic drag forces
F_r – rolling resistance forces
F_s – resistive gravity forces
F_a – acceleration force
m – mass of the vehicle
a – acceleration of the vehicle
g – local acceleration of gravity (gravity constant)
f – coefficient of rolling resistance between the tires and the road surface
ρ - density of the ambient air
A – cross-sectional area of the vehicle
v – magnitude of the velocity (i.e., speed) of the vehicle in the direction of travel v_{wind} – speed of the wind in direction of vehicle travel
α – angle of inclination of the road surface upon which the vehicle is travelling C_{trans} – coefficient of transmission
W_{sc} – accumulated energy into the super-capacitor
W_{sc_start} – SC accumulated energy at the beginning of the drive W_{sc_max} – maximal possible SC accumulated energy
U_{sc} – super-capacitor voltage
C_{sc}- capacity of the super-capacitor
U_{sc_max} – maximum voltage of the SC
U_{sc_prm1} – minimal allowed voltage of the SC
U_{sc_prm2} – minimal voltage that must be achieved after U_{sc} reaches U_{sc_prm1} U_{sck_pr1} – critical maximal voltage of the SC,
U_{sck_pr2} – minimal voltage after reaching the U_{sck_pr1}
I_{sc} – current in super-capacitor
U_{dc} – voltage on main DC circuit
I_{dc} – current in main DC circuit
U_{eps} – output voltage on EPS
I_{eps} – output current in EPS
U_{tm} – input voltage on TM
I_{tm} – input current in TM.
n_{ice} – revolutions of the ICE shaft
n_{tm} – revolutions of the TM shaft
M_{brake} – resistive torque on TM shaft “brake”
M_{ice} – torque on ICE shaft
f_m – motor power supply frequency
f_{TTL} – square-wave pulse TTL frequency

Contents

LIST OF TABLES

LIST OF FIGURE

1. Introduction

This thesis focuses on creating a control algorithm and strategy for state-of-the-art concepts in the power flow of hybrid electric vehicles (HEVs). A physical model of this system developed by the Department of Electrical and Electronic Engineering and Traction at the Czech Technical University in Prague called HEV-CVUT (Hybrid Electric Vehicle České Vysoké Učení Technické) was used to compare the simulation results with the test bench data.

Every hybrid vehicle company has its own unique hybrid propulsion system (HPS). This thesis describes, functionally analyses, and compares all elements of HPS implemented in commercial vehicle and compare them with HEV-CVUT. The control strategy of this HEV is designed and discussed in detail.

The concept of Hybrid Electric Vehicles(HEV) is quite old and unfortunately, in the last century, the low cost of fossil fuels subdued any traction that these Hybrid vehicles may have had. In the last two decades, though, there has been a boom in the Hybrid and electric vehicles market. The main reasons for HEV and EV becoming a growing market segment in transportation space are to minimize the impact of burning fossil fuel on the environment, reduce transportation operational prices, and customers' inclination toward modern technology. Now, the automakers' ultimate goal is to improve the mileage of passenger cars and reduce emission levels.

The commercial vehicle propulsion system has changed little since the first commercial vehicle was developed. In these vehicles, an internal combustion engine (ICE) is the main propulsion unit based on a four-stroke Otto's cycle or diesel cycle and consumes fossil fuel for generating energy. This system has a low energy conversion rate and high losses, therefore is less efficient. More energy-efficient systems are the electric propulsion systems. The main drive unit is an electric motor, which can be a DC motor, AC induction motor, or a synchronous motor. These systems are used in modern public transportation such as metros, trams, and cyclo-buses. It is possible and easy to have successfully implemented the electric

drive in public transportation for commercial purposes due to the availability of continuous power supply provided by overline wires that are directly connected to the main power grid. Electric passenger cars do not have this option of overhead cable connections. Their energy source is stacked chemical cells, which are heavy, bulky have low energy storage densities and are expensive. Also, the limited availability of battery charging stations and long charging time as compared to filling a fuel tank has led the EV's be an uncommon choice for commercial purposes despite their high energy efficiency.

A Hybrid Electric Vehicle however is a solution to these problems, which lies between a vehicle with a standard combustion engine to a fully electric vehicle. The drive of these vehicles consists of an ICE and an electric-driven motor. This concept represents a hybrid of a standard vehicle with an ICE and a complex electric vehicle drive system, taking advantage of both energy efficiency and power independence from low power density electrical storage units. The hybrid electric drive serves to increase the efficiency of the vehicle by achieving an efficient energy transformation from fuel to tractive power. The advantage of hybrid electric vehicles over standard ICE-powered vehicles is that they can recover kinetic energy (Energy recuperation) and have improved energy management of driving components. The use of an onboard computer and control system which monitors all aspects of the vehicle helps to achieve higher efficiency in a Hybrid vehicle.

The Kinetic energy recovery system (KERS) is used in vehicles to regenerate the energy which is then stored in the energy storage unit. This process is used when braking the vehicle and is called recuperative braking or simply recuperation. This process can be accomplished either by mechanical or electrical recovery methods. In practical use, electrical means are more efficient and are therefore commercially used. This system consists of precisely controlled electrical machines, motors, and generators connected to the drivetrain of the vehicle. In the recuperation phase, the vehicle is provided high resistance by a generator coupled to the wheel shaft directly or via a gearbox set. The generator is driven by the kinetic energy of the moving vehicle, which is converted from mechanical energy to electricity, braking the vehicle (decelerating) generates electrical energy. This energy is stored in chemical batteries or supercapacitors. This thesis focuses on recuperative systems with supercapacitors as an accumulative device for energy storage in hybrid electric vehicles.

The HEV system is an effective energy conversion system for commercial vehicles. The efficiency of this system depends strictly on the control strategy and algorithm of the system. This strategy defines the function of system components and the flow of power in the drivetrain. The quality and relevance of a hybrid vehicle depend on the quality of its control strategy.

The HEV-CVUT has a unique technical solution for hybrid propulsion systems that are different from the standard HEV solution. Commercial hybrid electric vehicles use planetary gears to split the power from the internal combustion engine and a separate generator to power the traction motor (TM) and charge the battery. In the HEV-CVUT hybrid system, power splitting is performed in an electro-mechanical way by using a special type of synchronous machine for the power splitter – An electric power splitter (EPS). It reduces one step of energy transformation and the overall efficiency of the system is improved. Instead of using chemical cells to store the kinetic energy of braking, we use supercapacitors as a new and innovative solution for storing electrical energy. This method stores energy from the generator to supercapacitors without converting the electrical energy to chemical energy, which is in the case of traditional chemical cells. This increases the efficiency of the system by reducing one energy transformation. Also, the high-power density of supercapacitors allows the system to be charged and discharged instantly with lower energy losses.

1.1 Project Goal

The thesis covers the theoretical foundations of hybrid electric vehicles (HEV), focusing on the origin of the technology, the principles of operation, the benefits of implementation, the pros, and cons of HEV-CVUT developing control strategies and drive algorithms, creating experimental conditions for driving cycle tests, running experiments, recording and analysing test results, computer numerical analysis, and comparing simulation results with experimental results. As part of the Josef Božek Research Center (RCJB) for Engine and Vehicle Technology, a test workbench has been set up in the H.26 laboratory at the Department of Electric Drives and Traction at the Faculty of Electrical Engineering. This test bench is used to test the performance and components of the HEV-CVUT hybrid electric system. This level is essential for understanding the operating characteristics of each component and functional unit of HEV-CVUT. The test bench has a SCADA system implemented and is used for automation testing of HEV-CVUT performances by measuring and acquiring test data from the test bench it is compared with MATLAB simulations.

2. LITERATURE REVIEW

2.1 Background

An increased living standard of people has increased the demand for personal transport. The auto market for personal transport is very wide and consumers get multiple options and power source combinations. The gas emission from ICE vehicles, high dependency on fossil fuel, and increasing cost of fuel is a problem for the environment and bring many ecological problems. These causes have led to the successful implantation of Hybrid electric technology in the automotive industry. All major car production companies are making Hybrid electric vehicles in significant numbers and it has become a popular choice among consumers.

2.1.1 Fuel and costs savings

The main goal of implementing a Hybrid technology is to improve the fuel economy of commercial vehicles. The target is to travel longer distances with a limited amount of fuel. This attribute has become even more important these days when oil prices are soaring high in Europe due to limited supply. This makes owning a pure ICE-driven vehicle costlier and is no longer an easily affordable commodity. Fuel efficiency is not just an important issue for car makers but also the consumers. Consumers are assured by the car makers that by buying a hybrid-electric vehicle they will have their investment returned by reducing fuel expenses. Also, on a large scale, this reduces the country's dependency on other nations for foreign oil imports.

2.1.2 Environmental impact and emission regulations

Demand for fuel-efficient consumption technologies is increasing as concerns about the environmental impact of fossil fuel consumption increase. The increasing number of cars around the world, especially in urban environments, leads to a negative impact on the an environment that manifests itself in air pollution. To improve air quality, it is necessary to reduce the harmful emissions from automobiles. This can be achieved by improving the efficiency of the vehicle or, if possible, using alternative fuels. A promising solution to these problems is a hybrid electric vehicle. Hybrid electric vehicles use alternative energy sources, which have the potential to improve fuel economy and reduce harmful emissions.

In some countries, the use of alternative vehicle drive systems is regulated by law. There are multiple zones declared by the government where only HEV or EV are allowed to enter. It promotes and mandates the sale of vehicles with significantly reduced harmful emissions. These government regulations on reduced emission vehicles are forcing people to be interested in hybrid vehicles. The hybrid electrical technology that uses ICE as an RPS allows the consumers to meet the PZEV requirements (PZEV – Partial Zero Emission Vehicles). Regulations are in place because the HEV uses an ICE that itself produces a small number of gaseous emissions. They are classified as Ultra Low Emission Vehicles (ULEV).

Environmental law is very strict in many countries. To be able to meet these requirements for automakers, new energy-efficient technologies are the solution. The only possible solution for heavy and medium-sized vehicles to comply with these regulations is the implementation of hybrid electric drivetrains.

In the European Union (EU), vehicle gas emissions are regulated by standards. The European emission standards define limits for emissions for the new vehicles sold in EU member countries. Emission standards are defined in a series of EU Directives, which provide for the gradual introduction of more stringent standards. These are currently in force at the Euro Vehicle Standard.

Stage	Date	CO	HC	HC+NOx	NOx	PM	PN
		g/km					#/km
Positive Ignition (Gasoline)							
Euro 1†	1992.07	2.72 (3.16)	-	0.97 (1.13)	-	-	-
Euro 2	1996.01	2.2	-	0.5	-	-	-
Euro 3	2000.01	2.30	0.20	-	0.15	-	-
Euro 4	2005.01	1.0	0.10	-	0.08	-	-
Euro 5	2009.09[b]	1.0	0.10[d]	-	0.06	0.005[e,f]	-
Euro 6	2014.09	1.0	0.10[d]	-	0.06	0.005[e,f]	6.0×10^{11} [e,g]
Compression Ignition (Diesel)							
Euro 1†	1992.07	2.72 (3.16)	-	0.97 (1.13)	-	0.14 (0.18)	-
Euro 2, IDI	1996.01	1.0	-	0.7	-	0.08	-
Euro 2, DI	1996.01[a]	1.0	-	0.9	-	0.10	-
Euro 3	2000.01	0.64	-	0.56	0.50	0.05	-
Euro 4	2005.01	0.50	-	0.30	0.25	0.025	-
Euro 5a	2009.09[b]	0.50	-	0.23	0.18	0.005[f]	-
Euro 5b	2011.09[c]	0.50	-	0.23	0.18	0.005[f]	6.0×10^{11}
Euro 6	2014.09	0.50	-	0.17	0.08	0.005[f]	6.0×10^{11}

* At the Euro 1..4 stages, passenger vehicles > 2,500 kg were type approved as Category N_1 vehicles
† Values in brackets are conformity of production (COP) limits
a. until 1999.09.30 (after that date DI engines must meet the IDI limits)
b. 2011.01 for all models
c. 2013.01 for all models
d. and NMHC = 0.068 g/km
e. applicable only to vehicles using DI engines
f. 0.0045 g/km using the PMP measurement procedure
g. 6.0×10^{12} 1/km within first three years from Euro 6 effective dates

Table 1. 1 EU emission standards for passenger vehicles [1]

2.1.3 Global warming

Global warming threatens our health, jeopardizes our national security, and threatens other basic human needs. Impacts such as record temperatures, rising sea levels, severe floods, and droughts are already frequent. The growing interest in HEVs has been driven by concerns about global warming. By improving the fuel efficiency of the HEV and the availability of alternative fuels, we can significantly reduce the emission of carbon dioxide CO2, the most important greenhouse gas. A hybrid electric car uses less gasoline to cover the same distance than an ICE car. The less fuel you burn, the fewer emissions are released. As emissions decrease, the pace of global warming slows down.

2.1.4 Noise Pollution

Electric and hybrid vehicles are the heart of eco-friendly vehicles. Electric drives are much quieter than mechanical ICE drives. Not only do they reduce air pollution, but they are also considered to be very quiet in urban traffic. This has the potential to reduce noise pollution in the city. When compared to a purely ICE-driven vehicle, an electric drive produces almost no sound. This plays an important role in urban transport, as noise reduction has a significant impact on improving the quality of life for citizens.

2.2 HEV’S Energy Efficiency potentials

HEVs have the advantage of the high efficiency and low emissions of pure electric vehicles, as well as the high range and refuelling capabilities of ICE-only vehicles. Also, unlike fuel cell vehicles, they do not require a specially manufactured energy carrier (such as the H_2 tanks), which makes them a more safe and better choice for a passenger car. Because HEVs use gasoline as fuel, they have the advantage of being easy and quick to refuel, as well as an affordable solution over fuel cells.

Overall advantages of Hybrid vehicles over traditional vehicles can be listed as:

- Regenerative braking,
- higher efficiency of ICE by operating in the fuel-efficient region,
- elimination or reduction of idling of ICE,
- smaller and lighter ICE because of two power sources.

2.2.1 Regenerative braking

Like electric vehicles, hybrid vehicles can use an electric traction motor in a generator regime to recover the energy which is normally lost as heat energy from mechanical brakes. When in a generator regime, the TM provides resistance which deaccelerates the vehicle, produces electrical energy, and charges the battery. This electrical energy is transmitted to TM in case of increased power demands like acceleration to supplement ICE and this helps in achieving higher fuel efficiency.

Regenerative braking, also known as recuperation, is highly effective in urban driving where vehicles need to accelerate and deaccelerate frequently and quickly. This recovery system saves more than 40 % of driving energy and significantly reduces vehicle fuel consumption.

2.2.2 Higher efficiency of ICE by operating in the fuel-efficient region

Most aluminium or steel ICE have a thermodynamic efficiency limit of 37%. Even with the help of turbochargers and engine electronics, their efficiency ranges between 18% - 20%. For dynamic driving profiles such as in city driving, the overall efficiency of the engine drops to less than 10%. Strict engine control algorithms allow the HEV to significantly avoid energy loss in the internal combustion engine. This is achieved by controlling the operation of the engine at the most efficient speed and load, as shown in the figure below.

The hybrid powertrain can adjust the engine revolutions at optimal revolutions based on the power required at the driveshaft. This is not possible in a standard ICE car where driveshaft power is directly dependent on the engine power. The power produced by the engine Price does not have to be proportional to the traction power demands P_{veh}. An excess or deficiency of energy is provided by or to an electrical accumulation unit. This process is made possible by using an energy storage device (battery or supercapacitors) to absorb or replace some of the power from ICE output, allowing it to operate only at the most efficient speeds and loads.

An ICE can only provide maximum working efficiency over a narrow operating range that is strongly dependent on specific output power and driveshaft speed. The HEV's driving strategy is based on providing the ICE with working conditions to keep it in an optimal revolutions area. In such conditions, the efficiency is closer to the theoretical, throughout the operating process.

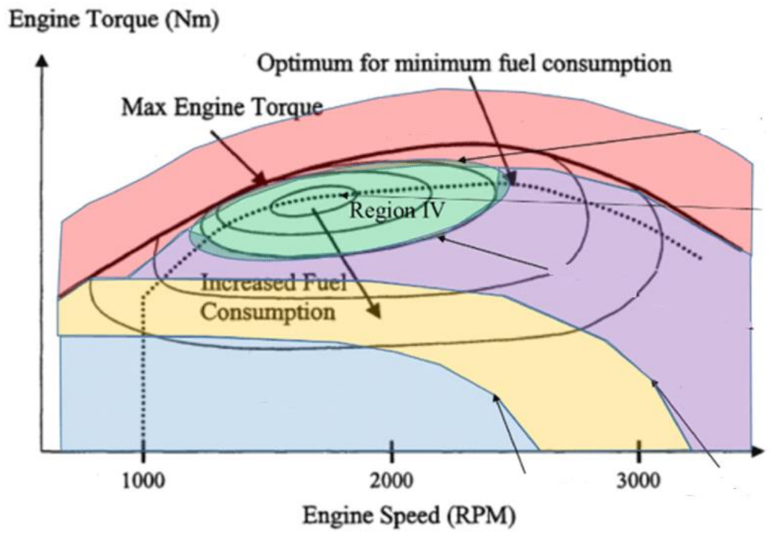

Figure 2.1 Optimum range for fuel consumption on engine map [2]

2.2.3 Elimination or reduction of idling of ICE

When the HEV goes to a complete stop, the control system turns off the ICE. This option eliminates running the ICE in a higher fuel consumption range of low RPM operation of ICE. During this time, the battery supplies auxiliary power needed (Air conditioning, headlights, infotainment systems, etc.). When required based on the power requirement, the ICE runs at higher revolutions than the idle (lower fuel consumption for the amount of power produced based on BSFC curve of the ICE) and the excess power generated is used to recharge the TB. The BSFC curve which is in shape of onion rings in an Engine power torque curve is the measure of fuel efficiency of an engine. It gives the information about the amount of fuel used to produce required power. When the ICE is turned off at idling, the drivetrain is designed to use the TM to act as a starter motor and restart the ICE very quickly and frequently due to the high starting torque of the TM.

The control strategy system uses TM to increase engine speed to optimum levels before fuel is injected when the engine is restarted, this reduces the high emissions which are caused due to cold start of the engine.

The HEV's driving strategy is based on shutting down and restarting the ICE multiple times during a driving cycle. The vehicle starts electrically and the ICE is turned on only when the vehicle reaches a set speed or when the total load of the car exceeds a given load. The

The HEV control strategy also involves turning off the ICE during braking (regenerative braking) and coasting (downhill driving).

2.2.4 Smaller and lighter ICE because of two power sources

In standard ICE powered vehicles, the ICE is designed for producing a high torque and power needed during rapid acceleration or peak performance during events such as Uphill climb. The level of performance needed in this case is multiple times higher than what is needed to keep the vehicle cruising at 80 km/h. As the ICE is the only power source, a bigger size of the engine is needed to fulfil all the power requirement in peak power requirement events. The bigger size engine results in higher fuel consumption and increased overall weight of the vehicle, increasing the fuel consumption of the vehicle.

A HEV has an electric motor in addition to the internal combustion engine, that provides additional propulsion. It can also provide higher and continuous torque even at low engine speeds. The HEV's electrical drivetrain makes it possible to reduce the power peak demands from the ICE. In an HEV as there is an electrical storage unit which supply power to the TM and the TM provides a supplement power along with the ICE power. The power requirement during peak load demands is reduced for ICE, which leads to selecting a smaller ICE for the hybrid vehicle. The ICE sizing for HEV can be done for sustained load during the driving cycle rather than selecting based on the maximum power needed during short high load demands such as in case of overtaking a vehicle.

As a result, the rated output of the ICE can be significantly lower than the engine of traditional ICE driven vehicles. Having the load distributed between the ICE and TM enables the engine to operate at lower speeds than its peak performance regime for major section of the driving cycle, resulting in lower fuel consumption and increasing the mileage. Downsizing the engine and yet having a higher peak power rating of the vehicles due to supplementary electrical drivetrain for same vehicle load results in higher range and less pollution than traditional powertrains.

3. HEV Types

HEV by definition is a vehicle with two different potential energy sources that can be individually converted into useful kinetic energy. Among these, one of the sources is electricity. This potential energy can be stored in a variety of forms, including supercapacitors (electricity), batteries (electrochemistry), pressurized fluids (mechanical), rotary flywheels (mechanical), and fuel (chemical).

Based on the connection between ICE and Electric motor, the HEVs can be categorized as follows according to the design.

- Parallel Hybrid
- Series Hybrid
- Power Split Hybrid

Based on the combination, the power of the electric motor that can be transferred to the wheels, and the HEVs can be classified as follows according to the degree of hybridization.

- Mild Hybrid
- Full Hybrid
- Plug-in Hybrid

3.1 Categorization by Design

3.1.1 Parallel Hybrid

Parallel hybrids have parallel connections between the ICE and Electric Motor transmissions. The two power sources can be used independently for the vehicle’s movement. In most cases, ICE is a major power source and runs continuously to keep the vehicle moving. The EM supports ICE during acceleration and braking. The advantage of using the Parallel Hybrid source is that if one power supply fails, the other alternative power source is available to provide tractive power.

The target of the control strategy is to use the TM to keep the ICE out of the inefficient operating range and keep the ICE revolution in efficient regions. The driving strategy is based on the fact that the ICE takes a smooth load of the vehicle in case of sudden requirement of energy as in case of rapid acceleration as the TM supplements the ICE for short intervals. This strategy reduces the transient loss from ICE but increases the battery loss (repeated discharge and charge).

The operational strategy is based on limiting the use of TM to an electric start of the vehicle, regenerative braking, and power boost when the ICE alone cannot handle the power demand. This means that after the electric start, the ICE will provide all power to drive the vehicle. When the vehicle is at a stop, the ICE stops too, then the accessories run on the battery, and the TM is ready for a quick electric start. The TM's high torque acts as a powerful a starter motor, instantly starting the ICE as soon as there is input for high acceleration from the driver such as in case of overtaking.

Without "all-electric" operation in a parallel hybrid, TMs and storage devices are relatively small and therefore can be cheaper. As the EM is used only for assisting the ICE or for a short-distance power supply, the size of the electric traction motor of the parallel hybrid is smaller than the size required for the series hybrid. Parallel Hybrids typically improve highway fuel economy with an efficient ICE operation at cruising highway speeds and less mass than a series hybrid. It also can withstand long hill climbs.

In a parallel hybrid there is dependency of engine speed on the wheel speed and load which forces engine to run in a particular range. This range when falls outside the optimal working regime of the engine results in higher fuel consumption. The TM shaft is coupled to the ICE shaft which limits braking energy recovery capabilities.

Parallel HEVs have an ICE and a TM linked together with a mechanical coupling, an additional Traction battery and control system, which makes it a complex system and expensive than a standard ICE vehicle. The key advantage of parallel hybrids is that they can achieve higher range and efficiency when compared to standard ICE. This is achieved by using regenerative braking, downsizing the engine, and maintaining ICE operation in a narrow efficient range. The most important advantage is the efficiency of connecting the ICE output to the wheel using transmission component. This transfer mechanical energy directly to the wheels for propelling the vehicle, reducing multiple power transformation and improving efficiency. In other words, the combination of transmission, torque converter, and differential has higher efficiency than the ICE-to-wheel path of the Series HEV, which will be discussed in next section.

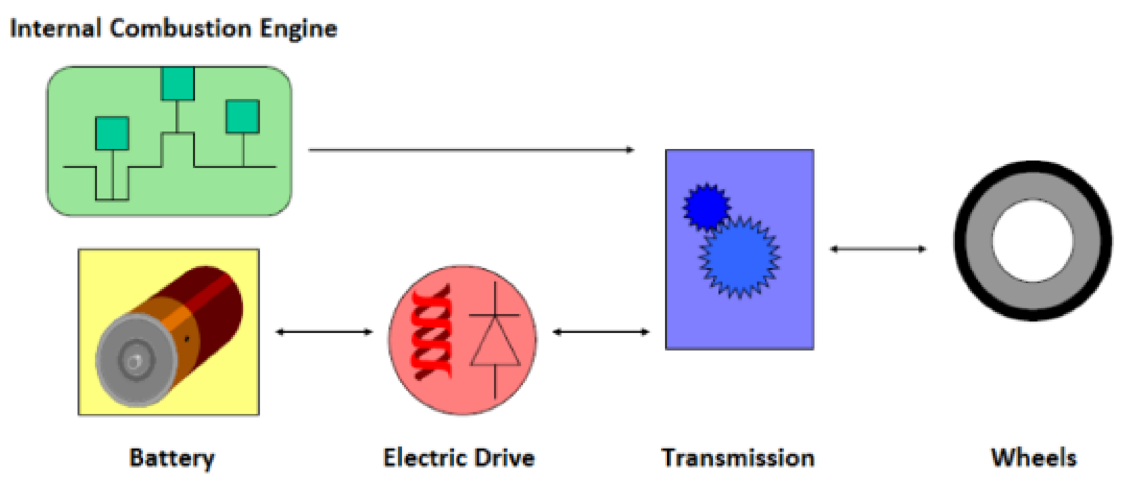

Figure 3. 1 Parallel Hybrid Electric Vehicle power flow diagram

3.1.2 Series Hybrid

The hybrid is a type that uses EM as the main source to drive the wheels. The EM should be designed for higher output as compared to the Parallel Hybrid's EM. The series hybrid can be reused as an extended-range electric vehicle. It is called a "series" due to the energy transformation process during the driving cycle. The ICE produces the mechanical power from fuel, which drives the rotor of the generator. The generator then generates electrical energy to charge the battery and runs the TM. The traction motor produces the mechanical power that drives the car. In the process of vehicle deacceleration, the TM switches to the generator regime, which does energy recuperation. It brakes the car and saves some of the vehicle's kinetic energy by charging the traction battery. Power management and control strategy is crucial in this system and is achieved by choosing the most optimal energy pathway.

This drive concept has better energy efficiency characteristics than vehicles equipped with the standard ICE. In case of frequent braking such as in urban driving, regenerative braking converts most of the KE to electrical and charges the accumulator, resulting in a higher efficiency. As the drive shaft of the ICE is only connected to the rotor shaft of the generator, it allows speed-independent revolutions, keeping the ICE operating range at the optimum level. By not having a direct link between ICE and the car's wheel, we can keep the ICE operating in optimum working range even in the event of a sudden drive change for short period, such as sudden acceleration during an overtake. During this period the added power requirements are overtaken by the battery power. This allows the ICE to operate at the most efficient levels throughout the driving regime and keep the engine operating within the most efficient operating range. The series HEV design makes it easier to mechanically connect to the wheel than the complex parallel hybrid and gives you more freedom in component placement. The electric motor can be easily set to the size, which requires only one small gearbox, reducing the losses which usually occur in a large multi-speed gearbox. High power is always available in series HEV, even in the ZEV mode. Since the TM is the only propulsion drive, it must be sized for the maximum input power. The remaining components (ICE, EG, and TB) need to be sized to provide full power to the traction motor. This will significantly inc. the weight of the vehicle. Additionally, the path (ICE → EG → TB →TM) is composed of multiple energy transformations due to which large energy losses occur. All of these drawbacks make the series HEVs less efficient than their parallel HEV counterparts.

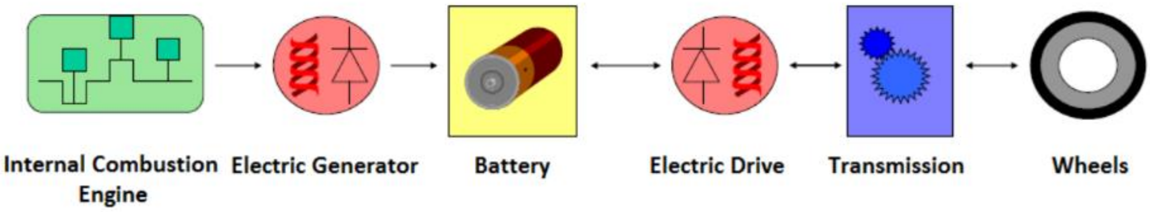

Figure 3. 2 Series Hybrid Electric Vehicle power flow diagram

3.1.3 Series Parallel Power Split Hybrid (also known as Series Parallel Hybrid)

In a series-parallel hybrid, the vehicle can be driven by an ICE only, an electric motor only, or both. The HEV system is equipped with an electric motor, ICE, and a generator. To integrate these systems, a power split device consisting of planetary gears is used. It provides the functionality of a power flow structure in various modes of operation. There are two types of motors in this system. A primary electric motor (MG2) is used to provide the mechanical driving force to drive the car and is powered by the ICE, and the same motor is also used to recharge the battery during the regenerative braking process. The secondary electric motor (MG1) acts as a generator and transfers power from the ICE to charge the battery. It also acts as a power source to power the MG2, and assists in the propulsion of the vehicle. A planetary gearbox is used as a mechanical power divider, which allows the mechanical power from the ICE shaft to be split into two energy paths to generate two drive powers. The first is a parallel path that connects the PCG to the TM wave and then transmits it to the wheel. The second is a serial path that connects the geartrain to another generator. Similar to the serial HEV, the is converted to an electric drive with additional power from the Traction Battery, thought control unit, and then powers the TM. The power at the wheels is the sum of power from ICE and the TM.

The planetary gears provide mechanical power transmission with independent rotation between planetary gears and ring gears. Therefore, the traction motor/generator shaft that controls the vehicle speed is connected to the ring gear and rotates at the revolution of TM. The internal shaft of the internal combustion engine is connected to the planetary carrier. The electric DC generator has a hollow shaft and is inserted into the ICE shaft. Its rotor is connected to a PGS sun gear and rotates with a variable rotation depending on the rotation difference between the ICE revolution and the TM revolution. The rotation of the shafts of TM and ICE is completely independent, so we tune ICE to operate in the higher efficiency region.

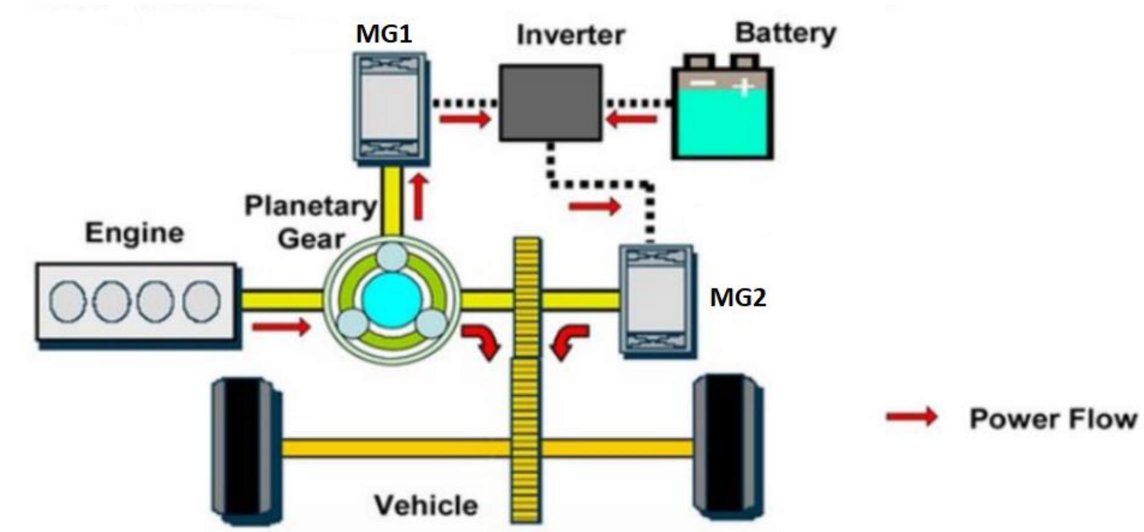

Figure 3. 3 *Series-Parallel hybrid vehicle power flow* [3]

3.2 HEV Types are based on the degree of Hybridisation

3.2.1 Mild hybrids

Mild hybrids are traditional vehicles that have limited hybrid capabilities. ICE is the primary source of tractive power and EM helps ICE accelerate the vehicle. When the EM is placed between the ICE and the gearbox, it is also used to start the ICE. This mild hybrid system features another lithium-ion battery that is charged during regenerative braking.

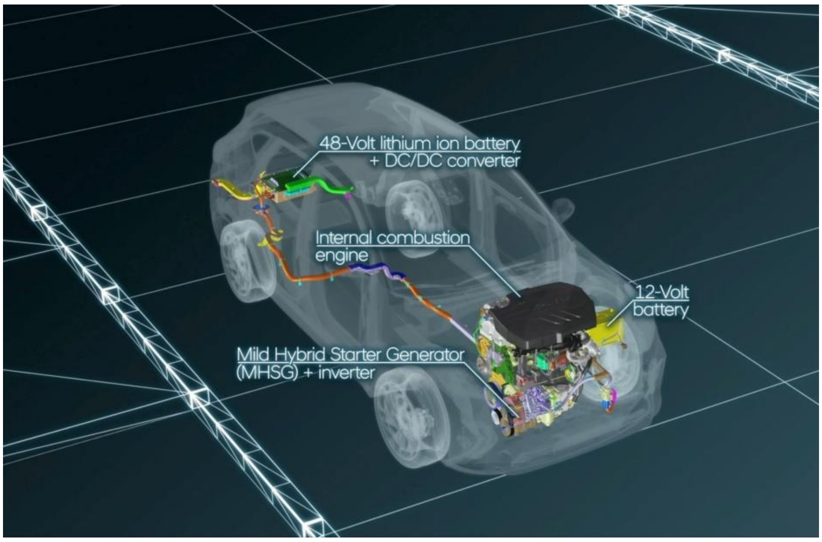

Figure 3. 4 Components of a mild Hybrid Vehicle [4]

3.2.2 Full Hybrid

A full Hybrid is a vehicle where the wheel power is provided either only by the ICE or by an EM or a combination of both ICE and EM. These vehicles require sophisticated deterministic algorithms to determine which power source to use during driving. A full hybrid vehicle can be operated in five regimes:

• EV mode: ICE is in off state and the battery powers the EM (also stores the charge generated during regenerative braking). For operating in this regime, the SOC (state of charge) of the battery should be high.

• Hybrid mode: When the vehicle is cruising (vehicle at constant speed) and the battery's SOC is low, the ICE power will be shared between the mechanical path to drive the vehicle and the generator which charges the battery. During this mode the engine is operated at higher power output to put it in more efficient condition, generally at high torque and RPM values and excess power is used for recharging the battery.

• Battery charging mode: When the battery SOC is low and car power requirements are also low then the ICE power is used to charge the battery.

• Power Boost Mode: When maximum power is required, the ICE and EM together power the vehicle during acceleration.

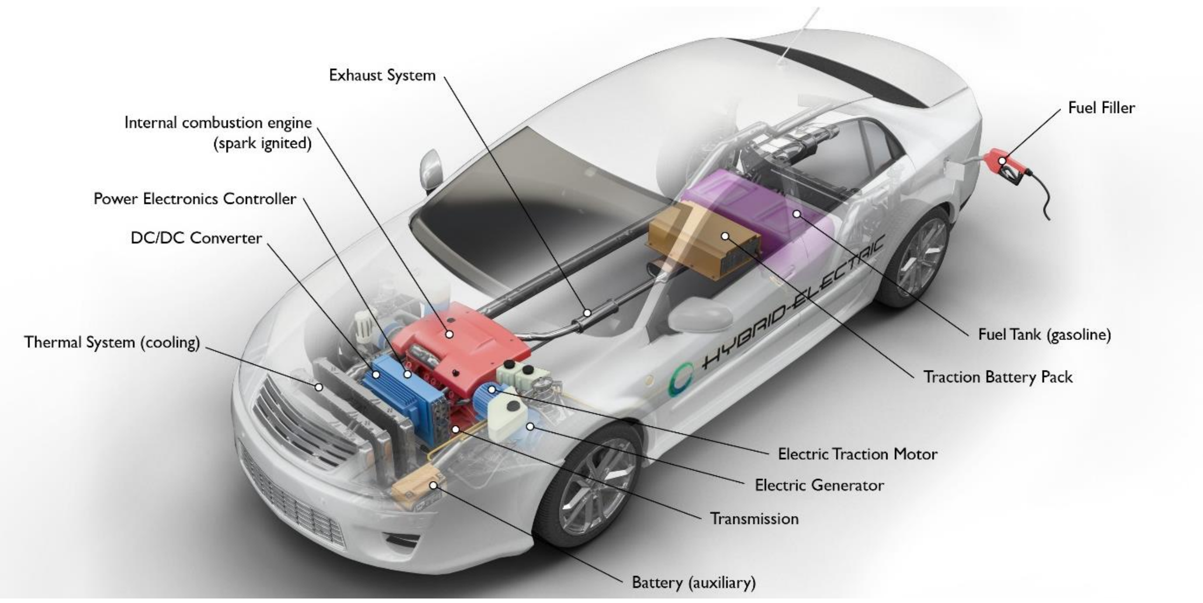

Figure 3. 5 Components of a Full Hybrid Vehicle [5]

3.2.3 Plug-in hybrid electric vehicle (PHEV)

A plug-in hybrid electric vehicle (PHEV) uses a battery to power the traction motor and and, to power an internal engine (ICE). PHEV batteries can be charged from a wall outlet or a charger, or via regenerative braking. The vehicle normally runs on power until the battery is almost empty, after which the vehicle automatically switches to using an internal combustion engine. PHEVs are a compromise between pure ICE vehicles and pure electric vehicles.

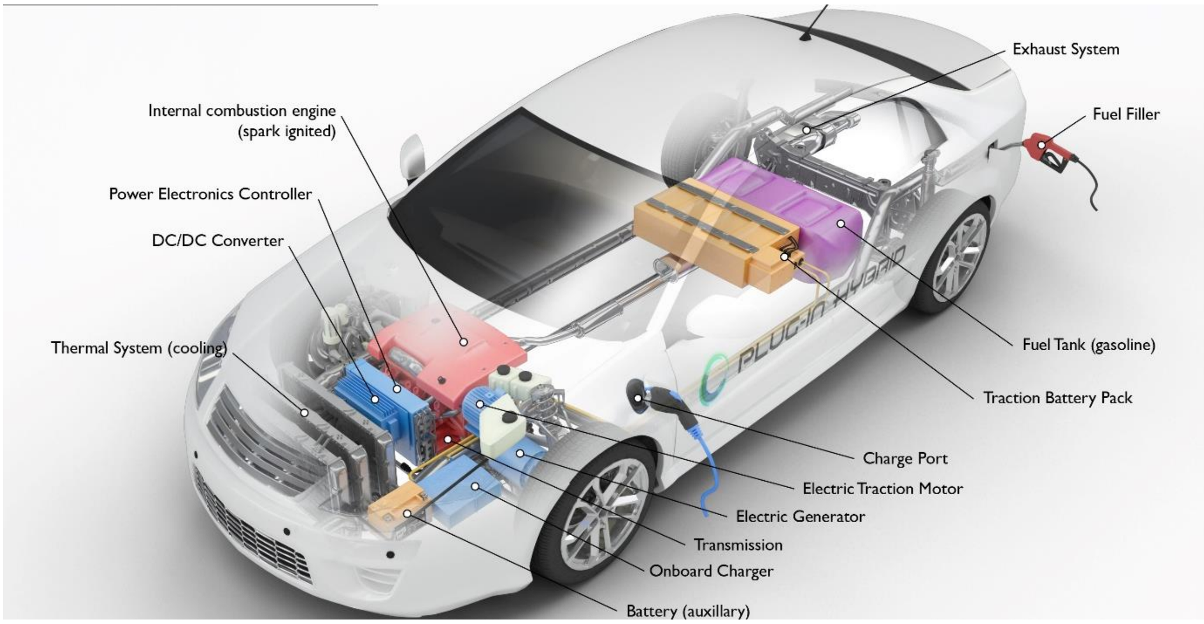

Figure 3. 6 Components of a Plugin Hybrid Electric Vehicle [5]

3.2.4 HEV-CVUT propulsion system

The main function of this hybrid powertrain's innovation is to use a supercapacitor (SC) as the energy storage unit and an electric power splitter (EPS) as the power division unit. The commercial hybrid electric vehicle uses a PGS and a separate EG to power the TM and charge the TB to split the power from the ICE. In the HEV-CVUT, the hybrid electrical system, the power split is completely electrical using EPS. Theoretically, one can expect to reduce the overall mass of the vehicle by reducing the weight of the component. This has direct effect on reducing fuel consumption. Also, eliminating one energy transformation means avoiding a significant energy transformation loss. The propulsion concept also uses the supercapacitor as a new technological element for storing electrical energy, instead of using chemical cells to store the kinetic braking energy in regenerative braking. This allows the SC to store energy without converting or converting energy from electricity to chemical energy, which would result in higher energy efficiency by reducing energy transformations.

The schematic representation of the HEV-CVUT working concept with EPS and the supercapacitor is shown in the figure below.

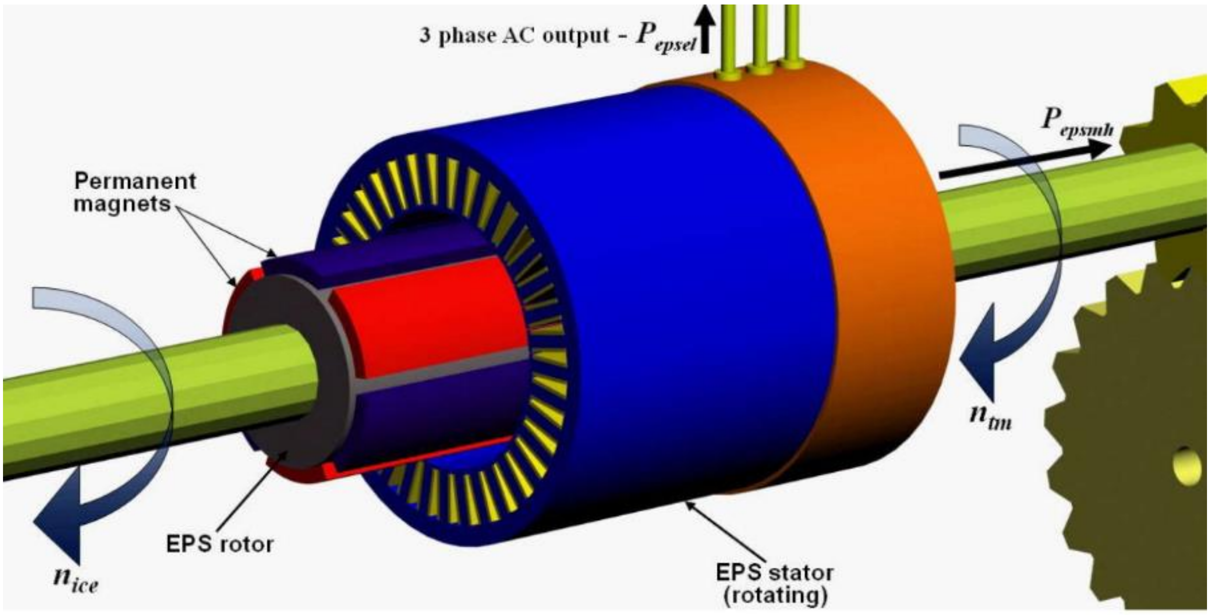

Figure 3 7 Detailed view of EPS unit [6]

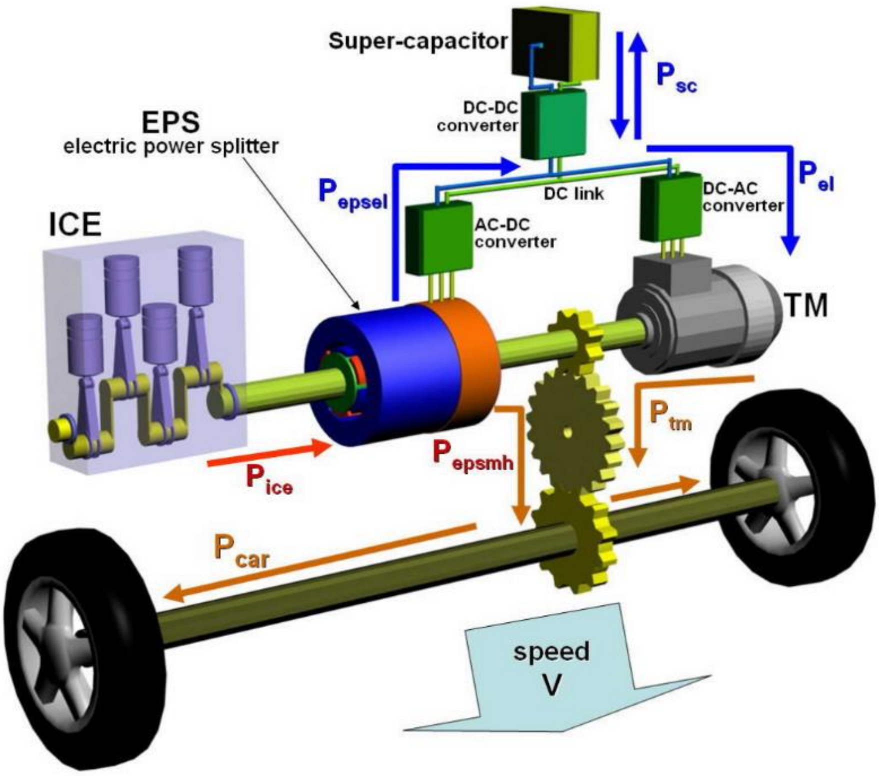

Figure 3 8 Power path for HEV-CVUT [7]

The internal combustion engine is the vehicle's primary and sole source of energy to produce mechanical energy. EPS is a special type of synchronous generator with two rotating components, a conventional permanent magnet rotor, and a rotating stator. The rotor is tightly coupled to the ICE drive shaft. The EPS stator is coupled to the gear that connects the TM to the car's wheels and spins at rpm in proportion to the vehicle speed. This technical solution allows the engine to run at optimal revs across the driving regimes, similar to serial HEVs.

This HEV system has distinguished powers at different paths of power transmission:

P_{ice} – mechanical output power on drive-shaft produced by ICE,

P_{epsmh} – mechanical output power on the stator shaft of the EPS,

P_{epsel} – electrical EPS output power to DC circuit,

P_{sc} – electrical charging (discharging) power to the SC,

P_{el} – electrical power of DC circuit that powers the TM,

P_{tm} – mechanical output power produced by the TM,

P_{car} – traction power at the wheel for propelling the vehicle

Mechanical power P_{ice} is split into electrical P_{epsel} and mechanical power P_{epsmh} by the concept made EPS. Electrical power division is done based on controlling the AC/DC power converter, which regulates the flow of current through the EPS stator windings. This current regulation regulates the magnetic field within the machine.

The regulated magnetic field allows the torque control on the stator shaft and by this means the mechanical power P_{epsmh}.

The induction traction motor (TM) is linked with the EPS rotating stator and the electrical power of the vehicle is transmitted to the TM. The EPS and TM are also electrically connected through two AC/DC and DC/AC power converters with an intermediate DC link. On the DC linkage, an electrical accumulator unit that consists of Super Capacitors(SC) is connected via charging and discharging DC-DC converter. TM is powered by electric current P_{el} which is generated by EPS(P_{epsel}) when it is being powered by ICE and by additionally stored power from SC(P_{sc}).

$$P_{el} = P_{epsel} + P_{sc} \cdot \eta_{dcdc} = P_{epsel} + P_{scdc} \qquad (3.1)$$

The Traction Motor TM converts this electrical power to mechanical power P_{tm}, which along with the mechanical power of EPS (P_{epsmh}) is transmitted to the wheels and propels the vehicle. The total mechanical power at the wheel of the car is the summation of these two powers from TM and EPS.

$$P_{veh} = (P_{epsmh} + P_{tm}).\eta_{trans} = (P_{epsmh} + P_{el}.\eta_{tm}.\eta_{dcac}).\eta_{trans} \qquad (3.2)$$

In braking conditions, TM changes its function from motor regime to generator regime. In the generator regime, it converts the kinetic energy that decelerates the vehicle into electrical energy which is then stored in the SC. This stored electrical energy is used for sudden acceleration and overcoming the resistive forces when starting the vehicle from a complete stop.

HEV-CVUT is a very complex hybrid electric drive concept. There are numerous power conversion and energy paths. Power control, energy path regulation, a detailed description of each component, and their capabilities and efficiencies are described in the next section of this task.

This hybrid electric propulsion concept has similar advantages as that of a parallel-series HEV. Using one power split device (EPS) instead of two separate devices (a Planetary gear set and a separate electric generator) results in higher fuel efficiency due to a smaller number of energy transformations and reduced component weight. EPS increases flexibility between the ICE drive shaft and the drivetrain. It is possible to have independent revolutions between both the shafts as it is not linked to each other mechanically. This is because the only connection between these two shafts is the magnetic field between the EPS stator and rotor. The energy accumulator unit gives more power during acceleration and regenerative power absorption, as it is fitted with supercapacitors instead of the traditional battery pack, which has a higher power density than the chemical cell.

With all these characteristics of the HEV-CVUT auto-hybrid system, this solution offers great technical potential for more fuel-efficient vehicles with the potential for more flexible and high-performance driving.

The HEV-CVUT is just a concept and has not been implemented into a vehicle that runs in real-time scenarios. For a comparison of this concept to similar available propulsion systems numerically calculated fuel consumption of the HEV-CVUT is compared with other commercial vehicles. It was later compared with the H.26 laboratory test bench results.

4 Electric drive in HEV

An electric drive in HEV is a connection between an electric machine (motor and generator) and a power conversion unit. The electric machine converts electrical energy from a source into mechanical energy which gives motion to the vehicle. A power converter unit is needed for the torque or speed control of the traction motor. The torque control and speed control are done based on the input from the driver's pedal position.

4.1 Electric motor

Many HEVs on the market today use the following two types of electric motor.

• Asynchronous induction machines (IMs)

• Permanent magnet synchronous machine (PMSMs)

4.1.1 Asynchronous induction motor (IM): Asynchronous induction motor (IM) is an AC motor with a 3-phase stator winding and a squirrel-cage type rotor. There are wound-type rotors as well but this type is not used in vehicles. The torque is produced by electromagnetic induction from the stator winding's rotating magnetic field. The efficiency of an IM is about 80 – 97%. The power losses occur due to copper losses caused by stator or rotor resistances, iron losses, and indirect losses caused by friction and ventilation.

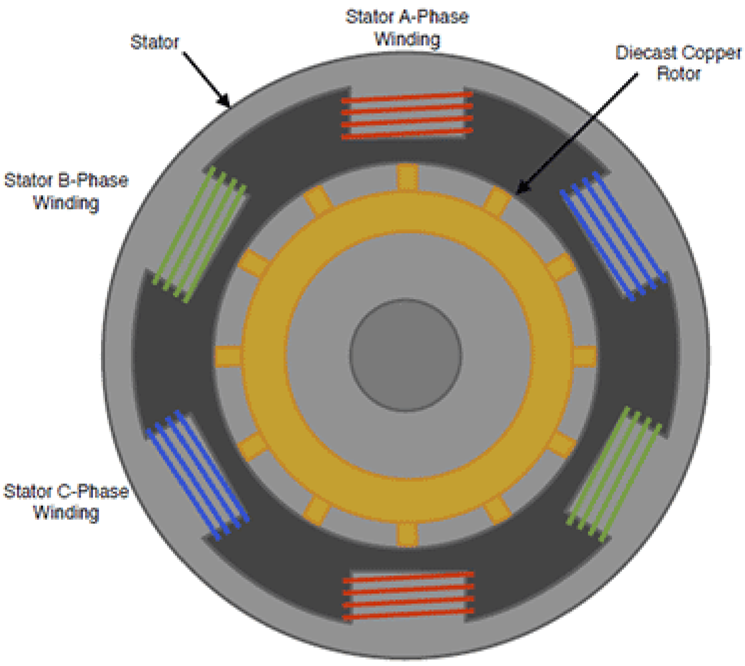

Figure 4. 1 Cross section of Asynchronous Induction Motor [8]

4.1.2 Permanent magnet synchronous motor (PMSM):

Permanent magnet synchronous motor (PMSM) is an AC electric motor with phase stator windings and a rotor with permanent magnets. Permanent magnets produce a constant magnetic field and the stator produces a rotating magnetic field. At synchronous speed, the rotor poles synchronize to the rotating magnetic field.

In the early days when the power electronics were not advanced, electric vehicles used a DC motor in series connection. Series connection means the connection of the armature winding and excitation windings is in series with a common DC source. This connection provides very high starting torque which is needed for bringing the vehicle in motion from a state of complete halt.

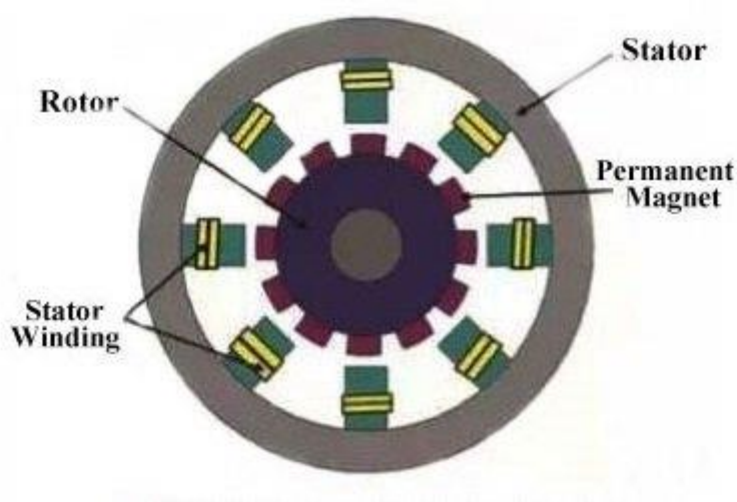

Figure 4. 2 Cross section of Permanent magnet synchronous motor [8]

An IM is not too sensitive to overcurrent and temperature whereas the magnets in PMSM have a maximum operating temperature of about 150°C. The magnets will lose the magnetic field if the temperature is more than the maximum operating temperature. IM tends to have a lower peak power density (50 kW / 48 kg) compared to PMSM (50 kW / 30 kg). However, the cost of PMSM is high because of the magnets normally used in motors. Size, weight, cost, and efficiency are some of the criteria based on which the electric motor is selected for the electric drive of Hybrid.

4.2 Battery

High voltage batteries are the main source of energy for electric motor drives. The capacity of a battery should provide enough energy to withstand normal operating hours of the day.

However, depending on the road conditions and the slope that occurs, the charge may not last long. Therefore, the control system needs to operate the vehicle and engine drive system as efficiently as possible to maximize the mileage per battery charge.

In urban traffic, where the vehicle must frequently slow down and stop, it is possible to convert part of the vehicle's kinetic energy back to electrical energy and store it in the battery.

Lithium-ion batteries have emerged as the leading type of most portable devices. However, in HEV-CVUT we are using supercapacitors to replace traditional battery packs as SC offers higher power densities as compared to chemical cells and a quicker charge/discharge cycle. The use of SC as an element for electrical storage allows storing energy without transformation from electrical to chemical and back. This brings higher efficiency in energy transformation.

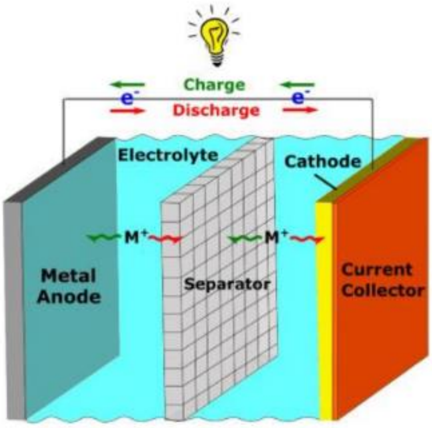

Figure 4. 3 Flow of charge in chemical battery [2]

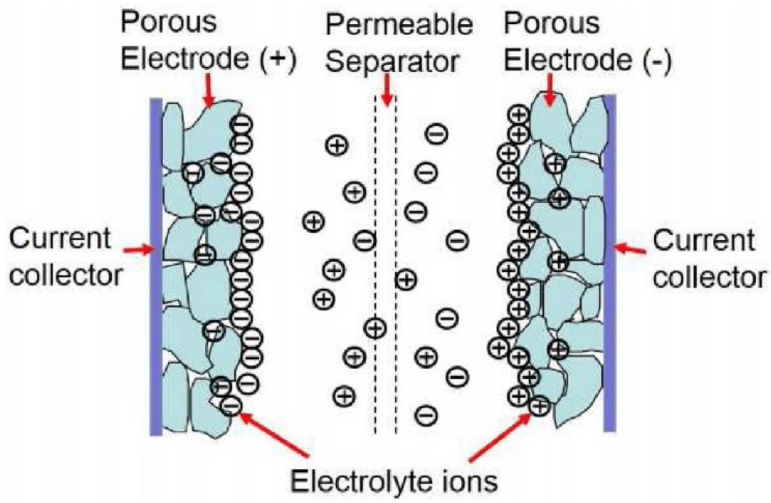

Figure 4. 4 Charging of a Super capacitor [2]

4.3 Inverter

The main function of the inverter is to convert DC voltage to AC voltage, and the frequency of the drive is synchronized with the rotor speed of the motor. The power inverter is used to generate a pulse width modulated voltage drive for the motor phase. This allows controlled currents to flow through the motor windings. Therefore, the inverter is an important part of the motor control circuit that allows control of the motor current, which produces a smooth torque output.

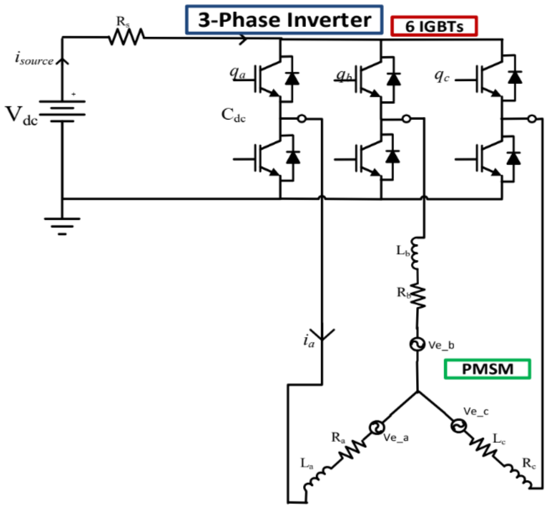

Figure 4. 5 Three phase inverter circuit [3]

4.4 DC-DC Converter

DC / DC converters are used for charging and discharging SC. By having DC-DC convertor the required voltage for device can be obtained. It also allows regulating power of each device by controlling the voltage input. Energy must be transferred from the high voltage side to the low voltage side and vice versa. Therefore, the converter must be bidirectional. Also, during regenerative braking, the power flow is in opposite direction, requiring the DC-DC convertor to be bidirectional.

To transfer energy from a higher voltage level to a lower voltage level, the DC / DC converter operates in buck mode, and to transfer energy from a lower voltage level to a higher voltage level, the DC / DC converter is in boost mode.

Figure 4. 6 DC-DC Converter Unit with cooling system [9]

5. Vehicle Dynamics

Driving performance simulation requires the creation of a vehicle motion model (KM), whether it is a conventional internal combustion engine, electric vehicle, or HEV. It is a mathematical representation of the vehicle's traction characteristics in a simulation program. The movement of vehicles on the road is a complex system described by multiple differential equations. The ideal rigid vehicle model is difficult enough for optimization purposes. There are different forces of different sizes, orientations, and points of application. Therefore, some simplifications have been introduced to create optimization algorithms that fit current computational capabilities and maintain sufficient accuracy. For these reasons, a simple linear KM is mathematically created for a particular vehicle model, which is based on factors such as vehicle weight, transmission efficiency, ICE's fuel consumption and output power, number of supercapacitors, or battery storage units, power converter efficiency. It also depends on environmental factors like road conditions, wind speed, and direction, air density. The vehicle's kinematic model is an approach that gives an estimation of the required traction power P_{veh} and required driving energy for a particular vehicle and driving conditions.

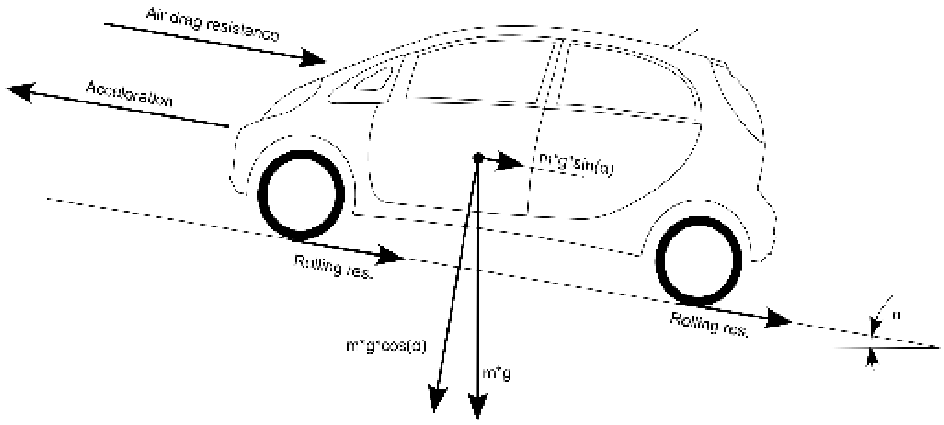

Figure 5. 1 Forces acting on a vehicle at a slope [10]

Once you know the mechanical energy required for the selected driving cycle, the next step is to analyse the efficiency of the propulsion and transmission system. Measuring resistance values at each time interval in the driving cycle is a consistent part of the vehicle dynamics calculation. These forces cancel the movement of the vehicle, and the sum of these forces provides traction performance and the total driving energy required for the entire driving cycle. While moving (driving), various resistances act on the vehicle.

- F_s – resistive gravity forces,
- F_{air} – aerodynamic drag forces,
- F_r – rolling resistance forces,
- F_a – acceleration force.

There are several variables in this force, a detailed description is the subject of the next section, and each of these forces will be examined individually.

5.1 Resistive gravity forces

Any two objects with a mass attract each other by a force called gravity. When gravity is applied to the mass m of the vehicle, the weight force F_g acts on the vehicle. This force is directly proportional to the product of their masses and is inversely proportional to the square of the distance between them. Our proposal considers a gravitational field with constant gravity when the distance between the vehicle and the earth is constant in terms of the size of the earth.

$$F_g = m \cdot g \tag{5.1}$$

The road is not flat and we need to consider the track profile where the track angle is still changing. When the vehicle is at an inclination (inclination at an angle α), F_g produces a force component in the direction of motion of the vehicle. This component is called resistive gravity force F_s and is the force that propels (or decelerates) the vehicle to a non-zero pitch angle α. This can be changed during time t.

$$F_s = F_g \cdot \sin\alpha(t) = m \cdot g \cdot \sin\alpha(t) \tag{5.2}$$

In this formulation, α (t) is the pitch angle concerning the horizontal motion of the vehicle, and m is the total mass of the vehicle, G is the total mass of the vehicle. Gravitational acceleration is constant. The weight force Fs depends on the slope of the road. When climbing a slope (α > 0) is positive (in the same direction as the rest of the drag). When going down a hill (α <0), it is negative and propels the vehicle. During road designing, a gradient of value lesser than 7% is used. In some passes, a high gradient of more than 7% is used and the following approximation is valid in such cases

$$\sin\alpha_{St} \approx \tan\alpha_{St} = \frac{q'}{100} \tag{5.3}$$

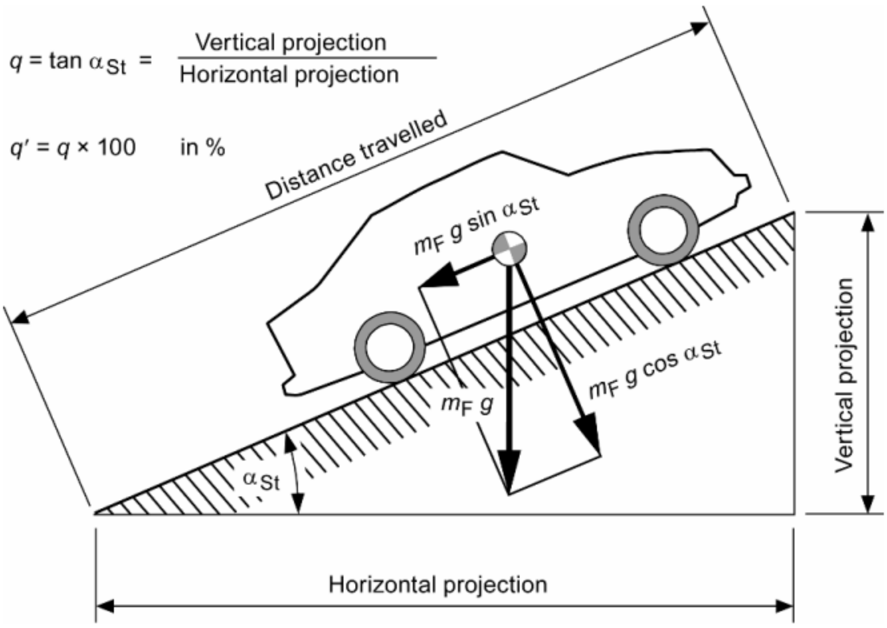

Figure 5. 2 Resistive force acting on a vehicle due to gradient of road [11]

5.2 Aerodynamic Drag Force

Air flows around the moving vehicle and through to fulfil the need for cooling and ventilation. Drag force F_{air} is due to the friction of the car body moving in the air. It is the resultant force of forces acting opposite to the relative motion of any object moving in respect to the surrounding fluid (between two fluid layers or a fluid and a solid surface). The drag force is directly proportional to velocity for laminar flow according to the Stokes law and squared for turbulent flow according to Newton's law.

$$R_e = \frac{v \cdot D}{\nu}$$

$$\nu = \frac{\mu}{\rho} \tag{5.4}$$

Here ν, is the kinematic viscosity of the liquid (viscosity μ divided by density ρ of fluid). and D is characteristic diameters. The type of flow changes from the hood of the car to the rear of the vehicle. Accurate measurement of flow along the vehicle is not suitable for this real-time simulation and optimization objectives. Therefore, Newton's resistance law based on the conservation of energy is used. An object moving through fluid pushes the originally still fluid. The force, that the vehicle exerts on the fluid, according to the principle of action and reaction, is equal to the drag force in the opposite direction. The work of this force is equal to the kinetic energy of the moving fluid. Drag forces depend on the front, shape, side mirrors, ducts, protrusions such as vents, spoilers, ground conditions, wheel impact, and many other factors. The force is expressed by the following equation.

$$F_{air}(t) = \frac{1}{2} \cdot \rho \cdot c_x \cdot A \cdot \left(V(t) - v_{wind}\right)^2 \tag{5.5}$$

This term is proportional to the square of the vehicle's speed V (t), so it tends to be smaller at low speeds, but increases rapidly with speed. The values of the equation are:

ρ -Density of air around,

c_x-Drag coefficient of the vehicle in the direction of travel,

A-Vehicle cross-sectional area,

V(t)- the magnitude of the velocity (i.e., speed) of the vehicle in the direction of travel,

v_{wind}- speed of the wind in direction of vehicle travel

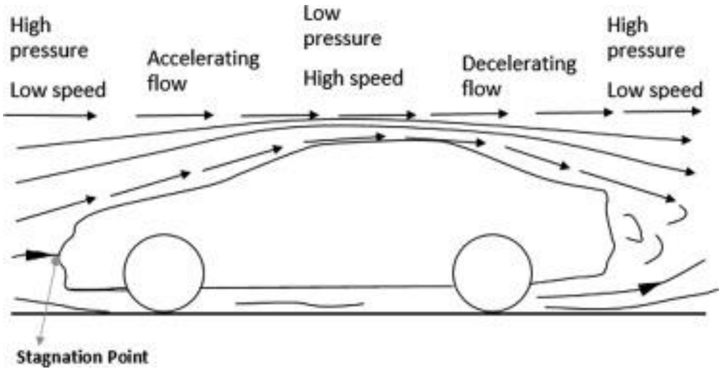

Figure 5. 3 Effect of air flow around the vehicle [3]

From the above-mentioned equation, we can see that the Drag resistance is directly proportional to the drag coefficient c_x. The drag coefficient c_x represents an assumed case of straight flow, that is when the wind direction is in line with the longitudinal axis of the vehicle. The drag coefficient c_x can be reduced by good vehicle design. This is a dimensionless value and is usually between 0.2 and 0.5. The aerodynamic drag coefficient of a sedan or hatchback is in general between 0.3 to 0.5, but some HEV designs reach as low as 0.19. The table below shows the drag coefficients for different vehicle types. The ideal aerodynamic shape is a teardrop with cx = 0.04. The ideal shape is the target of the vehicle's aerodynamicists. Modern fuel economy vehicle designs are usually as close as possible to this form. The aerodynamics of vehicles with bodies that block high air resistance, such as commercial vehicles, can be significantly improved by using air baffles.

Vehicle	c_x	A (m^2)	$c_x A$ (m^2)
***Motorcycle with rider**)*	***0.5–0.7***	***0.7–0.9***	***0.4–0.6***
BMW K 1200 S*)	0.58	0.71	0.41
BMW R 1200 GS*)	0.62	0.85	0.52
Convertible	***0.29–0.53***	***1.58–2.90***	***0.58–1.54***
Opel Tigra TwinTop			
Roof open	0.40	1.94	0.78
Roof closed	0.35	1.94	0.67
Mercedes-Benz SLK 200 K			
Roof open	0.37	1.93	0.71
Roof closed	0.32	1.93	0.62
Mercedes-Benz SL 500			
Roof open	0.34	2.00	0.68
Roof closed	0.29	2.00	0.58
Audi A4 Cabrio			
Roof open	0.34	2.11	0.72
Roof closed	0.31	2.11	0.65
Limousine/SUV	***0.25–0.39***	***1.97–2.90***	***0.50–1.54***
Ford Fiesta 1.4l	0.34	2.06	0.70
VW Golf V 1.4l	0.32	2.22	0.72
Mercedes-Benz B 180 CDI	0.30	2.42	0.73
BMW 320i	0.28	2.11	0.59
Audi A6 Avant	0.31	2.26	0.70
Mercedes-Benz S 320 CDI	0.26	2.40	0.62
Mercedes-Benz ML 280 CDI	0.34	2.81	0.96
Porsche Cayenne Turbo	0.39	2.78	1.09
BMW 645i	0.29	2.15	0.62
Porsche 911 Carrera	0.28	2.00	0.56
Van	***0.35–0.40***	***3.1–4.2***	***1.1–1.7***
Opel Vivaro Life	0.37	3.38	1.24
Ford Transit MWB, MJ06	0.35	4.14	1.45
Bus	***0.4–0.8***	***6.0–10.0***	***2.4–8.0***
Setra 415 HD	0.44	8.26	3.63
Light trucks	***0.40–0.60***	***4.5–6.0***	***1.8–3.6***
Truck (Solo)	***0.45–0.80***	***6.0–10.0***	***2.7–8.0***
Truck with trailer	***0.55–0.85***	***7.0–10.0***	***3.9–8.5***
Articulated vehicle	***0.45–0.75***	***7.0–10.0***	***3.2–7.5***

Table 5. 1 Reference values for drag coefficient c_x [10]

The atmospheric environment also has a significant impact on this F_{air} value. The density of air ρ in the surroundings depends on temperature, altitude, and humidity. A value of 1.2 [kg / m3] is a standard value used for theoretical calculations and in vehicle dynamics simulations.

5.3 Rolling Resistance

Rolling resistance is the result of the relationship between the tires of a car and the road on which the vehicle is moving. This is caused by the hysteresis of the tire material in the area of contact with the road. Hysteresis causes the asymmetric distribution of ground reactions. For stationary tires, the normal force on the road balances the distributed weight carried by the wheels at the points of contact along the vertical line below the axle. As the tire rolls, as shown in the figure, the centre of the vertical force on the wheel moves forward from under the axle in the direction of travel of the vehicle. Due to tire hysteresis, the weight of the wheel and the normal force of the road surface are out of alignment. They form a pair that exerts braking torque on the wheels. The pressure in the first half is higher than the pressure in the second half of the contact area. As a result, the force on the ground is displaced forward and appears as a rolling resistance F_r that opposes the movement of the wheels. This force is in contact with the roadway and always helps to slow down the brakes and movement of the vehicle. It consists of rolling resistance, road surface resistance, and skid resistance. The figure below shows the forces and moments acting on the wheel. The integral of the pressure distribution over the tyre contact area gives the reaction force R, the same as the wheel load G_R. Due to the asymmetric pressure distribution of the wheel contact area of the rolling wheel, the reaction point of the force R is in front of the wheel axis by the amount of eccentricity e. If the wheel is not accelerating and is driven by T_R,

$$T_R = F_U\, r_{dyn} + R\, e \tag{5.6}$$

for a rolling wheel with no drive torque and no brake torque ($T_R = 0$)

$$-F_U = \frac{e}{r_{dyn}} R \tag{5.7}$$

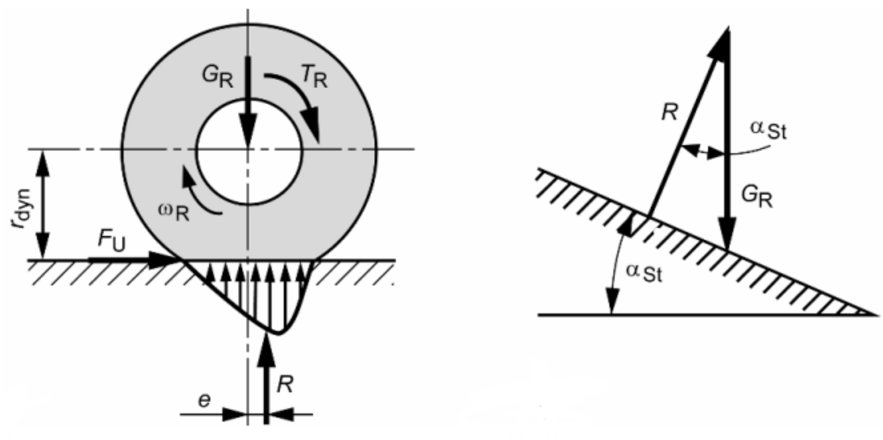

Figure 5. 4 Forces and torques at the wheel. (Left) On the level; (Right) on uphill/downhill stretch [10]

The circumferential force $-F_U$ is equal to the rolling resistance force $F_{R,Roll}$ based on these assumptions. On a levelled surface, $R = G_R$, and therefore

$$F_{R,Roll} = \frac{e}{r_{dyn}} G_R \quad (5.8)$$

There is an almost linear correlation between the rolling resistance force $F_{R,Roll}$, and the wheel load G_R. It is given by the formula

$$F_{R,Roll} = f_R \, G_R \quad (5.9)$$

The dimensionless proportionality factor f_r is known as the rolling resistance coefficient.

$$f_r = \frac{e}{rdyn} \quad (5.10)$$

The table below shows standard values for rolling resistance coefficients both on and off-road.

Road surface	**Rolling resistance coefficient f_R**
Firm road surface	
Smooth tarmac road	0.010
Smooth concrete road	0.011
Rough, good concrete surface	0.014
Good stone paving	0.020
Bad, worn road surface	0.035
Unmade road surface	
Very good earth tracks	0.045
Bad earth tracks	0.160
Tracked tractor on acre soil	0.070–0.120
Clamp wheels on acre soil	0.140–0.240
Loose sand	0.150–0.300

Table 5. 2 Reference values for the rolling resistance coefficient f_R [10]

Rolling resistance is chiefly a function of ground speed, wheel load, tyre pressure, and tyre type.

Since driving resistance calculations in normal cases is assumed as straight running on a dry surface, and rolling resistance is the dominant wheel resistance, and wheel resistance is normally assumed to be equal to rolling resistance. The following formula then applies

$$F_R = F_{R,Roll} \quad (5.11)$$

When traveling on an inclined path at an angle of α_{St}, then

$$R = G_R \cos\alpha_{St} \tag{5.12}$$

For a vehicle with a given mass of m_F, the wheel resistance of F_R, considered equal to the rolling resistance, is given by

$$F_R = f_R \ m_F \ g \cos\alpha_{St} \tag{5.13}$$

For the above-given formula when the vehicle is at low speeds, the rolling resistance factor can be taken as a constant. For a normal movement with an uphill/downhill slope of less than 10%, the slope angle α_{St} is 1 and is negligible.

There is a frictional connection between the tires outer surface and the road surface. Therefore, the transmittable circumferential force F_U is proportional to the wheel load reaction force R and is given by

$$F_{U,max} = F_{Z,max} = \mu_H \ R \tag{5.14}$$

The maximum traction F_Z between the tyres and the road surface is limited by the adhesion limit of the tyres.

Road speed (km/h)	**Static coefficient of friction μ_H**	
	Dry road surface	Wet road surface
50	0.85	0.65
90	0.80	0.60
130	0.75	0.55

Table 5. 3 Static coefficient of friction μ_H of new pneumatic tyres on road surfaces [10]

5.4 Acceleration Resistance

The mass inertia of the vehicle is represented by the acceleration force F_a. This force is derived from the basic equation of Newton's second law of motion of the solid body. In addition to the driving resistance which occurs in a steady state motion (v = const.), inertial forces also occur during the acceleration and braking period. It is non-zero only when the vehicle is accelerated ($a>0$) or decelerated ($a<0$) and has zero effect under constant-speed cruising conditions ($a=0$). This force is dependent on the total mass of the vehicle m_F (translatory component) and the inertial mass of internal rotating components which are being accelerated or braked (rotational component).

$$F_a = m_{red,i}\, a\,, \quad \text{with}$$

$$m_{red,i} = m_F + \frac{\sum J_{red,i}}{r_{dyn}^2} \tag{5.15}$$

The rotational component varies as per the gear ratios. The moment of inertia of the rotating elements of the engine, gearbox components, drive shaft, etc, including all the road wheels, are reduced to the driving axle. This reduces to $J_{red,i}$. The acceleration resistance is frequently represented in a simplified form as

$$F_a = \lambda\, m_F\, a \tag{5.16}$$

where λ is a rotational inertia coefficient, expressing the proportion of the total mass that is rotational. Standard values for the rotational inertia coefficient for passenger cars are given in the table below.

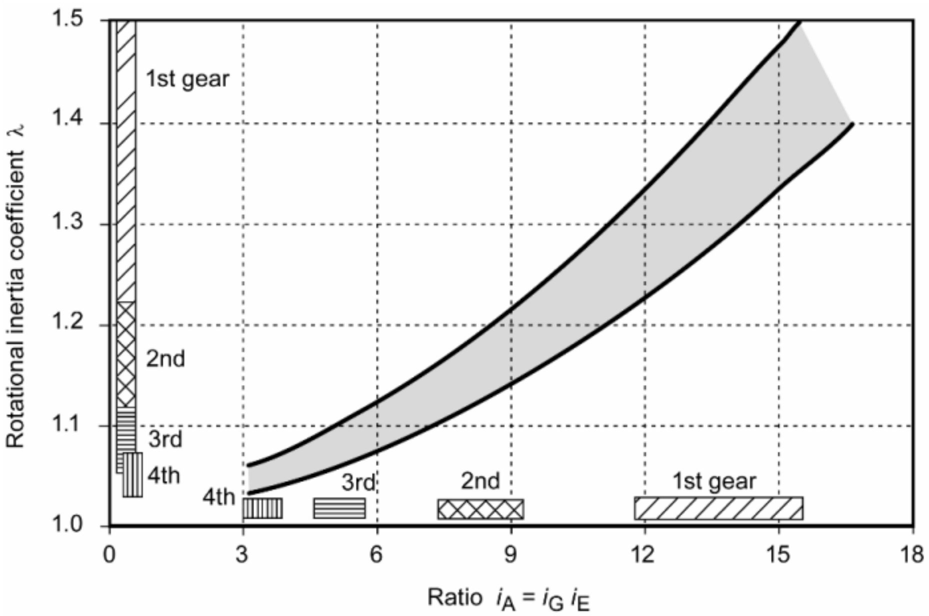

Figure 5. 5 Rotational inertia coefficient as function of the gear ratios [10]

This force is the major factor in a vehicle's traction performance (P_{veh}) value. For most of the driving period, the force F_a is very low or zero, i.e., when the vehicle is cruising ($\Delta V(t) = 0$), but for short periods the value might get 10 times higher than the sum of all other resistive forces. These short acceleration values are critical to the consumer when considering vehicle performance. For ICE or hybrid powertrains only, the power dimensions of the powertrain are strictly dependent on this power.

5.5 Total Driving Resistance

The above-discussed resistance forces act on the C.O.G(a theoretical point of the vehicle where all its weight and force components acts) of the vehicle. The force component is defined on the x-axis (towards the direction of travel of the vehicle) and the y-axis (perpendicular to the road). Resistive forces are in the opposite direction and counter the movement of the vehicle.
The traction force $F_{Z,B}$ needed at the drive wheels is the sum of the driving resistance forces we discussed above and is defined as

$$F_{Z,B}=F_s+F_{air}+F_r+F_a \tag{5.17}$$

When the above resistance value is inserted, the equation expands to

$$F_{Z,B}=m_F\ g\left(f_R\ \cos\alpha_{St}+\sin\alpha_{St}\right)+\frac{1}{2}\rho_L\ c_W\ A\,v^2+m_F\ \lambda\ a \tag{5.18}$$

This can be used to calculate power requirement $P_{Z,B}$

$$P_{Z,B}=F_{Z,B}\ v \tag{5.19}$$

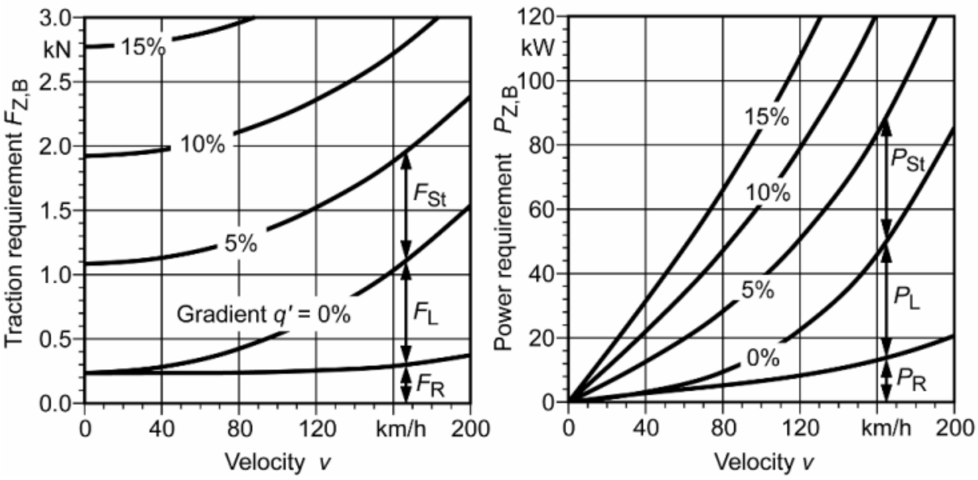

Figure 5. 6 Traction required and the resultant power required for a mid-size passenger car [10]

The road resistive power P_{road} as a function of vehicle speed V is calculated using the above formula. This computed characteristic is then compared with measured values from HEV-CVUT experimental working stand. During the transient process, when traction force F_{veh} overvalues road resistive forces, the result is a positive acceleration force.

5.6 Rating traction power of Vehicle

The vehicle traction force P_{veh} required as the propulsion force to overtake the resistances can be calculated based on the above-discussed formula. Instantaneous propulsion power P_{veh} (t) depends on system limits for starting acceleration, road gradient, rated, and maximum vehicle speed.

$$P_{veh}(t) = F_{veh}(t) . V(t) \tag{5.20}$$

Expanding the components of P_{veh} based on real driving conditions

$$P_{veh}(t) = [m \cdot g \cdot (f(t) \cdot \cos\alpha(t) + \sin\alpha(t)) + \frac{1}{2} \cdot \rho \cdot c_x \cdot A \cdot \left(V(t) - v_{wind}\right)^2 + m \cdot \frac{dV(t)}{dt}] \cdot V(t) \tag{5.21}$$

The torque at the wheels is

$$P_{veh\_road}(t) = M_{veh}(t) \cdot \omega_w(t) = P_{veh}(t) \cdot \eta_{trans}(t) \tag{5.22}$$

M_{veh} is the tractive torque

ω_w is angular velocity of the wheel.

Assuming zero slip between the tires and the road, the angular velocity and the vehicle speed can be calculated with the formula

$$V(t) = \omega(t) \cdot r_w \tag{5.23}$$

r_w is the radius of the wheel

When calculating the power requirements of an engine, we need to consider the loss between the engine, wheels, transmission, and the differential. The advantage of a hybrid vehicle with an electric drive system and an EPS is that it eliminates the need for multiple gears to keep up with vehicle and engine revolutions. An electric motor offers a wide speed range made possible by power electronics opens up the possibility of using a single ratio gear to instantly adapt the available motor torque M_{tm} to the desired traction torque M_{veh}. The gear ratio depends on the maximum motor speed n_{tm}, maximum vehicle speed V_{veh}, and wheel radius r_w. Higher motor speeds compared to vehicle speeds mean higher gear ratios, larger sizes, and higher costs. However, higher motor speeds are also desirable for higher output density. Therefore, to optimize costs, a compromise between maximum motor speed n_{tm} and gear ratio k_r is required.

The energy required from the powertrain unit depends on the required vehicle acceleration and the tyre load F_{veh} that the vehicle must overcome. The maximum acceleration a_{max} of the vehicle is limited by the maximum traction force P_{veh_max} available and the condition of the road (slip between the contact patch of tyres and the road) when the vehicle is in motion. The value of F_{veh} on the actual road is unknown, but research into possible scenarios can provide important insights into vehicle speed profiles and energy demand. This leads to the creation of a driving control strategy, which is a major design factor for HEV-CVUT propulsion systems. Vehicles are typically designed with specific goals, such as achieving higher fuel efficiency on specific road slopes in specific weather conditions. The total energy is calculated by integrating the instantaneous vehicle output P_{veh} for the entire driving cycle.

$$E_{veh} = \int_{t_1}^{t_2} P_{veh}(t)dt \tag{5.24}$$

Using the same equation, we can calculate the driving trajectory of the vehicle through the drive cycle

$$S_{veh} = \int_{t_1}^{t_2} V(t)dt = \int_{t_1}^{t_2} a(t)tdt \tag{5.25}$$

Total driving trajectory denoted by S_{veh} is a function of the fuel consumed for propelling the vehicle L_{veh} defines fuel consumption of the vehicle Q_{veh}.

5.7 Designing vehicle control strategy using a Quasi-static approach

All standardized and institutionally validated control strategies are created using a quasi-static approach to calculate the energy balance and power management of the vehicle's powertrain. The quasi-static approach assumes that velocity, gradient, and acceleration are constant at a time interval ΔT_h that is small enough to meet this assumption. Normally, this time interval is constant and standardized, such as in WLTP and NEDC cycles, whose values are equal to 1 second (ΔT_h = 1 [s]). The calculation time interval for the simulations created in this paper has been reduced (ΔT_h = 0.3 [s]). This value is done to improve the accuracy of the quasi-static calculation of the HEV-CVUT control strategy, at the same time the value is not kept very small to save computing time and memory needed for simulation.

The kinematical model of the vehicle is mathematically interpolated into MATLAB for simulation. For each computational time, sub-interval ($\Delta T_n = T_n - T_{n-1}$) of driving cycle following values are calculated and stored.

Acceleration

$$a_1 = \frac{V_2 - V_1}{t_2 - t_1},\ a_2 = \frac{V_3 - V_2}{t_3 - t_2},\ \dots,\ a_{n-1} = \frac{V_n - V_{n-1}}{t_n - t_{n-1}} \tag{5.26}$$

$$\Delta S_1 = \frac{a_1 \cdot \Delta t_1^2}{2},\ \Delta S_2 = \frac{a_2 \cdot \Delta t_2^2}{2},\ \dots,\ \Delta S_{n-1} = \frac{a_{n-1} \cdot \Delta t_{n-1}^2}{2}$$

Car trajectory distance (5.27)

Resistive forces $F_{a1}; F_{r1}; F_{air1}; F_{s1},\ F_{a2}; F_{r2}; F_{air2}; F_{s2},\ldots, F_{an-1}; F_{rn-1}; F_{airn-1}; F_{sn-1}$ (5.28)

Using the equations average traction power P_{car} is calculated for each sub-interval

$$P_{veh1} = F_{veh1} \cdot V_1, P_{veh2} \cdot V_2 = F_{veh2},\ldots, P_{vehn-1} = F_{vehn-1} \cdot V_{n-1} \tag{5.29}$$

Control strategy has pre-defined power management through the individual pathway of the propulsion system, which enables instantaneous calculation of energy efficiency of power transformation units.

$$\eta_{ps1}; \eta_{c1}; \eta_{tm1}; \eta_{c-dc1} \ldots, \eta_{ps2}; \eta_{c2}; \eta_{tm2}; \eta_{c-dc2} \ldots \ldots \eta_{psn-1}; \eta_{cn-1}; \eta_{tmn-1}; \eta_{c-dcn-1} \ldots$$

Since we know the efficiency of pathways we can calculate power flow.

$$P_{ice1}; P_{epsel1}; P_{epsmh1}; P_{tm1}; P_{sc1}; P_{car1}; \ldots,\ P_{ice2}; P_{epsel2}; P_{epsmh2}; P_{tm2}; P_{sc2}; P_{car2}; \ldots$$

Corresponding energy in each energy pathway is calculated from computed power

$$\Delta E_n = \int_{T_{n-1}}^{T_n} P_n(t)dt \approx P_n \Delta T_n \tag{5.30}$$

The quasi-static method is suitable for calculating fuel consumption in complex powertrain structures. This approach allows you to design a monitoring and control system that optimizes the power flow of the propulsion system. The effects of driving type and patterns can be included in these calculations. We will discuss modelling of the drive system and simulation of vehicle behaviour based on WLTC class 3 test cycle. Experimenting with the dynamometer engine test bench is one way to verify the quality of the predictions obtained by quasi-static simulation. Therefore, the HEV-CVUT propulsion system is tested in the H26 laboratory for comparing it to an HEV.

6. Approach for creating control strategy

The simulation of control strategy in a program begins with the definition of the driving cycle, in this case, the Worldwide harmonized Light vehicles Test Cycles (WLTC) class 3 driving cycle. We can also programmatically change the driving cycle and adjust other time-dependent parameters, depending on the requirements. For example, using the same simulation program structure and control strategy, we can get a silent drive for city driving where less noise pollution is beneficiary (electrically driven only with different road gradients). The simulation approach is based on a quasi-static method. It uses predictive computational logic. That is, the control strategy anticipates the following traction situations and adjusts the driving components of the system accordingly. This method is essential because the control strategy created in this task is not only used for simulation purposes but can also be used in real-world applications by predictive logic. In a real propulsion system, a control strategy based on onboard central computer controller control should be prepared for all possible unpredictable driving situations. At each time interval ΔT_n, the control strategy calculates all the parameters of the system and prepares for the next possible situations that can occur at the next time interval $\Delta Tn + 1$.

6.1 Defining basic vehicle parameters for simulation

The kinematical model parameters for determining the resistive forces and required power to propel P_{car} are defined in the program interface and altered according to the needed vehicle model and specific driving conditions. For our simulation purpose we have taken the following value of environmental conditions and vehicle parameters:
density of the air r=1.2[kg/m^2],
gravity constant g =9.81[m/s^2],
speed of the wind v_{wind}=0[km/h],
mass of the vehicle m=1600[kg],
coefficient of air-drag c_x=0.33,
cross-sectional area A=2[m^2],
coefficient of rolling resistance f=0.01,
number of supercapacitors N_{sc}=4,
the capacity of one SC unit C_{sc1}=200[F],
SOC of SC at the start of drive $W_{sc\_start}= W_{sc\_max},$
The engine block selected for simulation is a 4 cylinder 1.6L SI engine available in Simulink.
The acceleration is constant at any two vehicle speed points. The program calculates the acceleration for the entire driving cycle. It is calculated by the formula:

$$a_N = \frac{dV}{dt} = \frac{\Delta V_N}{\Delta T_N} = \frac{V_n - V_{n-1}}{T_n - T_{n-1}} \tag{6.1}$$

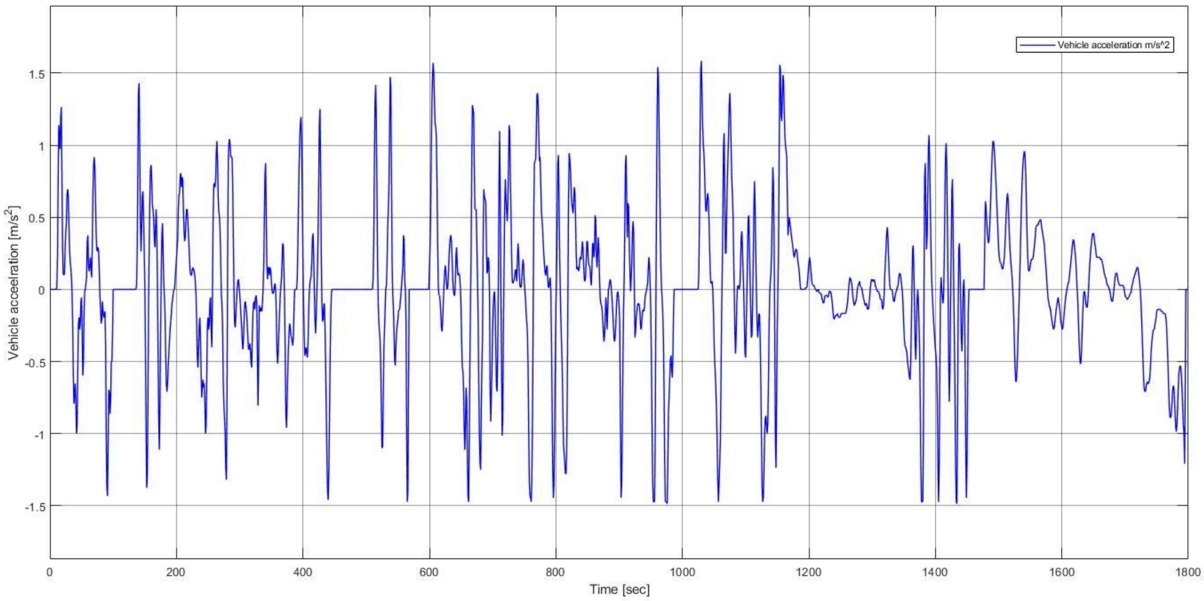

Figure 6. 1 Vehicle acceleration for the WLTC class 3 driving cycle

For a particular driving cycle, the acceleration at any point in time is known and assigned in advance. In this HEV-CVUT control strategy, the acceleration is calculated according to the instantaneous speed-time condition. This approach is used because the upcoming accelerations from the driver is an unknown variable in actual driving and the control strategy should be designed to be based on the measurement of acceleration continuously provided by the accelerometers, on-board.

Vehicle velocity- V_{veh} is calculated at any time:

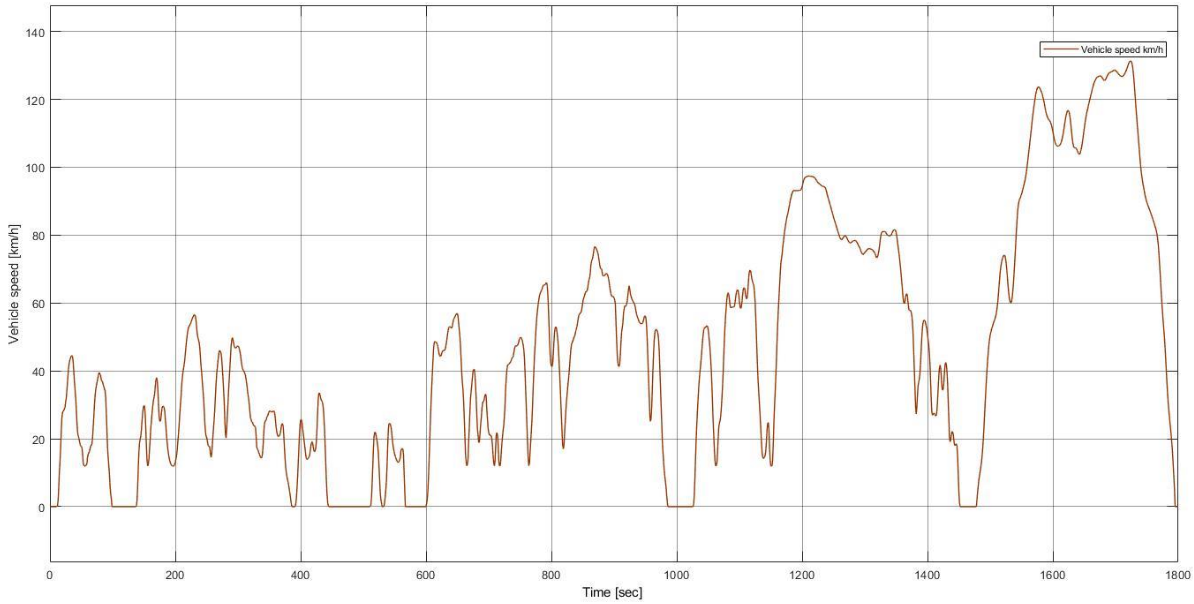

Figure 6. 2 Vehicle speed for WLTC class 3 driving cycle

6.2 Tractive power and resistance calculation

Driving resistances are calculated using the kinematic model relationships we discussed in the previous section of resistive forces. For a defined driving cycle and given vehicle parameters and driving conditions, the simulation program calculates all the resistances F_r (rolling resistance), F_s (gravity), F_{air} (aerodynamic), and F_a (acceleration).

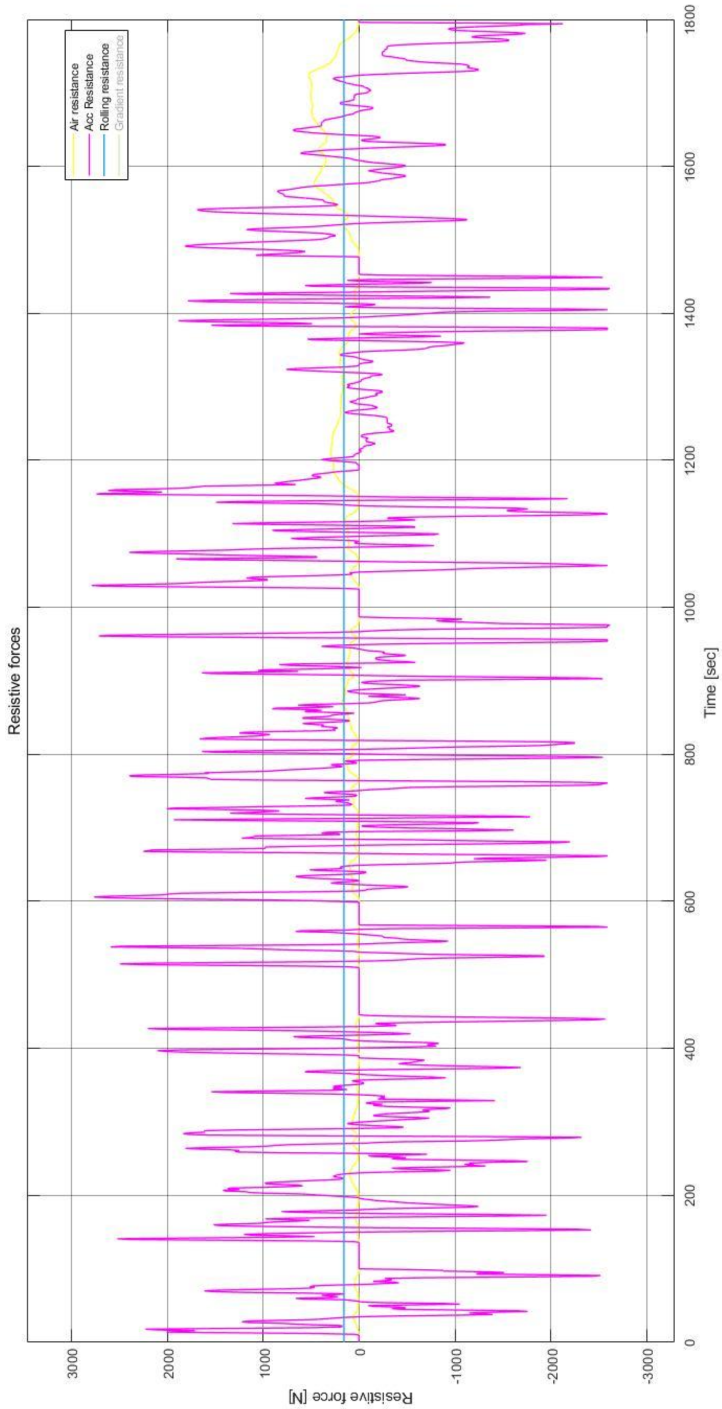

Figure 6. 3 Resistive forces F_{air}, F_a, F_r, and F_s simulated for WLTC class 3 driving cycle

Total driving resistive force acting on the vehicle at any point F_{veh} is the sum of all these resistive forces.

$$F_{veh}^{t_n} = F_a^{t_n} + F_r^{t_n} + F_{air}^{t_n} + F_s^{t_n} \tag{6.2}$$

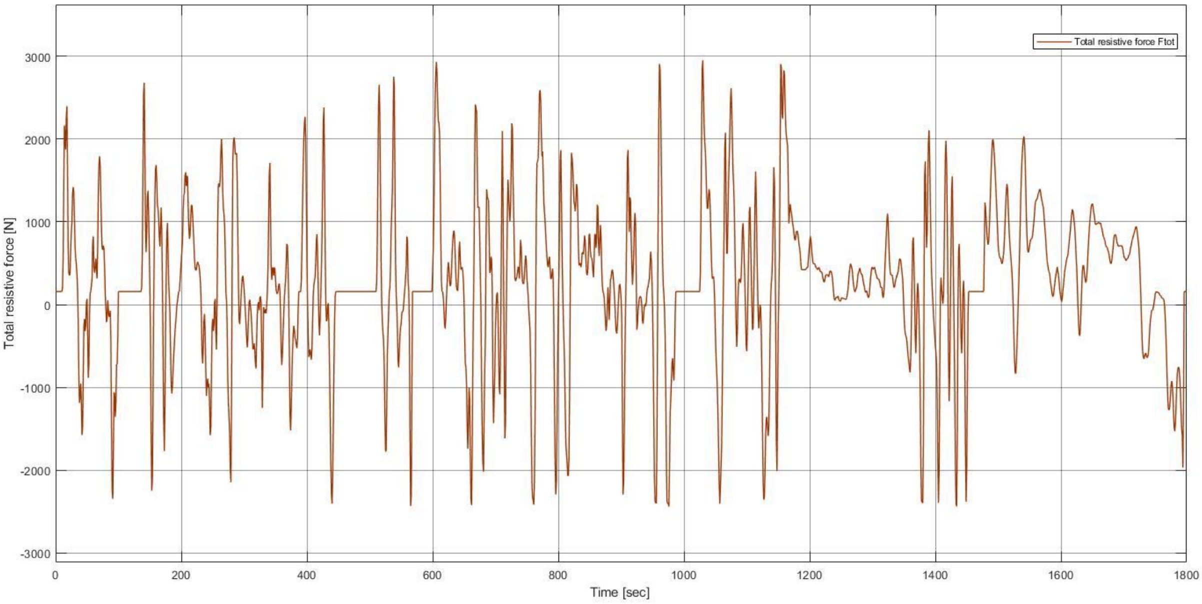

Figure 6. 4 Total resistive force acting on the vehicle in WLTC class 3 driving cycle

Calculating total resistive force F_{veh} and speed V_{veh} in each time interval provides data needed for calculating the vehicle's traction power P_{veh}:

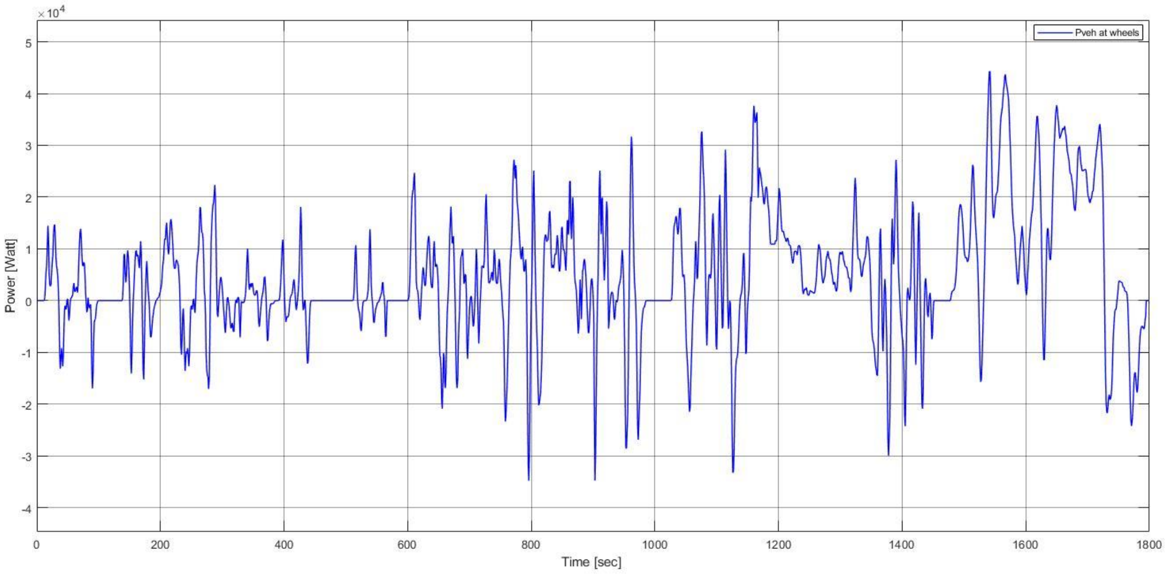

Figure 6. 5 Power on wheels in WLTC class 3 driving cycle

All other hybrid electric vehicle parameters, component functions, and driving parameters are directly dependent on the tractive power P_{veh}. As we have discussed before, the total output power to the wheels P_{veh} that propels the vehicle must be equal to the mechanical output P_{tm} generated by TM and the mechanical output P_{epsmh} of EPS. This power is given by the two power sources available on board which are the ICE and SC.

6.3 Control strategy for ICE

The internal combustion engine is the only source of power for the HEV system and does not take into account the power source of the accumulator unit. The best fuel efficiency results can be achieved by strategically defining the control strategy of the combustion engine. This strategy relies directly on many parameters such as vehicle power demand P_{veh}, amount of energy stored in supercapacitors W_{sc}, vehicle speed V_{veh}, vehicle acceleration, SC voltage U_{sc}, and instantaneous drivetrain efficiency.

For standard vehicles (ICE vehicles only), the relationship is $P_{veh} \leftrightarrow P_{ice}$:

$$P_{ice} = P_{veh} \cdot C_{trans} \tag{6.3}$$

The constant C_{trans} is the transmission coefficient. As a result, for the vehicle power demand P_{veh}, the engine power P_{ice} is the output value required from the engine. The P_{ice} should follow P_{veh} perfectly, with an additional increased value (to cover the transmit power loss). Due to such power demand, the Internal combustion engines have sudden power fluctuations with high-value peaks in short time intervals (engine power bursts). This working regime places the internal combustion engine in an inefficient working range where fuel consumption is higher. Rapid and instantaneous changes in engine speed and power output cause uneven combustion resulting in high inefficiencies. The ICE must be in constant operation throughout the driving cycle. When the vehicle is decelerating, idling, or completely stopped, the ICE operates at minimum power, wasting fuel. This regime theoretically has zero efficiencies because it consumes fuel without having any distance travelled.

The regulatory strategy for ICE in HEV-CVUT propulsion systems is very complex. The non-direct mechanical linkage between the engine output shaft and the wheel driveshaft allows the rotation of the ICE n_{ice} shaft to be freely adjusted regardless of the vehicle speed V_{veh}. HEVs also have another energy source, supercapacitors in our case. It can supply or absorb boost power P_{sc} to the drivetrain. All these properties allow smooth power control of the ICE, regardless of the traction power requirement P_{veh}. P_{ice} is calculated from the P_{ice_car} value. This number is derived directly from P_{veh}

$$P_{veh\_ice} = P_{veh} \cdot C_{trans} \cdot K_{sc} \tag{6.4}$$

We have declared a constant K_{sc} whose value is between 0 to 1 and is directly dependent on the actual voltage U_{sc} of the supercapacitor. This value is important because the energy stored in the supercapacitor W_{sc} can be obtained by measuring U_{sc}.

$$W_{sc}(t) = \frac{C \cdot U_{sc}(t)^2}{2}$$

(6.5)

By knowing the charge stored in the supercapacitors U_{sc}, the relation between the ICE power and energy in the super-capacitor is expressed with the coefficient K_{sc}:

$$K_{sc} = \left(U_{sc\_r}\right)^{S_{sc}}$$

(6.6)

The U_{sc_r} is about the value of the U_{sc} according to the highest value U_{max} in SC:

$$U_{sc\_r}(t) = \frac{U_{\max} - U_{sc}(t)}{U_{\max}}$$

(6.7)

The S_{sc} is a numerical value for K_{sc} expressed with the equation:

$$S_{sc} = \frac{1}{1 - 20 \cdot U_{sc\_r}}$$

(6.8)

The coefficient K_{sc} allows direct numerical adjustment of P_{veh_ice}. As shown in the figure below, K_{sc} changes its value from approximately 1 (when the SC voltage is half U_{max}) to a sharp drop near U_{max} (100 [%] of U_{sc}). This means that P_{veh_ice} has about the same value as a standard ICE vehicle P_{ice}. When the supercapacitor reaches a value close to its maximum capacity, the P_{ice} will decrease immediately or the ICE will be turned off completely.

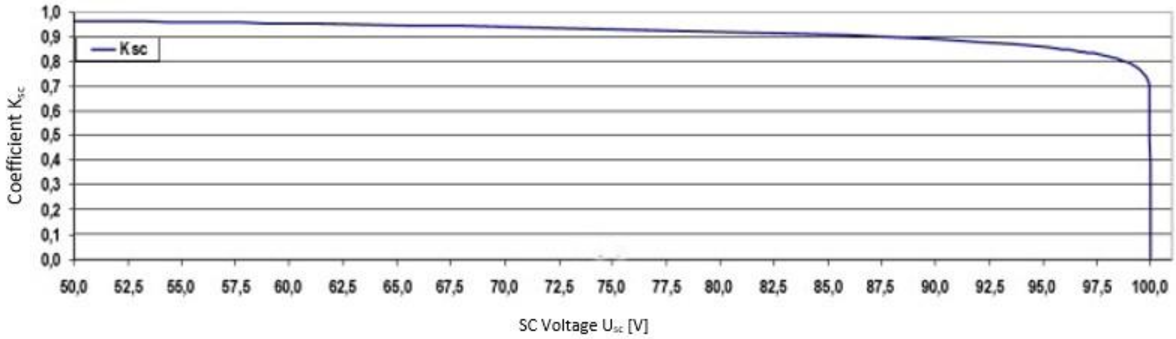

Figure 6. 6 Value of coefficient K_{sc} in relation to Supercapacitor voltage

When the vehicle is in an idling or slow driving phase, the drive system operates at very low loads at the corresponding time intervals. It is difficult to calculate the efficiency of an energy converter at these moments. In fact, at very low loads (or torque in the case of ICE), efficiency is approximately zero, and as a result, such low measurement uncertainty can lead to significant errors in fuel consumption estimation. The control strategy for hybrid electric powertrain systems is based on turning off the engine with such low load conditions. This is because the electric drivetrain can independently propel the vehicle in these low power demand conditions. With this approach, the fuel consumption required to maintain a predefined torque and velocity combination is directly calculated based on the engine map which has a value of the ICE torque, engine speed, power, and fuel consumption rate. This representation allows us to visualize idling loss and overrun cut-off limits. Therefore, in the HEV-CVUT control strategy, the minimum vehicle speed V_{veh_min} and the minimum vehicle traction force P_{ice_min} are defined as parameters that indicate when to turn off the ICE. If the vehicle's deceleration (a_{veh}) provides enough force to overcome all resistances F_{veh}, the fuel supply can be shut off completely.

The actual value of P_{ice} is derived from P_{veh_ice}. When compared to a car with ICE only, the change in the value of P_{ice} on the HEV-CVUT is smooth and is tuned by the control strategy. ICE's performance strategy is based on eliminating engine operation in conditions like low power demand, idling, and regenerative braking. Nevertheless, with the limited energy capacity of the supercapacitor and the limited power of the traction motor, the ICE can still be running for a short period during the above-mentioned conditions to keep the powertrain system fully prepared for all operating conditions which can occur in future. This approach is crucial in the predictive control strategy system.

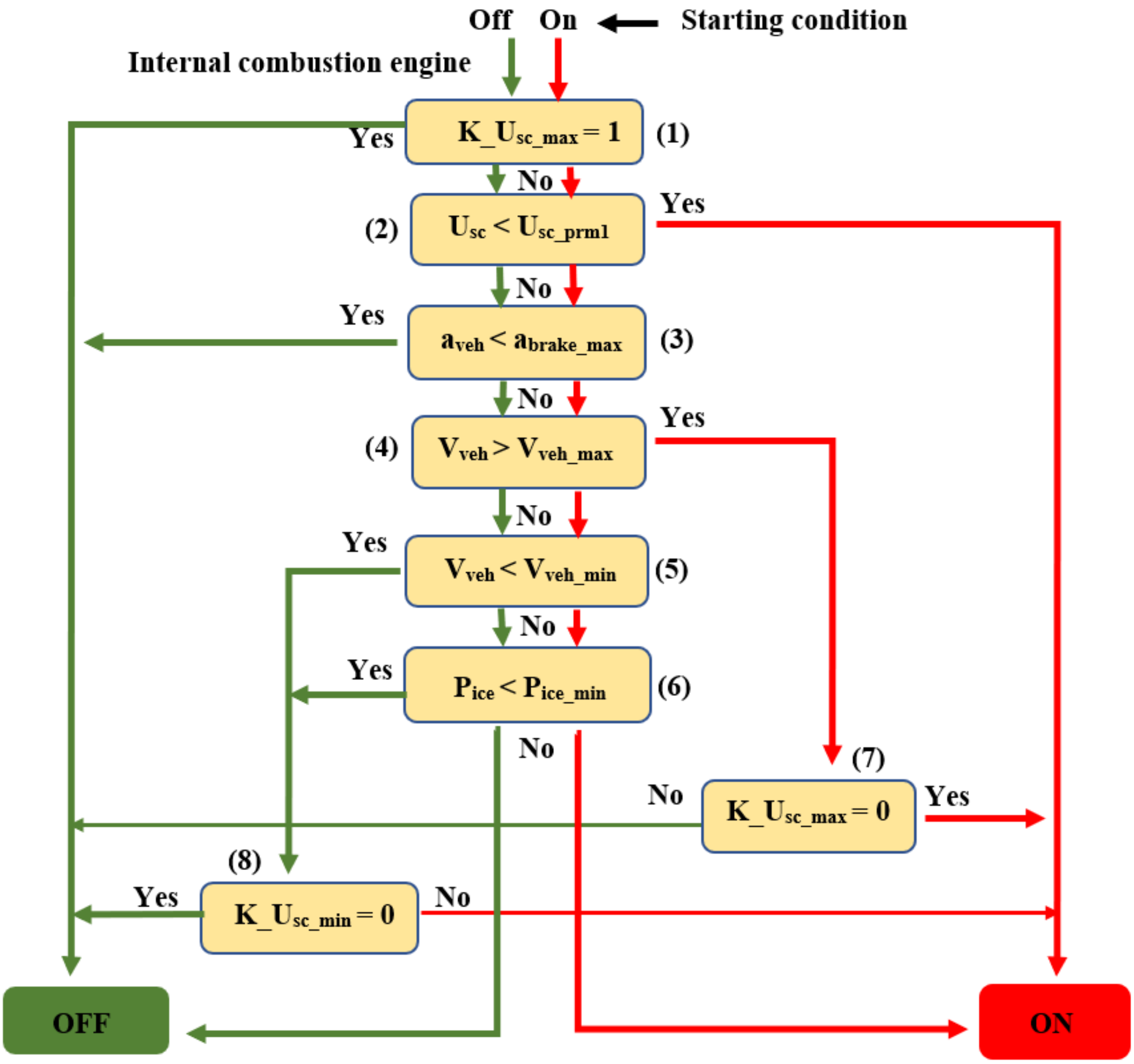

Figure 6. 7 HEV-CVUT control strategy algorithm for ICE operation

The control strategy monitors the function of ICE based on the flowchart shown above. From the start of the basic time interval, the control strategy program checks the initial state of the ICE (switch on or off, level 1 of the structure). This condition changes when the condition defined above occurs (the value is a function of the If-else case defined). From the algorithmic structure we know, that the operating conditions of the ICE are dependent on the complex conditions of the supercapacitor voltage level U_{sc} and other value factors such as the vehicle acceleration a_{veh}, the ICE power P_{ice}, and the vehicle speed V_{veh}.

6.4 The energy of the Super-capacitor

In discussed case the propulsion strategy presented is for HEV-CVUT with four supercapacitors as an energy accumulator. N_{sc} = 4. These are connected in series with the capacity C_{sc1} = 200 [F] of each unit. The total capacitance of the entire storage unit and all four supercapacitors is:

$$C_{sc} = \frac{C_{sc1}}{N_{sc}} = \frac{200}{4} = 50[F] \tag{6.9}$$

Each SC unit has a maximum rated voltage U_{max1}=56[V], therefore, the total maximum voltage being connected in series is:

$$W_{sc\_max} = \frac{C_{sc} \cdot U_{sc\_max}^2}{2} = \frac{50 \cdot 224^2}{2} = 1254.4[kJ] \tag{6.10}$$

$$U_{sc\_max} = N_{sc} \cdot U_{max1} = 4 \cdot 56[V] = 224[V] \tag{6.11}$$

Since we know the maximum available charge and voltage in super-capacitors, we can calculate the maximum energy that can be stored in this unit.

The HEV-CVUT driving strategy is established on the strategy of keeping the SC energy level between the maximum W_{sc_max} level and the set minimum W_{sc_min} level. The starting value of the energy W_{sc_start} at the beginning of the cycle should be the same as the end of the cycle. This requirement is important to maintain energy fluctuation levels same at the beginning and end to ensure that no extra energy is used from the supercapacitor and all the energy generated was from ICE. This is done for having accurate fuel consumption calculations.

An easy measurable value from SC is its voltage. The Energy in SC (W_{sc}) is directly represented by U_{sc} in the equation mentioned previously. This method is of a significant advantage over chemical batteries, as in chemical batteries the voltage levels do not directly relate to stored energy in batteries. The energy stored in a supercapacitor can be calculated instantaneously and accurately easily by knowing U_{sc} values.

$$U_{sc} = \sqrt{\frac{2 \cdot W_{sc}}{C}} \tag{6.12}$$

The working strategy of the ICE in this HEV-CVUT system is dependent on the value fluctuation of SC voltage $U_{sc}=f(t)$. The following SC voltage values are defined for a more accurate control strategy of SC:

U_{sc} – current voltage of the SC,

U_{sc_max} – maximum voltage of the SC,

U_{sc_prm1} – minimal allowed voltage of the SC,

U_{sc_prm2} – minimal voltage that SC should charge if U_{sc} reaches U_{sc_prm1},

U_{sck_pr1} – critical maximal voltage of the SC,

U_{sck_pr2} – minimal voltage after SC reaches critical max voltage U_{sck_pr1}.

U_{sc_max} is the maximum voltage in SC, which we calculated based on rated capacity (U_{max}=224[V]). U_{sc_prm1} indicates that the SC is on a critically low energy level. In this case, the ICE should be producing enough power to propel the vehicle and to charge the SC, regardless of the driving demands (even when the vehicle is at a halt). The engine will charge the SC and it will have an "ON" position until voltage U_{sc} reaches the U_{sc_prm2} value.

$$U_{sc\_prm1} = 0.5 \cdot U_{sc}; \qquad U_{sc\_prm2} = 0.7 \cdot U_{sc}$$

This prerequisite is defined in the control strategy using the parameter $K\_U_{sc\_min}$. This parameter is either one "1" or zeroes "0". The value condition for this parameter in the program is executed according to the algorithm pattern defined. $K\_U_{sc\_min}$ is an important parameter in the operational strategy of the combustion engine. During low load conditions ($V_{veh}<V_{veh\_min}$ and $P_{ice}<P_{ice\_min}$), the combustion engine is in the "off" or "on" position according to the parameter $K\_U_{sc\_min}$.

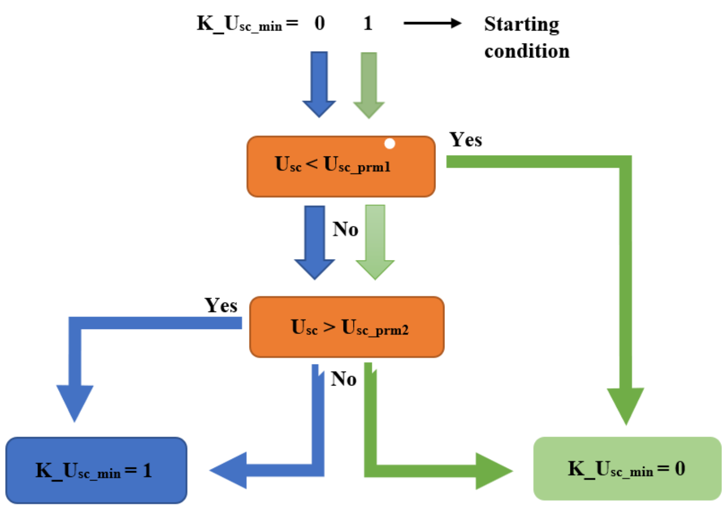

Figure 6. 8 Logic control of parameter $K\_U_{sc\_min}$

U_{sck_pr1} is an important peak value for U_{sc}. When the energy stored in the SC reaches this value, it indicates that the ICE should be turned off. Once this value is reached, the ICE will be "OFF" until the U_{sc} level drops to U_{sck_pr2}. ICE is turned off so that in case of energy recuperation the absorbed energy can still be stored in SC. This is controlled based on the predictive logic of the HEV-CVUT control strategy. This requirement is defined in the program algorithm using the parameter $K\_U_{sc\_max}$. Similar to $K\_U_{sc\_min}$, the value of this parameter is "1" and "0" according to the algorithm structure.

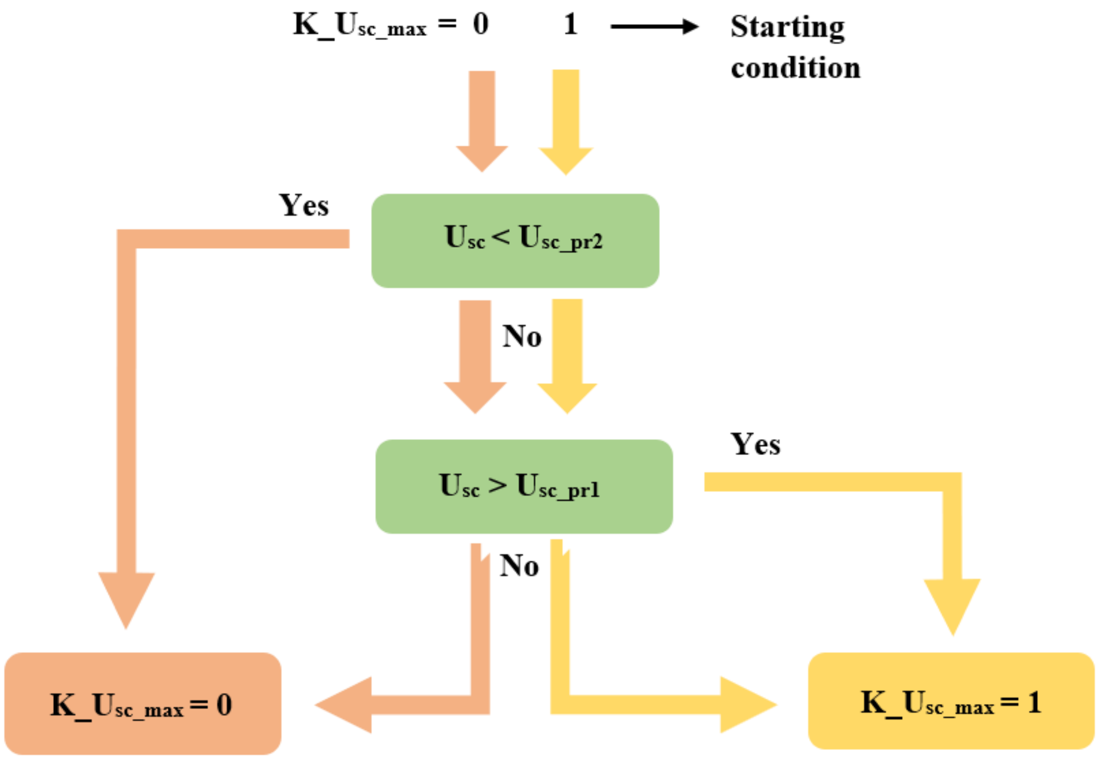

Figure 6. 9 Logic control of parameter $K\_U_{sc\_max}$

The predictive control strategy assumes that when the energy capacity W_{sc} exceeds 81% of the maximum amount W_{sc_max} (U_{sc}>0.9U_{sc_max}), turning off the ICE is correlated with the vehicle speed V_{veh}. Normally, 20% of SC energy is retained as a free cumulative reserve for any abrupt energy recuperation (sudden braking). However, at high vehicle speeds (above 100 km/h), this stored reserve is reduced in favor of already stored energy and is saved for the final sudden acceleration demand. This can be seen in WLTC class 3(t = 1500 [s] to t = 1700 [s]) where V_{veh} accelerates from 100 [km / h] to 130 [km / h].

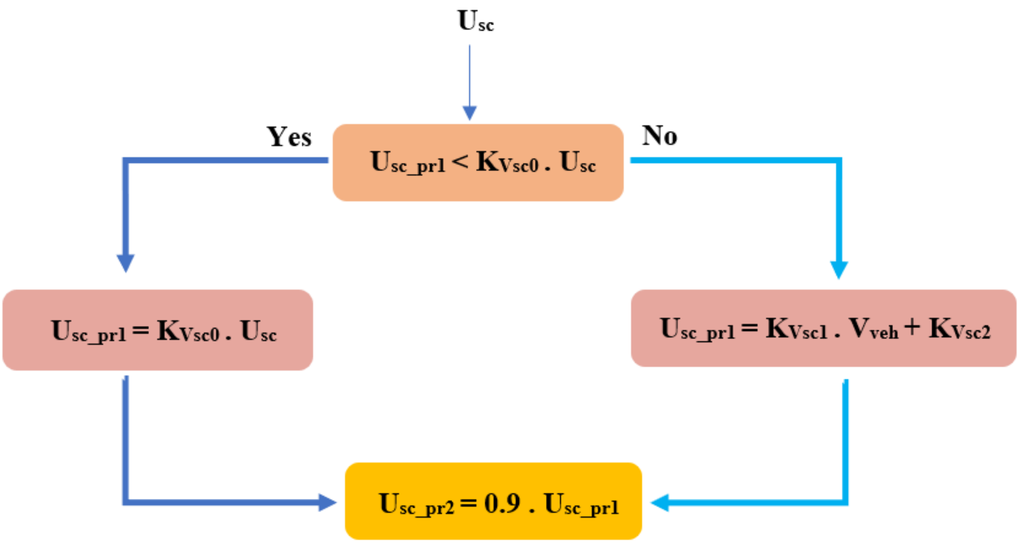

Figure 6. 10 Computation of U_{sc_pr1} and U_{sc_pr2} values

$K\_U_{sc\_max}$ is a variable of the ICE working strategy that plays an important role. If the value of $K\_U_{sc\_max}$ is "1", the ICE will turn off immediately. If the vehicle speed V_{veh} is higher than V_{veh_max}, the control strategy requires an immediate engine switch-on, but there is a prerequisite that only if the previous $K\_U_{sc\_max}$ has a value of "0".

6.5 Other factors in the ICE control strategy

In addition to the supercapacitor energy balance (directly measured and controlled by voltage level in the SC U_{sc}), other parameters of the ICE control strategy are vehicle speed V_{veh}, vehicle acceleration, and required engine output P_{ice}, and engine revolution n_{ice}. When the vehicle speed drops below the minimum V_{veh_min} <5[m / s], the engine is expected to turn "OFF". During high deceleration $a_{veh}<a_{brake\_max}= -0.6[m/s^2]$ ICE is immediately switched to “OFF” as there would be high recuperative energy generated during braking and needs to be accumulated. According to the algorithm, deceleration is defined as a negative value variable ($a_{veh}<0$) and acceleration is a positive value variable ($a_{veh}>0$). If the vehicle speed V_{veh} is greater than $V_{veh\_max}>10$[m/s], the ICE will be turned “ON” with preconditions.

ICE has a prerequisite to keep the engine in the most fuel-efficient operating condition, also there is a limit to the engine output. The control strategy program structure assigns a minimum P_{ice_min} = 5 [kW] and a maximum of P_{ice_max} = 30 [kW] engine power output. When P_{veh_ice} exceeds P_{ice_max}, P_{ice} is limited to P_{ice_max}. It is possible to do so because there is another power source, the SC, that provides the additional power demand for short time intervals, as in the case of sudden acceleration. When P_{veh_ice} falls below P_{ice_min}, the ICE is switched off and the power P_{ice} is 0. As the only electric mode of TM can supply power during low load conditions, it is possible to keep the ICE off and avoid it from being operated in an inefficient regime. But other prerequisites are checked before shutting down the ICE. If these conditions are not met, the ICE will operate with a minimum power of P_{ice_min}. These program logic prerequisites define the operating regime ("on" and "off") and power management of the engine in all states of HEV-CVUT propulsion. Engine output shaft rotation speed depends strictly on this ICE power management which we discuss in the next section.

6.6 Control strategy for Electric Power Splitter unit (EPS)

The rotation speed of the permanent magnet rotor of the power splitter is the same as the rotation speed of the ICE driveshaft n_{ice}. The number of revolutions of the EPS stator shaft is the same as the number of revolutions of the rotor shaft of the traction motor and is defined as the "brake" shaft (n_{brake}). This shaft has revolution proportional to the drive wheel shaft ω_{wheel} with a fixed transmission ratio constant K_{trans}. Wheel angular velocity ω_{wheel} is proportional to the vehicle speed V_{veh}. The overall speed transfer coefficient K_{hev_trans} between vehicle speed and rotation of the traction motor (EPS stator) shaft can be calculated by the following equations.

$$n_{tm} = K_{trans} \cdot \omega_{wheel}; \qquad \omega_{wheel} = r_{wheel} \cdot V_{car}$$

$$n_{tm} = K_{hev\_trans} \cdot V_{car}$$

$$K_{hev\_trans} = \frac{n_{tm}}{V_{car}} = 8.33 \frac{[\min^{-1}]}{[km/h]} = 0.5 \frac{[s^{-1}]}{[m/s]} = 0.5[m^{-1}] \tag{6.13}$$

The rotational speed difference between the revolutions of the stator (n_{brake}) and the rotor (n_{ice}) of the EPS, defines the relative revolutions of the electric power splitter n_{eps}.

EPS has input power P_{ice}. Output powers are electrical power P_{epsel} and mechanical power P_{epsmh} which are two distinct powers "split" from total EPS power P_{eps}. Power splitting ratio K_{epe_mhel} between electrical and mechanical power as expressed with the equation below and experimentally assigned.

$$K_{eps\_mhel}(P_{eps}) = \frac{P_{epsel}}{P_{epsmh}} \tag{6.14}$$

In the program structure of the control, the strategy is K_{eps_mhel} numerically interpolated with the formula below.

$$K_{eps\_mhel} = \frac{P_{epsel}}{P_{epsmh}} = C_{eps1} \cdot (\frac{P_{eps}}{P_{epsn}})^{C_{eps2}} \tag{6.15}$$

C_{eps1}=0.8 and C_{eps2}=-0.4.

The output voltage U_{eps} of the EPS, like all other synchronous machines, is proportional to its shaft revolution speed n_{eps}. This voltage is rectified with an AC-DC converter into U_{eps_dc} to be added to the main DC circuit. The numerical correlation between U_{eps} and U_{eps_dc} can be given by the formula

$$U_{dc}(\alpha) = \frac{6}{2\pi}\int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}+\alpha}\sqrt{2}U_s \sin\omega t d(\omega t) = \frac{3\sqrt{2}}{\pi}U_s \cos\alpha = \frac{3\sqrt{2}}{\pi}\sqrt{3}U_{eps}\bigg|_{\alpha=0} = 2.34U_{eps} \tag{6.16}$$

Hybrid systems require a stable voltage in their main DC circuit. In commercial HEV, this is achieved with a separate chemical traction battery with low voltage fluctuations. To maintain the constant voltage level of the DC circuit, such as in a traction battery U_{tb} = 240 [V], the pulse-controlled AC / DC converter needs to raise the EPC output voltage to U_{tb} (when $U_{eps\_dc}<U_{dc}$). In the opposite condition, i.e. when $U_{eps\_dc}>U_{dc}$, an additional DC-DC pulse converter is needed to reduce the DC circuit output voltage to U_{tb} level.

6.7 Efficiency in the energy transformation

A hybrid electric drive is a complex energy conversion system. Energy flows from various paths such as ICE to SC and to the wheels, which includes different energy transformations like mechanical to electricity (EPS and TM in generator regime), electrical to electrical (in SC and power converters), and electrical to mechanical (TM during motoring), etc. Each of these conversions has an energy loss. These losses are represented by energy efficiency coefficients calculated according to the type of energy transformation that correlates with the characteristics of the hybrid drive component.

In our concept vehicle HEV-CVUT, seven different energy efficiency coefficients are defined for each energy conversion:

The efficiency of AC-DC rectifier η_{ac_dc},

The efficiency of EPS mechanical part η_{epsmh},

The efficiency of DC-AC inverter η_{dc_ac}

The efficiency of traction motor TM η_{tm},

The efficiency of EPS electric part η_{epsel},

The efficiency of transmission η_{trans}

The efficiency of SC recuperative circuit η_{sc}

When the first control strategy is created, these coefficients were theoretically defined and formulated. The properties of each coefficient are numerically formulated and interpolated into the program structure of the control strategy. The efficiency of an internal combustion engine is defined by the engine power map. An individual efficiency coefficient of ICE is not defined because its energy efficiency characteristics are represented by fuel consumption obtained from an engine map.

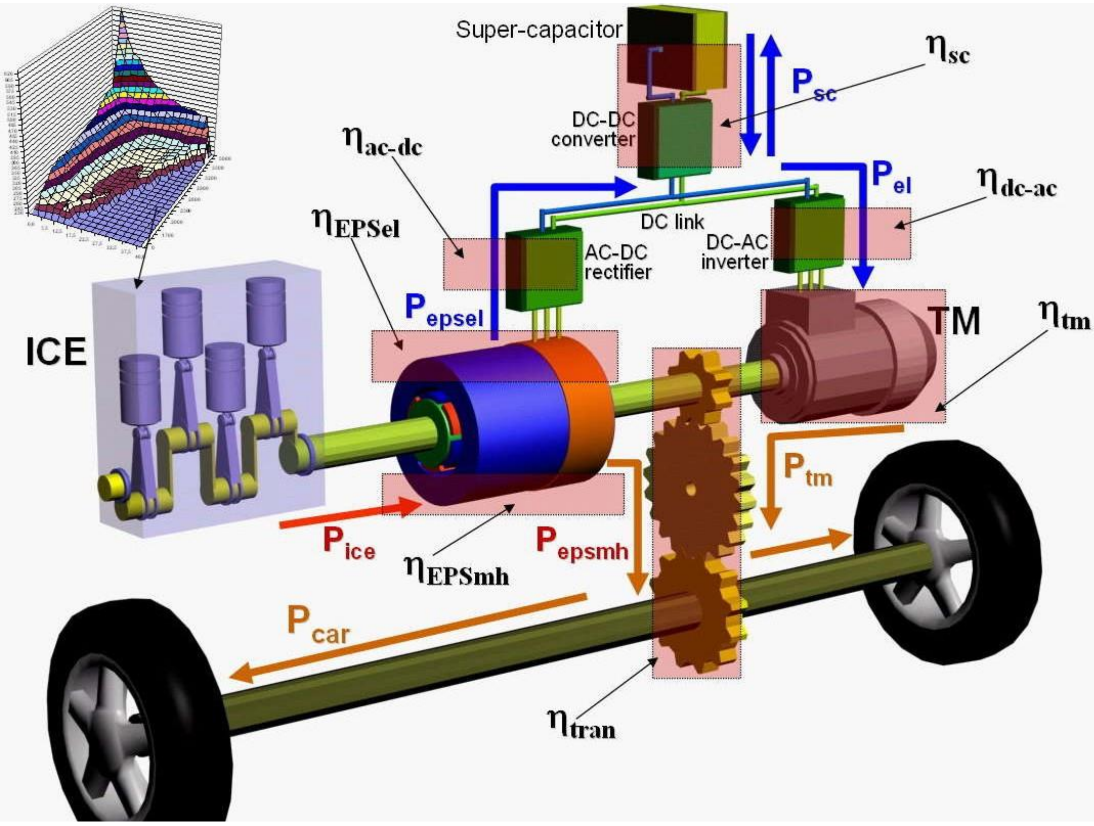

Figure 6. 11 Energy efficiency and the power flow path in HEV-CVUT [14]

The energy efficiency of a traction motor (generator) is numerically formulated by:

$$\eta_{tm} = K_{tm\_2} \cdot P_{tm\_r}^2 + K_{tm\_1} \cdot P_{tm\_r} + K_{tm\_0} \tag{6.17}$$

The traction motor is powered from a DC-AC inverter where the intermediate DC circuit provides power P_{el}. Energy efficiency $\eta_{dc\text{-}ac}$ of this converter is formulated with
Constants in the equation are: K_{tm_2} = -0.2258, K_{tm_1} = 0.382, K_{tm_0} = 0.73.

$$\eta_{dc-ac} = K_{dcac\_2}^2 \cdot P_{el\_r}^2 + K_{dcac\_1} \cdot P_{el\_r} + K_{dcac\_0} \tag{6.18}$$

Polynomial constants are: K_{dcac_2} = 0.0344, K_{dcac_1} = -0.088 and K_{dcac_0} = 0.99.
During the driving cycle, this converter changes its function from inverter to rectifier (DC-AC ↔ AC-DC) in a similar manner to how a TM changes its function from the motor to the generator. For our program algorithm, its index marking stays “dc-ac”, despite its dual function.
Power splitting by EPS is defined and computed with K_{eps_mhel}. Coefficient of energy efficiency of generated P_{epsel} is defined numerically by:

$$\eta_{epsel} = K_{trans\_3}^3 \cdot P_{epsel\_r}^3 + K_{trans\_2}^2 \cdot P_{epsel\_r}^2 + K_{trans\_1} \cdot P_{epsel\_r} + K_{trans\_0} \tag{6.19}$$

Where the coefficients are K_{epsel_3} = 0.1695, K_{epsel_2} = -0.553, K_{epsel_1} = 0.5392 and

K_{epsel_0} = 0.79.
The AC-DC converter rectifies P_{epsel} in the DC link. Its efficiency $\eta_{ac\text{-}dc}$ is calculated with a polynomial expression which has constants K_{acdc_2} = 0.0344, K_{acdc_1} = -0.088,
K_{acdc_0} = 0.99

$$\eta_{ac-dc} = K_{acdc\_2}^2 \cdot P_{epsel\_r}^2 + K_{acdc\_1} \cdot P_{epsel\_r} + K_{acdc\_0} \tag{6.20}$$

Driving wheels to “brake” shaft mechanical transmission efficiency is determined by:

$$\eta_{trans} = K_{trans\_1} - K_{trans\_2} \cdot P_{car\_r}^2 \tag{6.21}$$

Constants are Ktrans_1=0.98 and Ktrans_2=0.05.

The efficiency of mechanical components of EPS between ICE shaft and "brake" shaft lies between 98% to 99%. For our calculation, we have taken $\eta_{epsmh}=0.98$.

The efficiency of recuperative circuit η_{sc} depends on instantaneous current in SC I_{sc}. This current I_{sc} is a function of SC available power P_{sc} and actual voltage level U_{sc}.

$$I_{sc} = \frac{P_{sc}}{U_{sc}} \tag{6.22}$$

η_{sc} can be given by the expression

$$\eta_{sc} = K_{sc\_1} - I^2_{sc\_r} \cdot K_{sc\_2} \tag{6.23}$$

Where Ksc_1=0.90 and Ks c_2=0.6.

For SC to be more efficient as an energy accumulation unit, the control strategy must maintain U_{sc} on a higher level to keep I_{sc} to be lower for the same required power P_{sc}.

The efficiencies in all the energy paths are found out mathematically and experimentally from the test bench, which is then used for the Simulink model.

6.8 Power management and energy flow in HEV-CVUT

Seven different types of power are defined in this hybrid system, which has been functionally described in previous sections. The most important criterion for the HEV-CVUT control strategy is the well-defined power management of this hybrid electric system. At each time step, we need to know the exact values for each of these power components and use a predictive control strategy approach to determine their control strategy. P_{veh} is defined by the driving cycle and vehicle characteristics. The engine output P_{ice} is calculated according to the ICE control strategy. The power components of EPS, Electrical power P_{epsel} and Mechanical power P_{epsmh}, are calculated according to the EPS control strategy. The output from TM (in generator regime) P_{tm} is calculated as the difference between the values of P_{veh} and P_{epsmh}, taking into account the efficiency of EPS, TM, and the gearbox. This characteristic indicates that P_{tm} has positive and negative values. If $P_{tm} > 0$, the TM is in the motor regime and propels the vehicle. When $P_{tm} < 0$, then the TM is in the generator regime. The TM provides resistance and brakes the vehicle, which produces the electrical energy stored in the SC. This regime is defined for vehicles' energy recuperation period.

Supercapacitors are electric energy storage units that use P_{sc} to provide power boosts to propulsion systems. It can be quickly charged and discharged according to the power demand of the HEV

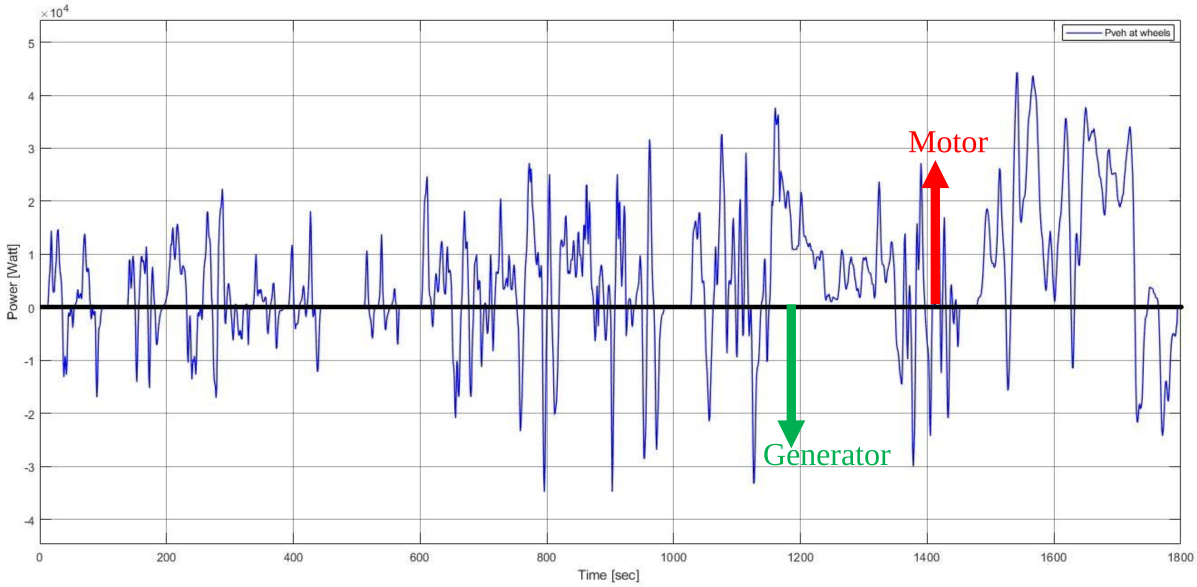

Figure 6. 12 Power characteristic of Traction motor

propulsion system. P_{sc} is used to overcome the power difference between P_{el} and P_{epsel}, taking into account the efficiency of SC and DC-DC power converters. P_{sc} can have positive and negative values. When $P_{sc} > 0$, the SC will be used to propel the vehicle and it will be discharged, and if $P_{sc} < 0$ SC will be charging. Both P_{sc} and P_{tm} power is derived from energy path power management strategies.

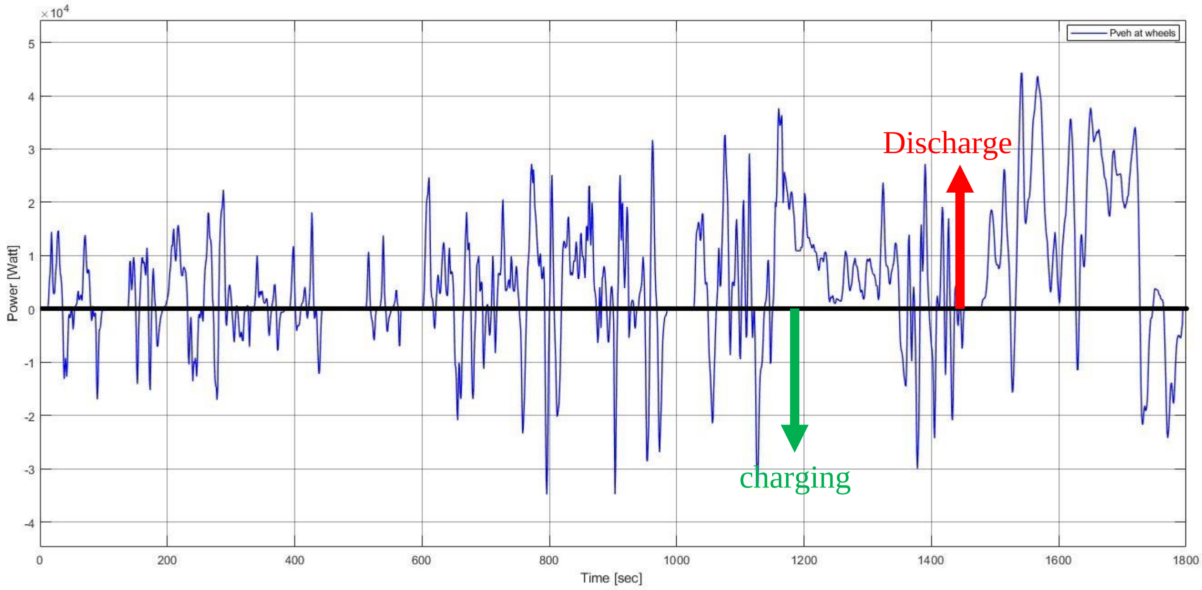

Figure 6. 13 Charging and discharging in SC

Now we will discuss six different functional energy path structures in HEV-CVUT. They are the result of the previously discussed control strategy.

6.8.1 Low load condition (ICE OFF)

In this condition the path is simple and the vehicle is propelled only by electric drive by power from SC.

Figure 6. 14 Only electric motor powered

SC provides the required power P_{sc} calculated by expressions:

$$P_{veh} = P_{tm} \cdot \eta_{trans} = P_{el} \cdot \eta_{dc-ac} \cdot \eta_{tm} \cdot \eta_{trans}$$

$$P_{sc} = \frac{P_{car}}{\eta_{dc-dc} \cdot \eta_{dc-ac} \cdot \eta_{tm} \cdot \eta_{trans}} \tag{6.24}$$

6.8.2 High load condition (ICE-ON)

This is the case when both SC and ICE provide power to propel the vehicle. Complex energy transformation begins. This is when the traction needed is very high and the power generated by the ICE does not cover the entire power demand. SC is activated to fill the power gap by providing additional power burst P_{sc} to the drivetrain. Commercially, this process is commonly referred to as "full throttle”. This condition is formulated by the following expressions.

$$P_{veh} = (P_{tm} + P_{epsmh}) \cdot \eta_{trans} \tag{6.25}$$

$$P_{tm} = P_{el} \cdot \eta_{dc-ac} \cdot \eta_{tm} = (P_{scdc} + P_{epsel}) \cdot \eta_{dc-ac} \cdot \eta_{tm} \tag{6.26}$$

$$P_{scdc} = P_{sc} \cdot \eta_{dc-dc} \tag{6.27}$$

$$P_{epsel} = P_{ice} \cdot \eta_{epsel} \cdot \eta_{ac-dc} \cdot \left(\frac{K_{eps\_mhel}}{K_{eps\_mhel} + 1}\right) \tag{6.28}$$

$$P_{epsmh} = P_{ice} \cdot \eta_{epsmh} \cdot \left(\frac{1}{K_{eps\_mhel} + 1}\right) \tag{6.29}$$

$$P_{el} = P_{scdc} + P_{epsel} = P_{sc} \cdot \eta_{dc-dc} + \eta_{epsel} \cdot \eta_{ac-dc} \cdot \left(\frac{K_{eps\_mhel}}{K_{eps\_mhel} + 1}\right)$$

(6.30)

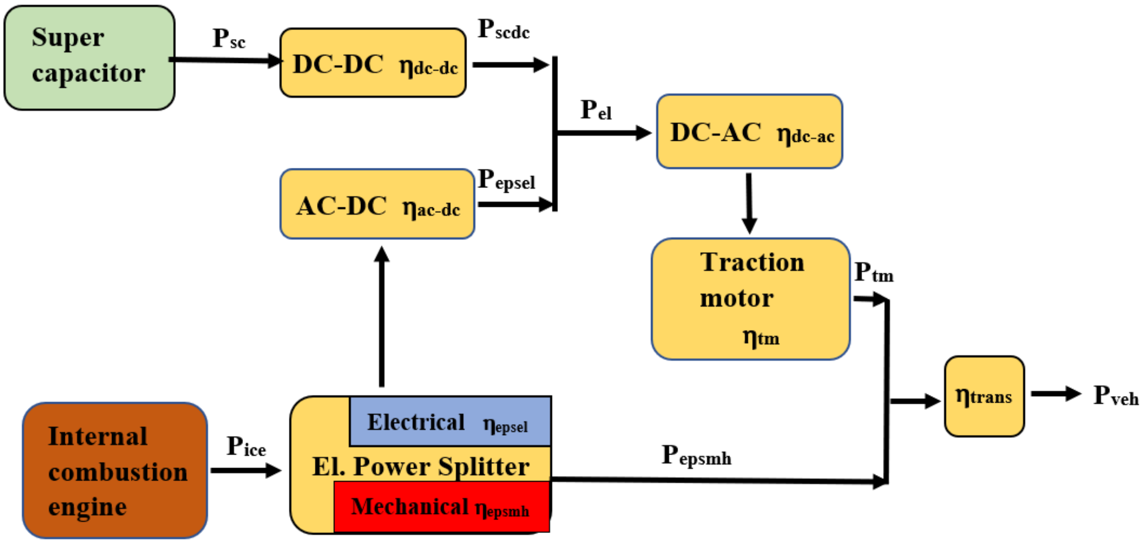

Figure 6. 15 Full throttle in HEV

6.8.3 Medium load condition (ICE "ON", SC charges)

In this condition the ICE for a short period has higher power output than the vehicle requires to propel itself (P_{ice}>P_{veh}), the excess energy is absorbed by the SC.

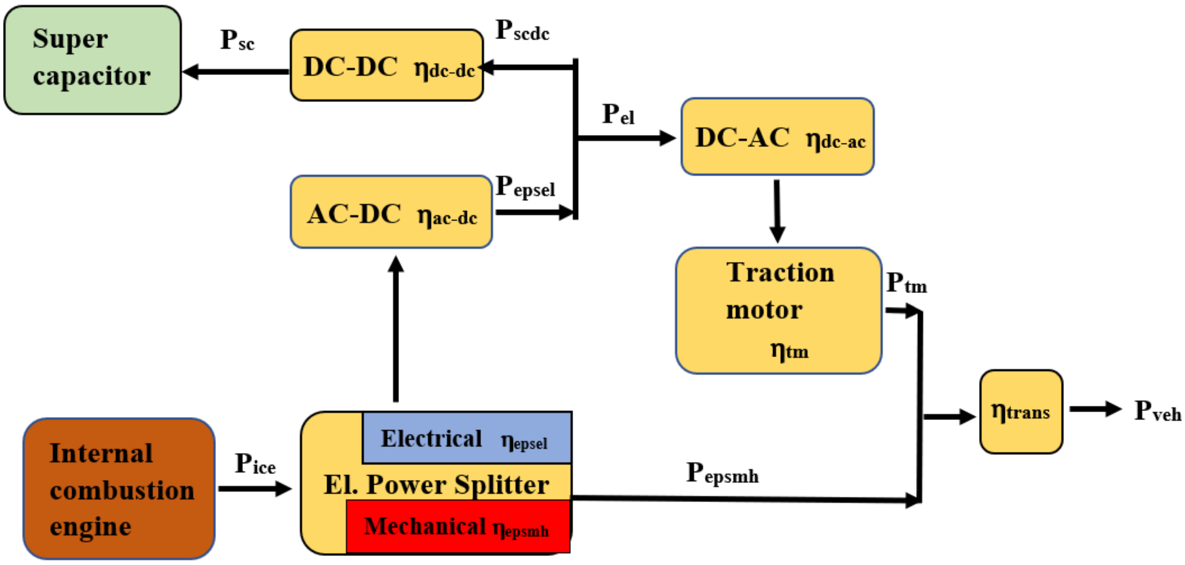

Figure 6. 16 Charging of SC with excess energy

$$P_{tm} = P_{el} \cdot \eta_{dc-ac} \cdot \eta_{tm} = (P_{epsel} - P_{scdc}) \cdot \eta_{dc-ac} \cdot \eta_{tm} = \tag{6.31}$$

$$= P_{ice} \cdot \eta_{epsel} \cdot \eta_{ac-dc} \cdot (\frac{K_{eps\_mhel}}{K_{eps\_mhel} + 1}) \cdot \eta_{dc-ac} \cdot \eta_{tm} - P_{sc} \cdot \frac{\eta_{dc-ac} \cdot \eta_{tm}}{\eta_{dc-dc}} \tag{6.32}$$

$$P_{veh} = (P_{tm} + P_{epsmh}) \cdot \eta_{trans} = P_{tm} \cdot \eta_{trans} + P_{ice} \cdot \eta_{epsmh} \cdot (\frac{1}{K_{eps\_mhel} + 1}) \cdot \eta_{trans} \tag{6.33}$$

$$= P_{ice} \cdot \frac{K_{eps\_mhel} \cdot \eta_{dc-ac} \cdot \eta_{epsel} \cdot \eta_{ac-dc} \cdot \eta_{tm} \cdot \eta_{trans}}{K_{eps\_mhel} + 1} - P_{sc} \cdot \frac{\eta_{dc-ac} \cdot \eta_{tm} \cdot \eta_{trans}}{\eta_{dc-dc}} + P_{ice} \cdot \frac{\eta_{epsmh} \cdot \eta_{trans}}{K_{eps\_mhel} + 1} = \tag{6.34}$$

$$= P_{ice} \cdot \frac{\eta_{trans} \cdot (K_{eps\_mhel} \cdot \eta_{dc-ac} \cdot \eta_{epsel} \cdot \eta_{ac-dc} \cdot \eta_{tm} + \eta_{epsmh})}{K_{eps\_mhel} + 1} - P_{sc} \cdot \frac{\eta_{dc-ac} \cdot \eta_{tm} \cdot \eta_{trans}}{\eta_{dc-dc}} \tag{6.35}$$

6.8.4 Full recuperation (ICE - "OFF")

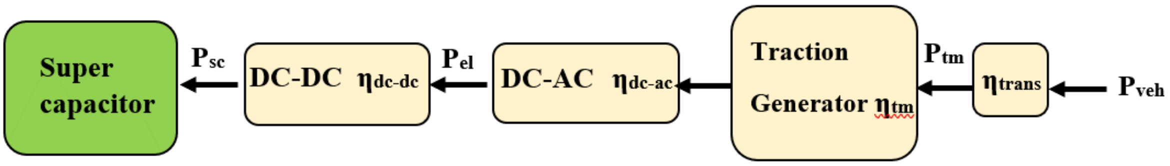

Figure 6. 17 Recuperation with ICE OFF

The control system turn-off the ICE when the vehicle is in recuperating. The kinetic energy of moving vehicle P_{veh} is converted into electric energy by TM (in generator regime) and accumulated as charge in SC by the following pathway.

Recuperative power into SC is calculated by:

$$P_{sc} = P_{veh} \cdot \eta_{dc-dc} \cdot \eta_{dc-ac} \cdot \eta_{tm} \cdot \eta_{trans} \tag{6.36}$$

6.8.5 Short recuperation (ICE - "ON")

In some cases, the recuperation can occur when the SC has reached critical low voltages and the ICE does not switch off during the recuperation process. This ensures rapid charging of the SC, as it gets power from the ICE P_{ice} and the kinetic energy from vehicle recuperation P_{veh}.

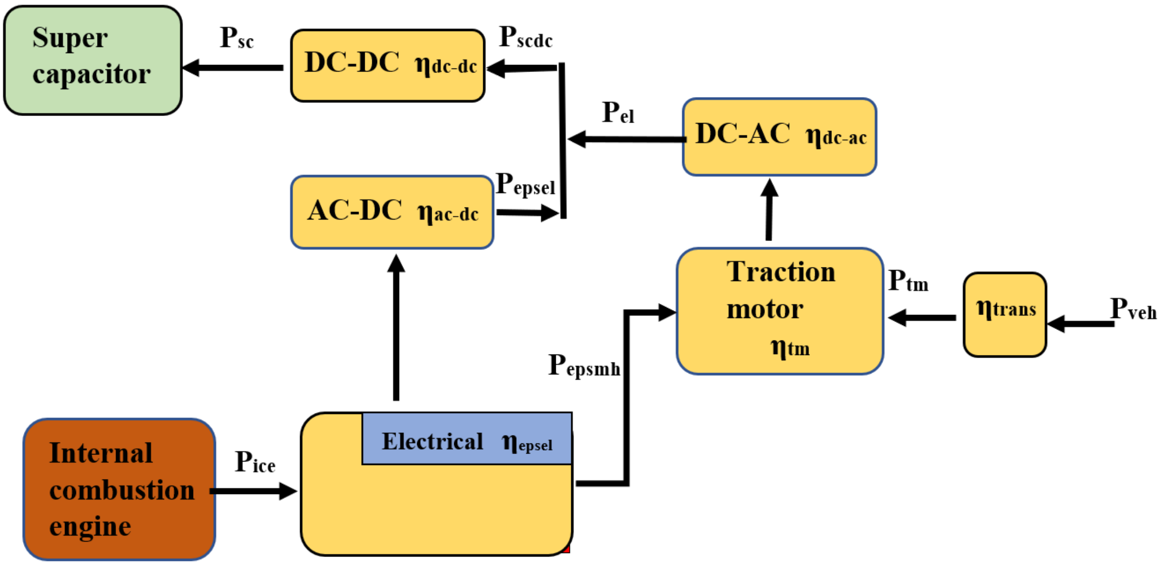

Figure 6. 18 Recuperation with ICE ON

The occurrence of such conditions is less frequent and for short period. Charging the super-capacitor from two methods instantly increases the charge and the voltage reaches the set critical level and then ICE is turned OFF. The equations explaining the condition are as follows:

$$P_{el} = (P_{tm} + P_{epsmh}) \cdot \eta_{tm} \cdot \eta_{dc-ac} = (P_{veh} \cdot \eta_{trans} + P_{epsmh}) \cdot \eta_{tm} \cdot \eta_{dc-ac}$$

$$P_{sc} = (P_{epsel} + P_{el}) \cdot \eta_{dc-dc} = P_{ice} \cdot \eta_{epsel} \cdot \eta_{ac-dc} \cdot \left(\frac{K_{eps\_mhel}}{K_{eps\_mhel} + 1}\right) \cdot \eta_{dc-dc}$$

$$+ \left(P_{veh} \cdot \eta_{trans} + P_{ice} \cdot \eta_{epsmh} \cdot \left(\frac{1}{K_{eps\_mhel} + 1}\right)\right) \cdot \eta_{tm} \cdot \eta_{dc-ac} \cdot \eta_{dc-dc} \tag{6.37}$$

The final expression for energy transmitted to SC P_{sc} from P_{veh} and P_{ice} is:

$$P_{sc} = P_{veh} \cdot \eta_{trans} \cdot \eta_{tm} \cdot \eta_{dc-ac} \cdot \eta_{dc-dc} + P_{ice} \cdot \frac{\eta_{dc-dc} \cdot (K_{eps\_mhel} \cdot \eta_{epsel} \cdot \eta_{ac-dc} + \eta_{epsmh} \cdot \eta_{tm} \cdot \eta_{dc-ac})}{K_{eps\_mhel} + 1} \tag{6.38}$$

6.8.6 ICE ON and vehicle at a halt (SC charging)

When U_{sc} reaches a critical level, the control strategy keeps the ICE running even when the vehicle is at a complete stop. During this process, there is no traction force demand by the vehicle $P_{veh}=0$ and the

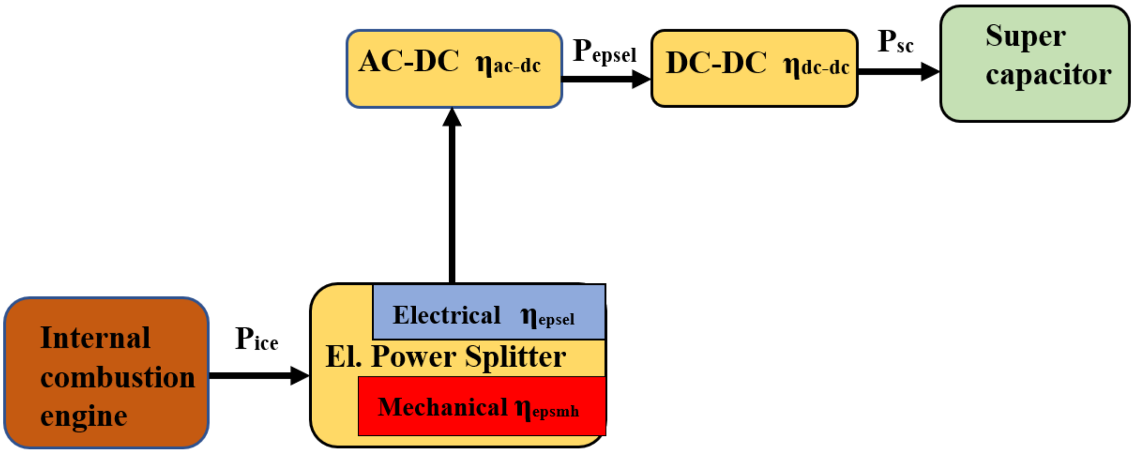

Figure 6. 19 Charging the Super capacitor when vehicle is at a complete stop

Traction shaft does not rotate at $n_{brake} = 0$. During this period EPS functions as a synchronous generator – power from ICE is converted to electrical energy output. Power transformation formulation is given with the expression:

$$P_{sc} = P_{ice} \cdot \eta_{epsel} \cdot \eta_{ac-dc} \cdot \eta_{dc-ac} \tag{6.39}$$

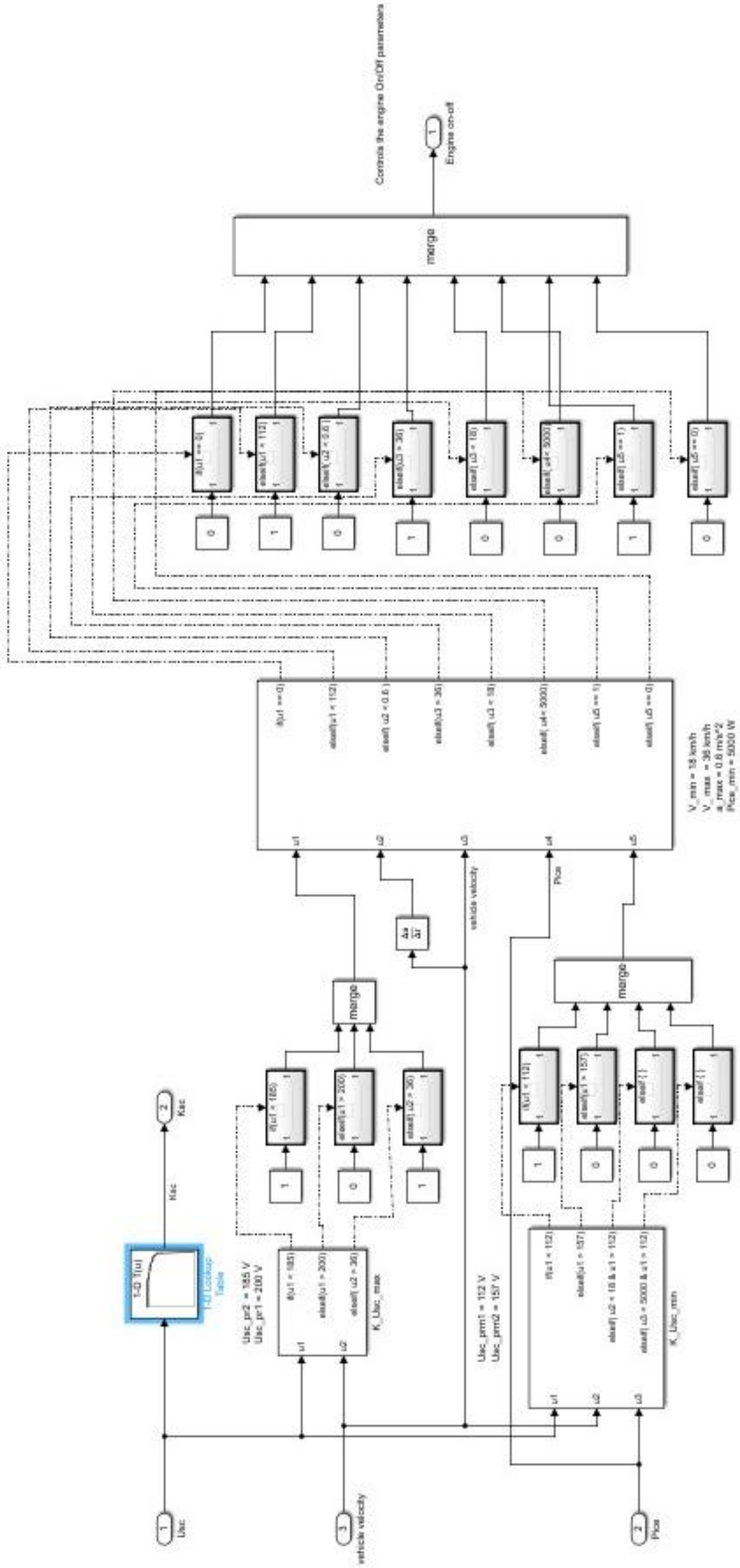

Figure 6.20   Control Algorithm in Simulink logic control block

7. Experimental Hybrid-Electric Laboratory Working Stand Based on SCADA System

7.1 Hybrid Electric Vehicle experimental working stand

An experimental working test bench as part of the Josef Božek Research Center was set up in the H.26 laboratory at the Department of Electrical Drives and Traction of the Faculty of Electrical Engineering, Czech Technical University in Prague. The purpose of this stand is to test the performance of each functional component of the conceptual HEV-CVUT.
A schematic diagram of this experimental setup is shown below.

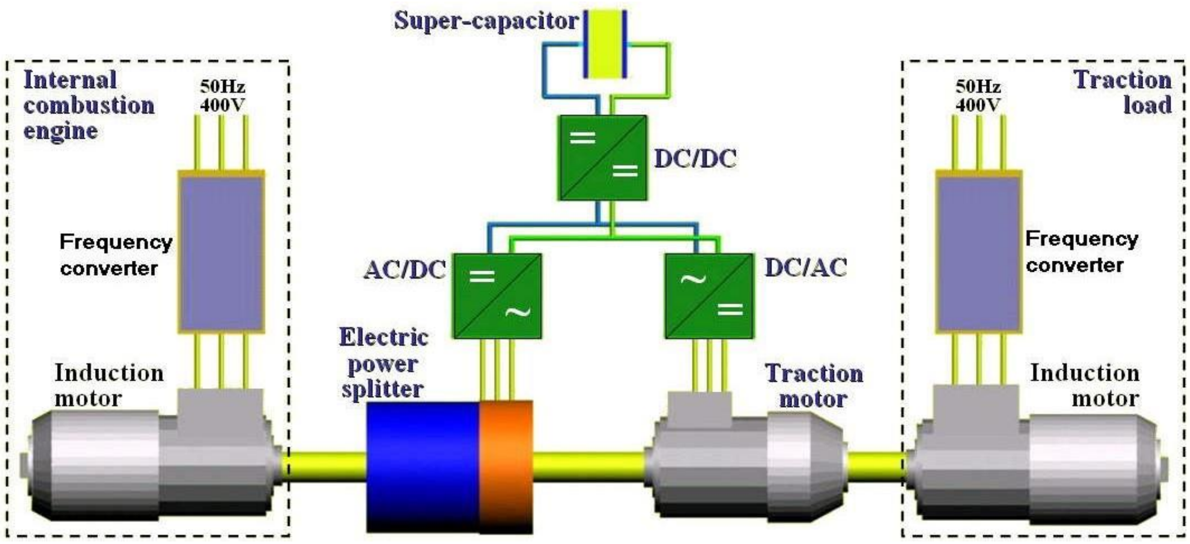

Figure 7. 1 Diagram of HEV experimental working bench [13]

The main function of this test bench has been previously discussed in this document. The HEV model which is set up in H.26 laboratory has the ICE and vehicle wheels replaced by two precisely regulated induction motors. The generated power P_{ice} and rotation n_{ice} of the ICE output shaft are simulated by an AC induction motor controlled through a variable frequency converter (FC). This frequency converter adjusts power and speed according to the required ICE operating power. The traction load which provides driving resistance (brake) is simulated by another regulated AC induction motor. This AC IM generates a brake torque M_{brake} on the shaft proportional to the tractive force needed to propel the vehicle for different driving conditions. In this way, a laboratory test bench is created for testing the components and control strategies of HEV without the need for real vehicles. There are two rotating shafts on both ends. The first is the ICE shaft, which is fitted to the ICE (controlled induction motor) and EPS rotor shaft. The second shaft is the traction shaft, which connects the EPS rotating stator with the traction motor and induction motor (brake motor). During operation, these two shafts are mechanically independent but magnetically linked with each other by EPS magnetic field. During testing, the test bench connects these shafts with an electromagnetic clutch firmly so that it can function as a single shaft.

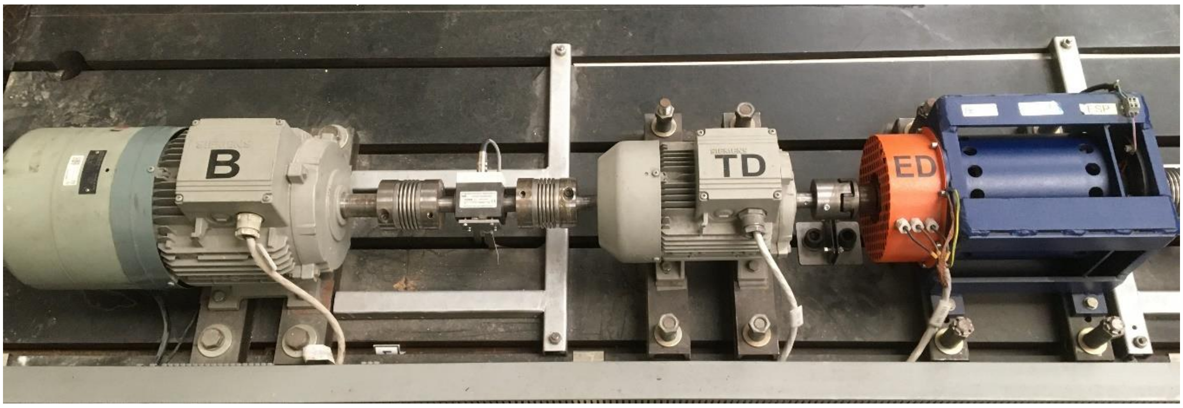

Figure 7. 2 Electrical machines of the HEV working stand

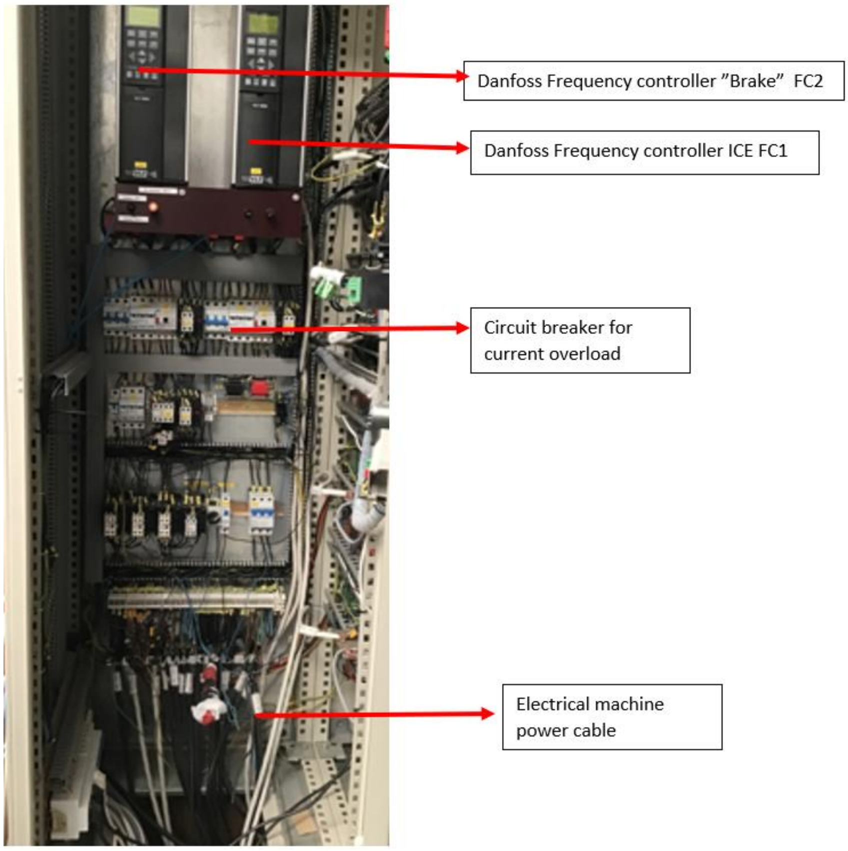

Figure 7. 3 Frquency control unit in HEV-CVUT workbench

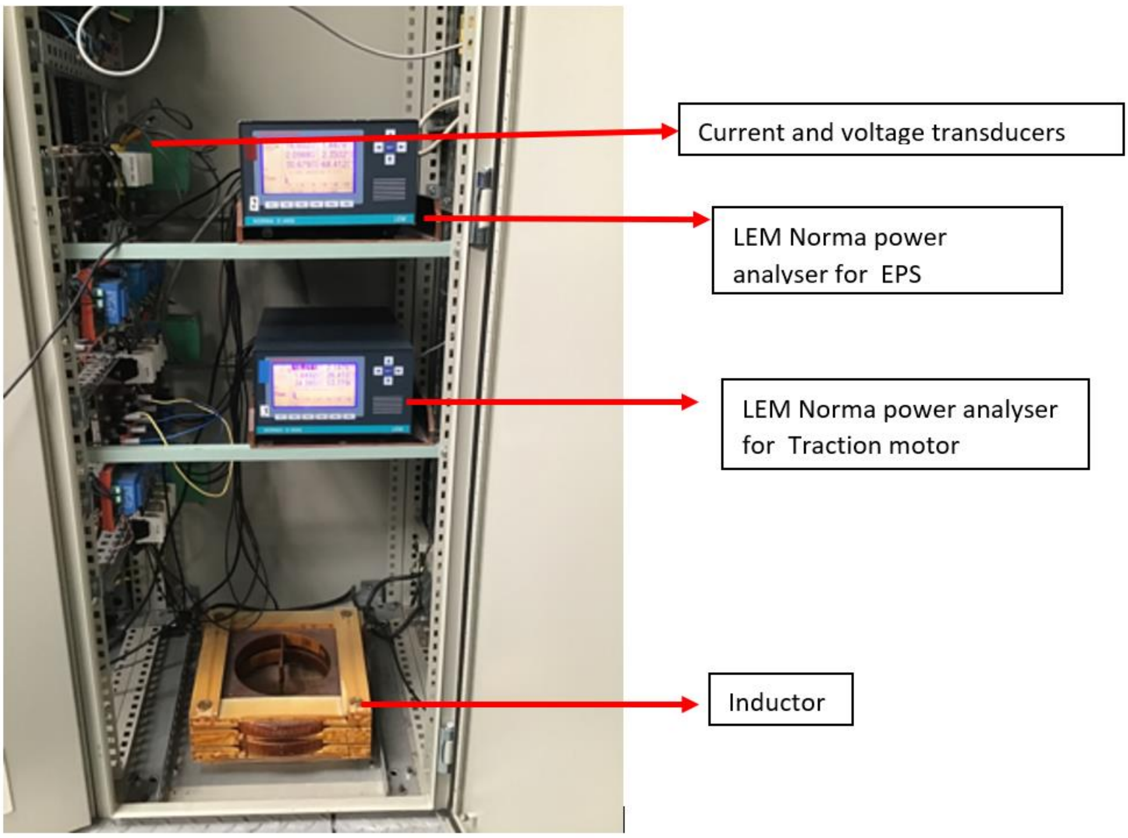

Figure 7. 4 Power analyser unit in work bench

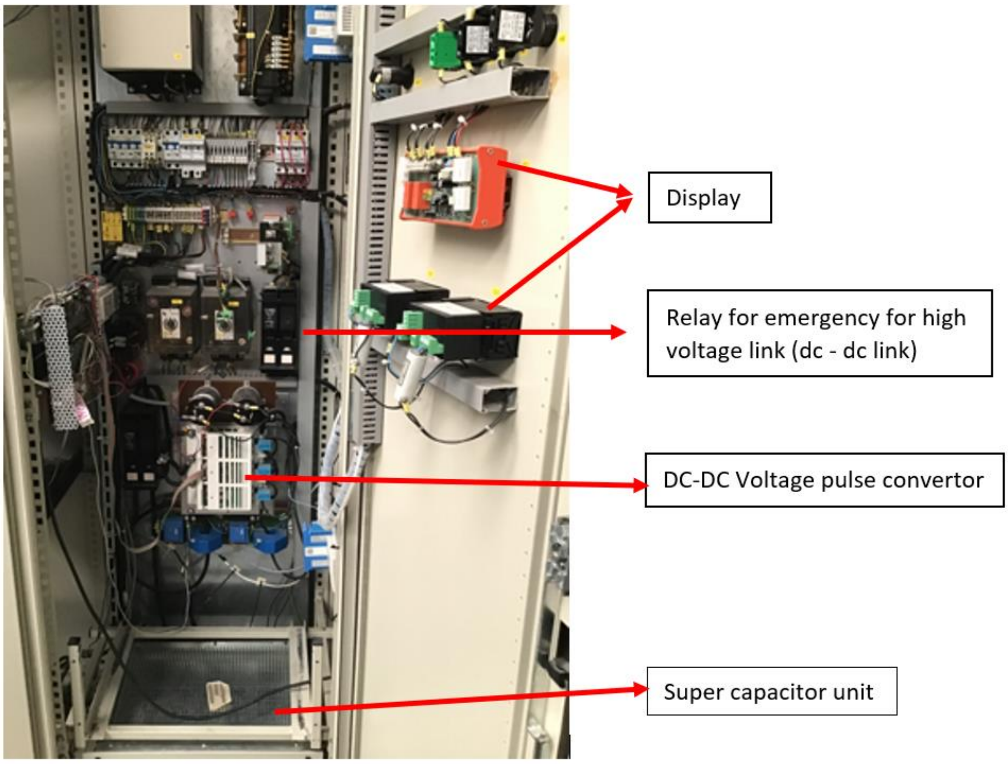

Figure 7. 5 Accumulator unit (SC)

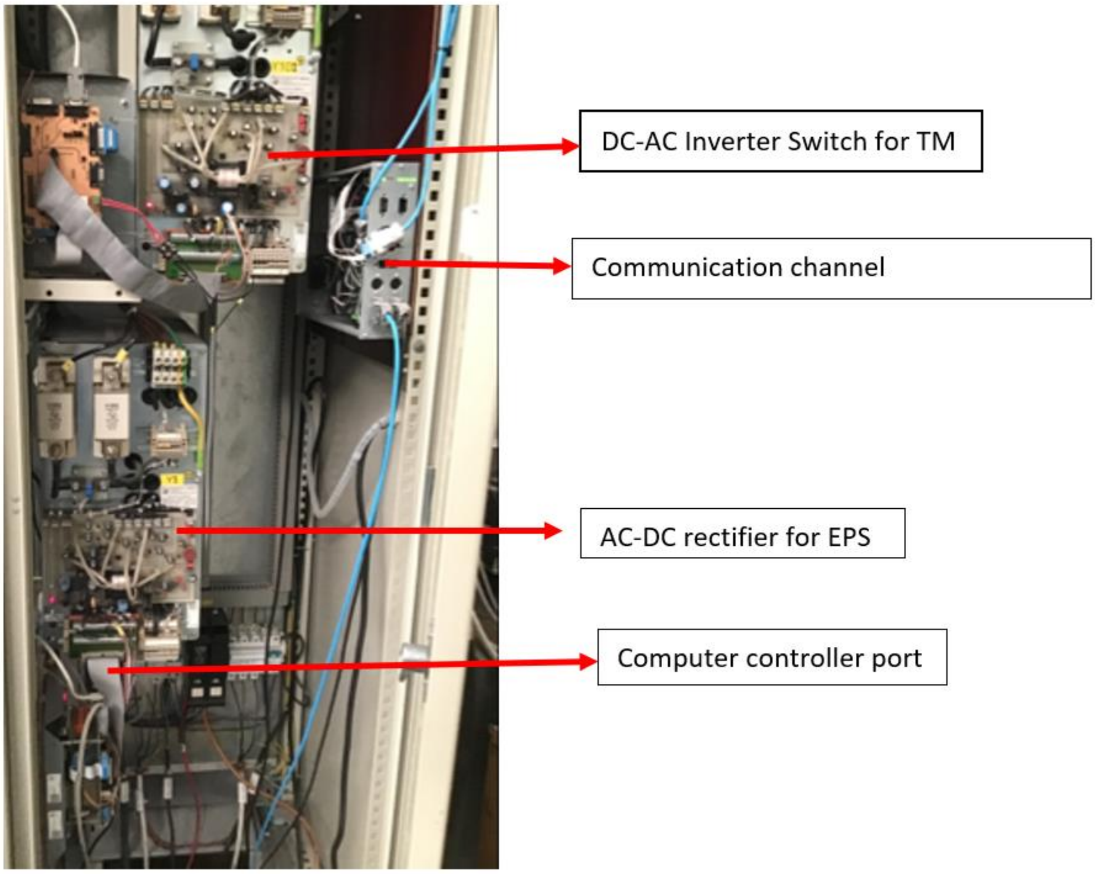

Figure 7. 6 power converter unit and PC interface

The HEV-CVUT test bench consists of four electrical machines, Super-Capacitors, power supplies, required instrumentation for data acquisition, control systems, and protective equipment. The figure above shows the electrical machines (two induction motors [ICE and Brake], Electric Power Splitter unit, and a traction motor). Additional, components of the test bench are, two Danfoss frequency converters, power control units (traction AC - DC, DC-AC, and DC-DC converters), control and circuit breakers, and transducers for variable measurements, instrumentation, status indicators, monitors, etc. They are functionally interconnected and housed in a cabinet of the test bench. The HEV-CVUT laboratory stand consists of electrical drives, power electronics, and related electrical equipment. The test bench does not contain traditional vehicle parts such as an actual ICE, transmission unit, and wheels. The entire experimentation is based on applying traditional electrical engineering with electric drives.

7.2 Applying SCADA to HEV-CVUT

The HEV test bench can only be used efficiently if a monitoring system is installed that provides real-time information about all the important parameters of the components. In addition, real-time control is required to synergistically use all the functional units of the working stand. Creating a vehicle driving condition like an actual one is only possible if this integration between all components is fully functional. A supervision system is also required to control the vehicle parameters while the vehicle goes through the driving cycle.

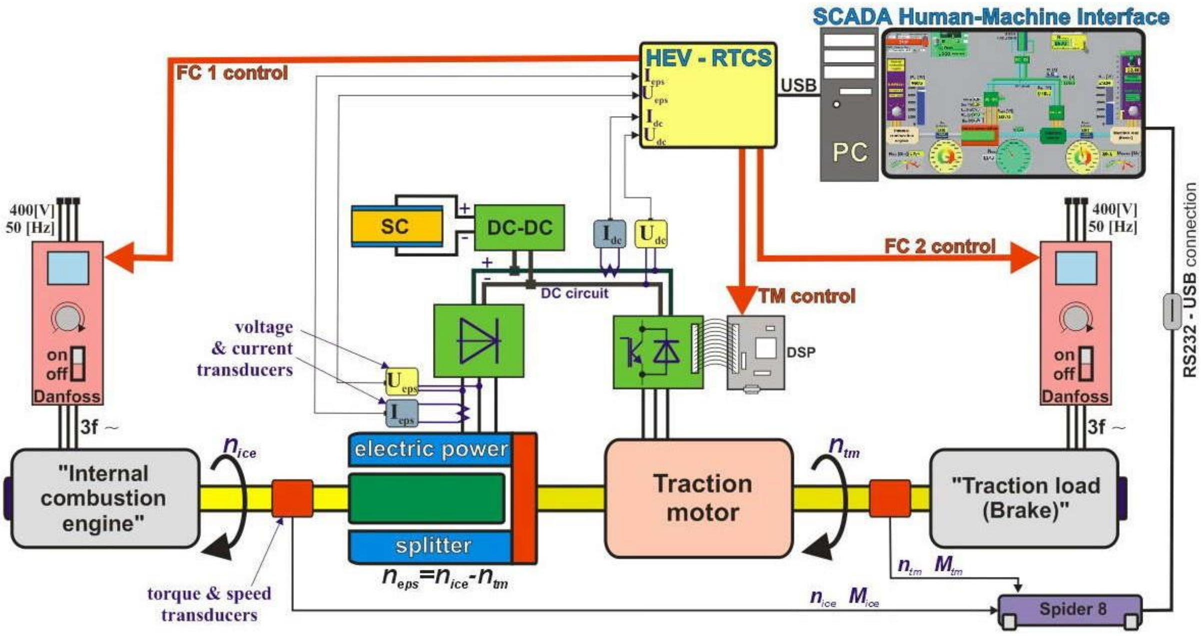

Figure 7. 7 ICE and brake motor control using SCADA system [11]

The HEV experimental stand is a very complex experimental system. It has a variety of electrical and mechanical variables that need to be controlled and adjusted. As described, all measuring devices operate as separate and independent sets. Thus, a supervisory control and data collection system SCADA (HEV-SCADA) for the HEV-CVUT test bench is created. The functional components and the interlink between them in this SCADA system are shown below in the figure

A key intelligent part of SCADA is a supervisory computer that collects signal data, analyzes real-time information captured from the electrical components of the test bench, and sends feedback control commands to the system to control the process. This subsystem is a PC-based solution running on Windows operating system. The use of standardized computing structures allows the versatility of this SCADA system, which can be used on any other PC-based platform, offering a further scope of development and flexible upgrade options according to the future needs of the HEV stand.

A major contribution to the creation of this SCADA for the HEV-CVUT test bench is to enable operators to have a user-friendly human-machine interface (HMI). The HMI is a device that processes all data from the system and presents it to the operator in user-friendly form. This allows the operator to monitor and control the process easily. By this method, the entire working stand needs only one person to operate.

Operation controls from one PC in a user-friendly method make it easy for the operator to work with the test bench. The operator can perform numerous test cycles, gathering real-time data and being able to analyze the results instantly. For HEV-SCADA is used the software package LabVIEW is. The software provides a graphical programming environment for creating sophisticated measurements, testing , and control systems. A human-machine interface for the HEV is used within this software system. The GUI panels of HEV-SCADA give detailed visualization, monitoring, and process-specific control in the HEV stand. The LabVIEW software package is used as a platform to get intuitive graphical programming for advanced analysis and data visualization. It provides easy electrical equipment integration with the hardware devices and also has embedded libraries. These properties allow the integration of the remote terminal unit Spider8 with the HEV-RTCS. LabVIEW offers the possibility of acquiring and adjusting communication BUS systems for sensor and device data transmission.

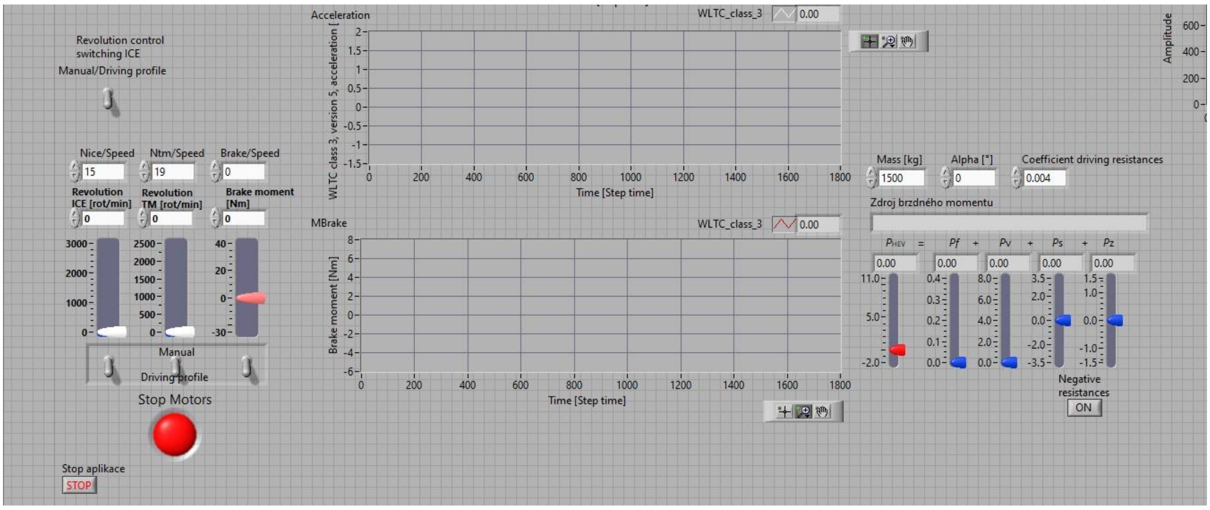

Figure 7. 8 HEV-CVUT GUI in LABVIEW

7.3 HEV Remote Terminal Control Set (HEV-RTCS)

A special remote terminal unit is installed to record the change in electrical variables. Sensor signals from voltage and current transducers are recorded by two NI USB-6009 multifunction DAQ devices. These devices using a USB are connected to the SCADA supervisory computer. Each of these DAQs has 4 analog inputs, 2 analog outputs, and 12 digital inputs. The analog inputs are interconnected and electronically modified for signal acquisition by voltage and current transducers. The analog output is a 12-bit voltage signal used for process control. By converting these signals with an analog pulse generator, an accurate pulse signal is created. The first signal is used to control the frequency converter (FC1) of the motor which is ICE.

The second signal is used for the pulse control of the frequency converter (FC 2) linked to the Brake motor. The third signal is used to control the TM by direct pulse voltage control of the digital signal processing board (DSP) which controls the DC-AC converter.

This RTU also functions as a distributed control unit (DCU). The signal processing, data acquisition equipment, sensors control, signal conditioning, and control signal transformers are all kept in a single compartment. This set is the main control and adjustment unit for the HEV-CVUT test bench. Therefore, it is called HEV Remote Terminal Control Set (HEV-RTCS).

The NI USB-6009 multifunction DAQ is used as the central data acquisition and control device for SCADA implementations in HEV-CVUT. This device provides data acquisition capabilities for data logging, offsite measurements, and laboratory experiments. It is a universal and flexible data collection tool that can be connected to any PC running compatible software via a USB interface. Our system runs on a WINDOWS OS and is fully compatible with the DAQ system.

Figure 7. 9 NI USB6009 Data acquisition device [12]

NI USB6009 does not require a separate power supply to function. Powered directly from the PC's USB port, it's easy to connect. The NI USB6009 provides a stable supply voltage of 5 [V] and 2.5 [V] and has a maximum current of 200 [mA], which allows direct connection of relays and optocouplers to DAQ.

Each NI USB-6009 comes with four differential voltage analog inputs (AI). They also have two analog outputs (AO) channels.

These analog inputs are used for data acquisition from voltage and current transducers. For each power circuit in the working stand, there are OMX305LEM current and OMX38DC voltage measuring devices. These are used to acquire the voltage and current readings from the Danfoss controller, which controls the ICE and Brake motors. The output from these transducers is in form of current signals, which offers advantages such as being impervious to electromagnetic interference from the surrounding devices. Also, the accuracy is not compromised by the long length of the transmission line used for data transfer.

The four AI channel on one of the data logger NI USB6009 is defined for the following data inputs:

U_{eps} - output voltage in EPS (on channel AI0),

I_{eps} - output current in EPS (on channel AI1),

U_{dc} - DC circuit intermediate voltage (channel AI2),

I_{dc} - DC circuit intermediate current (channel AI3),

There are three AI channels that we use on the second data logger (NI USB6009-B). These channels acquire signals from the recuperative circuit:

I_{scdc} - intermediate DC circuit leads to SC (channel AI0),

I_{sc} - current in SC (channel AI1),

U_{sc} - voltage in SC (channel AI3).

7.4 ICE and Brake motor control

In the HEV-CVUT working bench, the ICE and traction resistance (brake) are replaced by two similarly controlled motor sets. Each of them consists of an induction motor driven and controlled by two Danfoss VLT5011 frequency converters. The specifications of the induction motor are shown in the table below.

Type	**1LA7 131-2AA60**
Rated power	**7.5 [kW]**
Rated revolutions	**2930 [min^{-1}]**
Rated voltage	**3 x 400 [V] Δ**
Rated current	**13.8 [A]**
Frequency	**50 [Hz]**
Manufacturer	**Siemens**

Table 7. 1 Specification of motor used

Both of these Danfoss frequency converters are programmed to regulate the Induction Motors to function as an ICE or Brake of a vehicle.

7.5 ICE motor control

The first Frequency controller (FC1) is programmed to regulate the revolution of the ICE induction motor. This frequency controller takes the input signal from the USB6009 data logger and is regulated by the data logger's output voltage U_{daq}. This signal is transformed into a digital TTL signal with f_{TTL} frequency. Using this method, the frequency of motor f_m and the motor rotational speed n_m are regulated. The IM used in the test bench is an asynchronous induction motor, which means it will have motor slips. This slip results in different motor speed n_m for an assigned frequency n_m. Slip is dependent on instantaneous motor load P_m and speed n_m.

This slip is small and does not have a significant role in the control strategy of the HEV-CVUT workbench.

7.6 Brake motor control

The traction load on the vehicle which acts as a resistance force is generated by the brake motor in form of brake torque M_{brake} on the brake motor shaft. This IM is regulated by the second Danfoss Frequency controller (FC2). The method used here is "Torque control" and it requires real-time values of actual rotor speed n_{brake}. FC2 receives encoder signal on its control cable terminal CCT from Siemens 1 XP8001 rotary pulse encoder. The FC2 CPU calculates the required braking moment M_{brake}, according to the real-time signal received from encoders at its control board. The FC-CPU regulates the pulse width modulation(PWM) for output motor frequency f_m and voltage U_m control, which alters the motor torque M_{brake} accordingly. The produced braking torque M_{brake} is applied in the opposite direction of the shaft rotation, this requires the program logic of FC2 to be setting it as a negative value.

7.7 The electronic Power Splitter control

An electric power splitter (EPS) is simply a synchronous generator with the following ratings.

Type	**PMG112-K08**
Rated power	**5 [kW]**
Rated revolutions	**4000 [min^{-1}] (max 6000)**
Rated voltage	**3 x 486 [V] Δ**
Rated current	**6.45 [A]**
Frequency	**266.6 [Hz]**
Manufacturer	**VUES Brno**

Table 7. 2 Power specification of EPS

EPS is a specially designed 8-pole AC machine with two rotating parts as shown in the figure below. The main rotor is a permanent magnet rotor that is rigidly coupled to the ICE motor driveshaft. The stator is functionally similar to other AC machines, but it can freely rotate and is bearing mounted. This part of the EPS is coupled to the TM shaft. Both these rotating shafts of EPS are directly controlled and regulated by HEV-SCADA. The rotation of the rotor shaft n_{ice} is controlled by frequency controller FC1, and the stator shaft load M_{brake} is controlled by FC2. The revolution of this shaft n_{brake} is regulated by the control of TM which is rigidly linked to the stator of EPS.

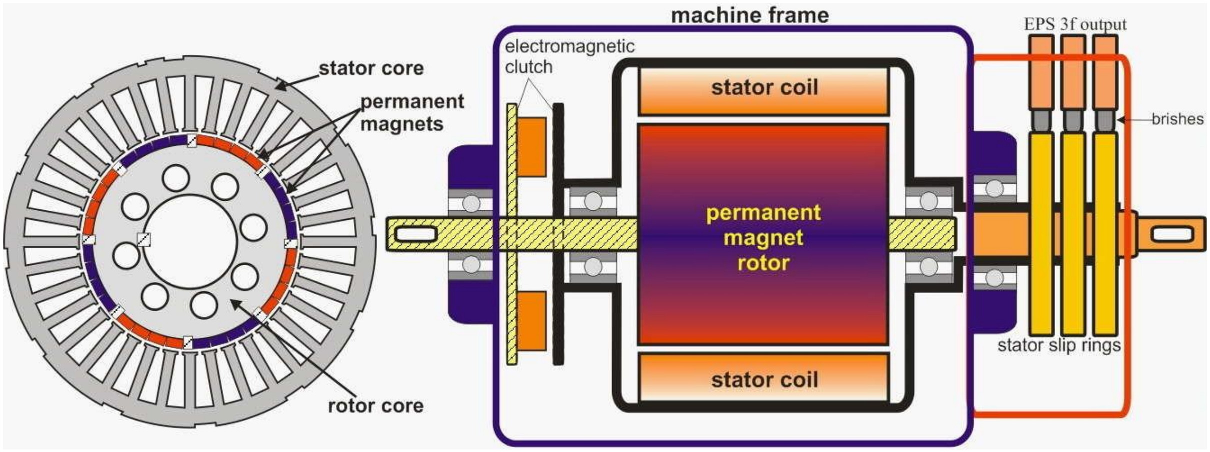

Figure 7. 10 Cross section of EPS [11]

EPS is an 8-pole synchronous AC machine:

2p=8

p=4

For synchronous generators, the output frequency of the current generated is in direct correlation with its shaft revolution n_{eps}:

$$f_{eps} = \frac{n_{eps} \cdot p}{60} \tag{7.1}$$

As the stator and rotor both are rotating, EPS revolution n_{eps} is a relative difference between both rotating shafts:

$$n_{eps} = n_{ice} - n_{brake} \tag{7.2}$$

By controlling the number of revolutions of EPS, the output voltage U_{eps} of the machine is directly controlled. A three-phase stator winding with a slip ring and contact brush is connected to the AC input of the AC-DC converter. The generated voltage U_{eps} is rectified by this currently untuned converter (α= 0) and creates a DC link voltage U_{dc}.

$$U_{dc}(\alpha) = \frac{6}{2\pi} \int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}+\alpha} \sqrt{2} U_s \sin \omega t d(\omega t) = \frac{3\sqrt{2}}{\pi} U_s \cos \alpha = \frac{3\sqrt{2}}{\pi} \sqrt{3} U_{eps} \Big|_{\alpha=0} = 2.34 U_{eps} \tag{7.3}$$

The dependence of EPS output voltage U_{eps} and U_{dc} as a function of n_{eps} is linear. The increase in machine load results in a voltage drop. In the HEV SCADA system, the relative rotation speed of the EPS n_{eps} and the rectified voltage U_{dc} are used as directly measured feedback values to control the ICE rotation speed. This speed regulation is achieved by controlling the frequency converter FC1. Thus, the HEV-SCADA system maintains a stable DC link voltage.

7.8 HEV-SCADA data acquisition

For HEV-SCADA, another RTU is applied in addition to the previously discussed remote terminal unit HEV-RTCS. For torque and speed sensors, use the HBM Spider8 data acquisition device as an RTU to acquire mechanical variables. This unit collects data from two transducers that measure four quantities: RPM (n_{ice}) and torque (M_{ice}) from the ICE drive shaft, RPM (n_{tm}) and torque (M_{tm}) on the TM "brake" shaft. Sensor signal data is captured, processed, and sent as a data stream via the RS232 output interface. An RS232-USB converter is used to connect this data stream to the SCADA supervisory computer.

Figure 7. 11 Torque and speed sensing units [11]

The HBM T20WN Inline Torque Transducer is used in the HEV stand. It consists of a static part (stator), a rotating torsion shaft (rotor), and measuring electronics. The stator is fixed to the body of the machine and the rotor is connected in series with the shaft of the machine with a clutch coupling. These sensors use a torsional deflection method based on the effect of surface tension ε on the rotor shaft caused by the applied torque. Strain gauges in Weston's bridge circuit are placed on the rotor shaft. The output of this bridge circuit is proportional to the torque applied to the rotor. This transducer has special contactless electronic transmission components which provide the supply voltage to the power sensor and transmits the measured signal. Being a contactless transmission system, it allows sensors to have a longer life and supports high shaft revolutions. The output torque signal of the converter is a proportional analog voltage signal ranging between -10 [V] to +10 [V].

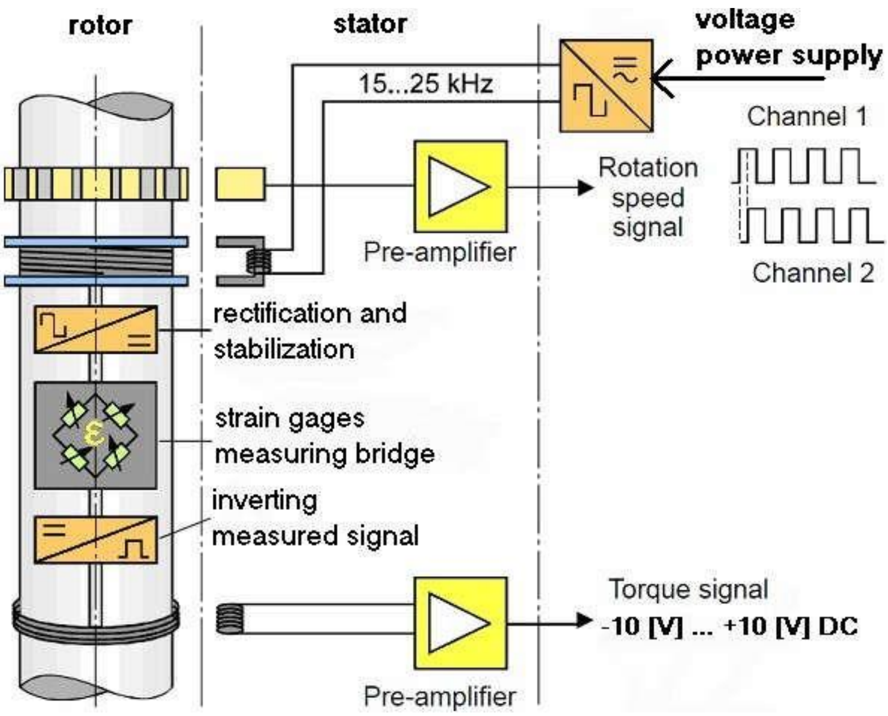

Figure 7. 12 Circuit for torque and RPM sensor [3]

The speed and rotation angle of the shaft is measured by an optical system. As the rotor rotates, voltage pulses are generated as per the number of slots passing the sensor front per revolution, the frequency of which is proportional to the speed of the shaft. The T20WN produces 360 pulses per revolution. The pickup nodes or detection diodes are offset from each other to generate two pulse trains with a 90° phase shift. The direction of rotation is known by the phase shift between two diodes. A preamplifier transforms the pulse sequence into a pure square wave voltage. All four individual sensor signals are connected to the Spider8 remote terminal unit. Spider8 is a multi-channel PC measurement device for computer-aided parallel and dynamic measurement data acquisition. It has embedded input signal amplifiers and an A/D converter. The advantage of this device is that it can perform simultaneous data acquisition at a high sampling rate of 16 bits, and has a metal body that prevents Electro-magnetic interference.

The signals are processed by a built-in CPU. The TTL pulse signal from the speed sensor is directly sent to the CPU, which allows for high-speed pulse measurement and direct processing. The signals from the torque sensor in analog output voltage form are amplified and digitized by an A/D converter for CPU processing. Data from all connected sensors are converted as a data stream through the RS-232C port. This port with an RS232 USB converter is connected to a SCADA computer. This allows for direct integration with Spider8's HEVSCADA system.

8 Laboratory Measurements and Experimental Results

Laboratory experiments were conducted on the HEV-CVUT test bench in H.26 laboratory at the Department of Electric Drive and traction at FEE, CVUT. The SCADA system of this working bench has helped to verify the simulation result of HEV simulation based on the feedback systems and is crucial for control strategy verification. The test bench helps gain the necessary data such as losses and energy transformation for the HEV propulsion system. This data helped to create an accurate HEV mathematical model. This approach gave access to the creation of new vehicle control strategies and utilizing experimentally gained results in computer analysis.

Vehicle driving performances based on WLTC class 3 driving cycle are shown below. The graphs are plotted using the sensor data stored in HEV -CVUT SCADA system.

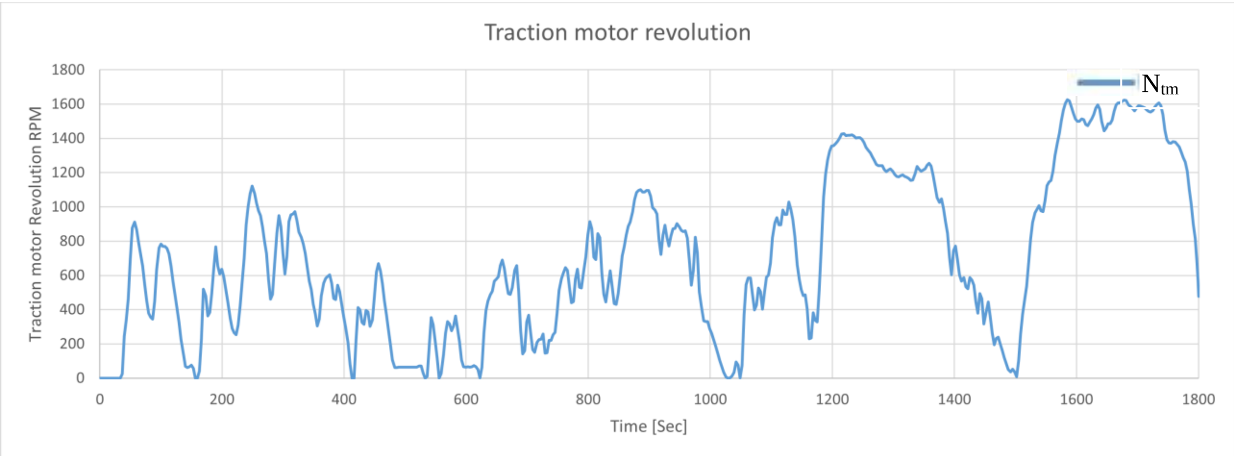

Figure 8. 1 Traction Motor revolution measured for WLTC class 3 cycle

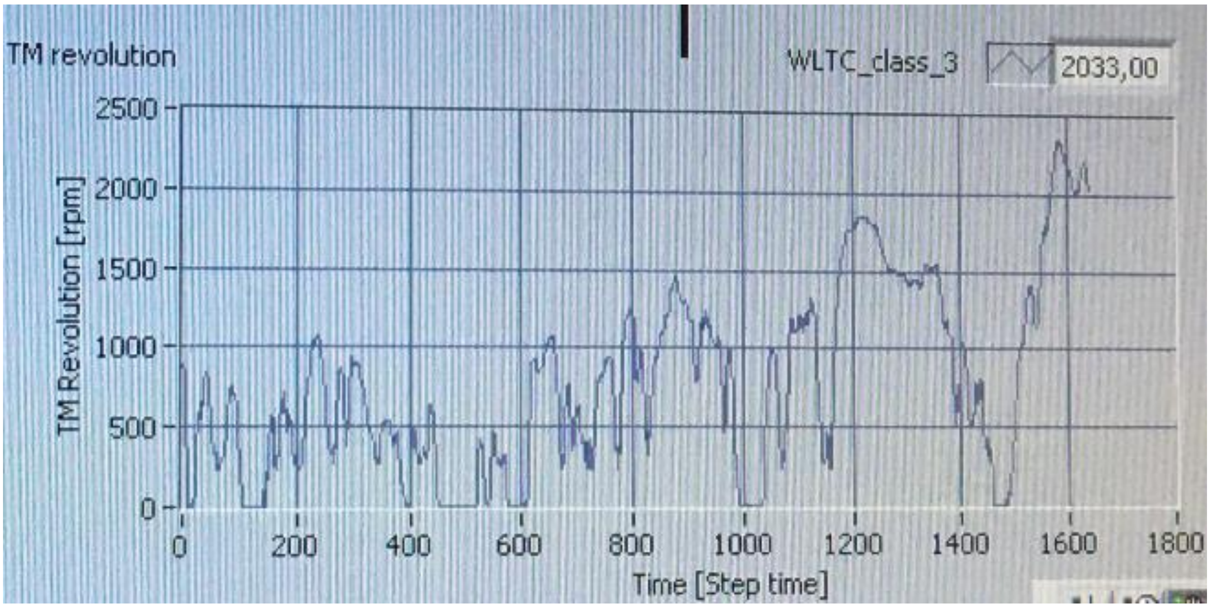

Figure 8. 2 Traction Motor revolution measured for WLTC class 3 in LabVIEW

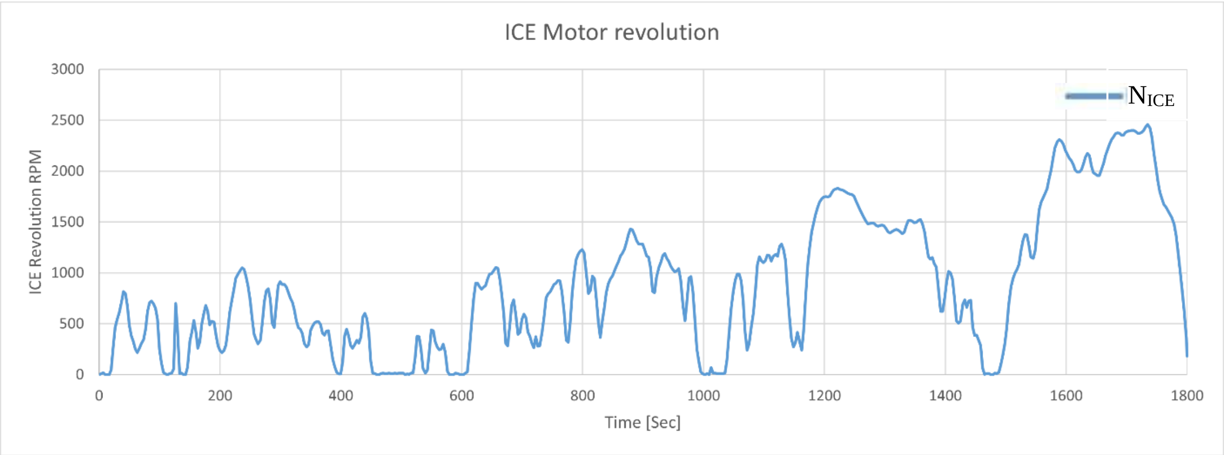

Figure 8. 3 ICE Motor revolution measured for WLTC class 3

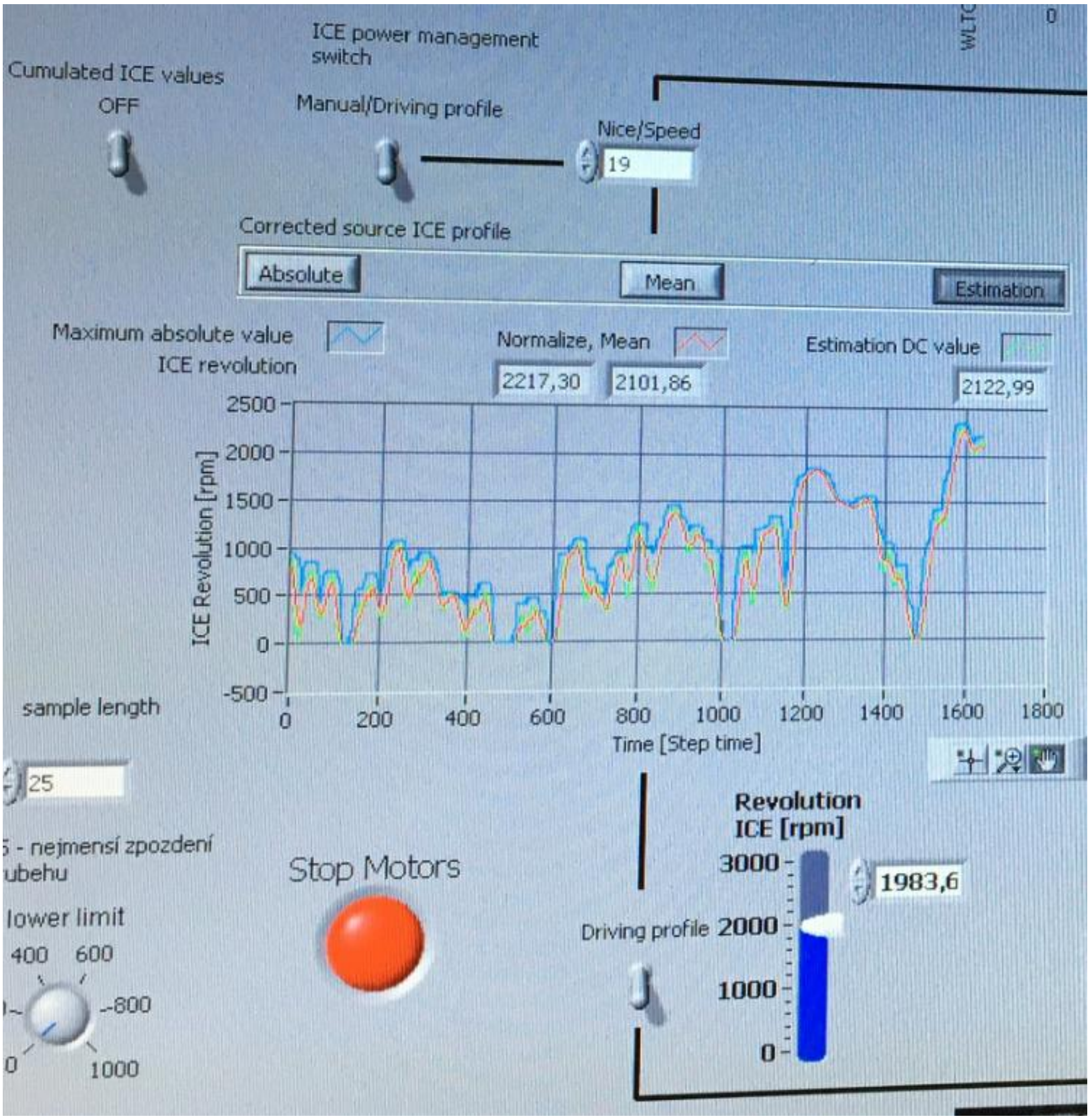

Figure 8. 4 ICE Motor revolution measured for WLTC class 3 in LabVIEW

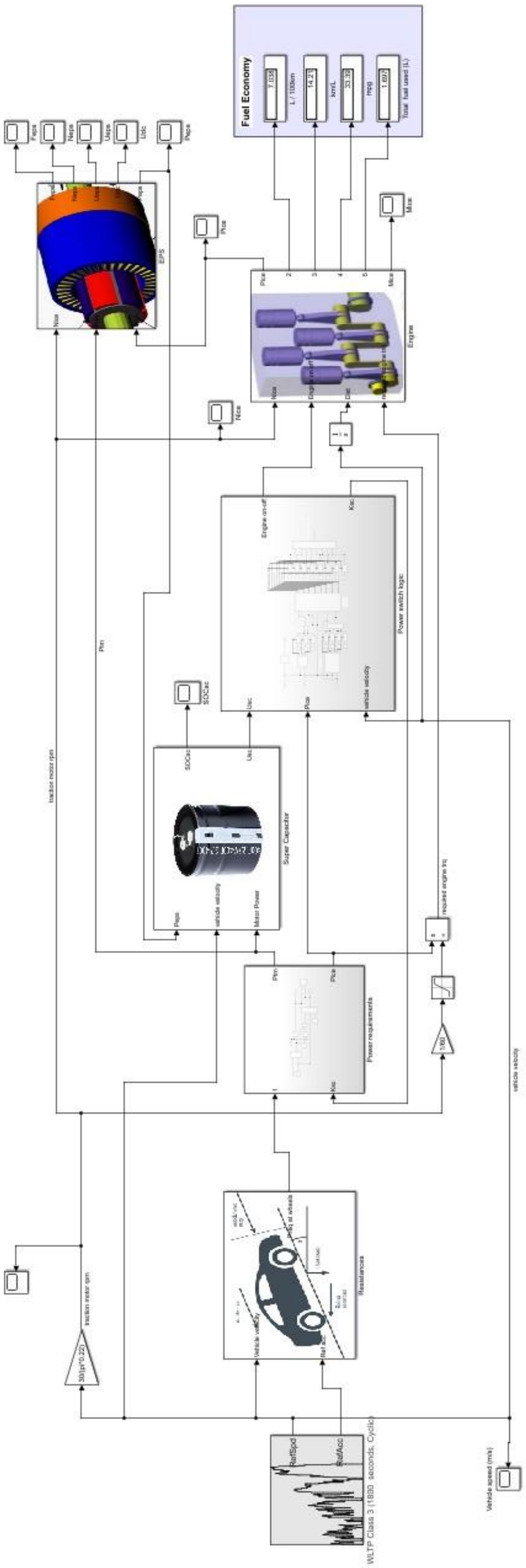

Figure 8. 5 Simulink model for the HEV-CVUT

Mice[Nm]	Nice[rot/min]	Neps[rot/min]	feps[Hz]	Ieps[A]	Ieps[A]Filter	Ueps[V]Filter	cosFI[o]	Peps[W]	Seps[VA]
1,558	13,280	13,280	0,000	0,055	0,000	0,000	NaN	0,000	0,000
1,558	13,280	13,280	0,000	0,055	0,000	0,000	NaN	0,000	0,000
1,516	13,600	13,120	0,000	0,053	0,000	0,000	NaN	0,000	0,000
1,479	15,360	15,360	0,000	0,049	0,000	0,000	NaN	0,000	0,000
1,497	26,080	17,120	0,000	0,056	0,000	0,000	NaN	0,000	0,000
1,527	143,520	102,080	17,716	0,050	0,054	6,837	0,287	0,183	0,638
1,673	330,560	330,720	30,966	0,716	0,060	8,053	64,280	53,375	0,830
2,309	455,840	454,240	32,623	1,478	0,086	10,661	90,229	143,050	1,585
2,334	497,920	513,120	35,539	1,689	0,172	15,781	37,246	174,890	4,696
2,267	566,080	524,640	35,076	1,974	0,267	20,427	21,053	199,046	9,455
2,470	679,520	526,880	32,452	2,495	0,436	27,533	11,236	233,584	20,789
4,358	723,680	494,240	30,107	2,405	0,668	35,673	4,972	205,369	41,302
6,429	730,240	450,080	26,213	1,431	0,952	43,385	1,458	104,276	71,519
6,693	729,280	397,920	23,459	0,121	1,281	50,504	0,044	4,941	112,040
4,882	728,800	351,520	18,226	0,048	1,473	54,226	0,001	0,178	138,374
3,299	729,440	279,360	14,315	0,051	1,571	55,565	-0,000	-0,051	151,174
2,286	727,520	244,480	21,724	0,058	1,560	54,653	-0,002	-0,288	147,640
1,810	728,000	329,280	26,705	0,052	1,421	52,181	-0,005	-0,662	128,415
1,766	729,440	408,800	30,623	0,060	1,170	49,356	-0,007	-0,715	100,056
1,770	728,640	449,760	30,582	0,395	0,876	47,086	0,547	39,101	71,436
1,761	727,040	463,680	33,168	0,549	0,615	45,726	1,067	52,010	48,745
1,853	727,520	492,800	33,684	0,635	0,415	45,922	1,816	59,983	33,024

Figure 8. 6 Measured and calculate for the WLTC driving cycle

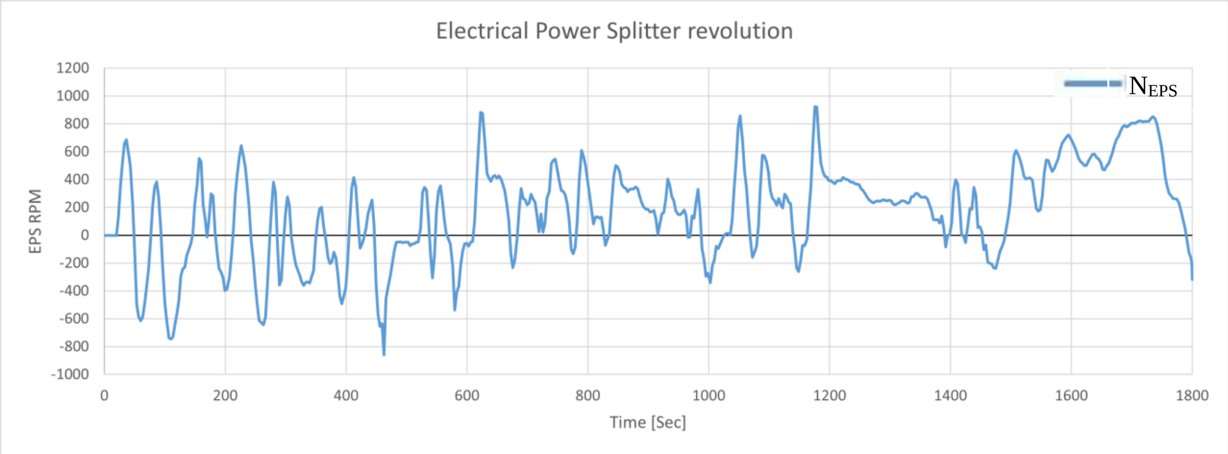

Figure 8. 7 EPS revolution measured for WLTC class 3

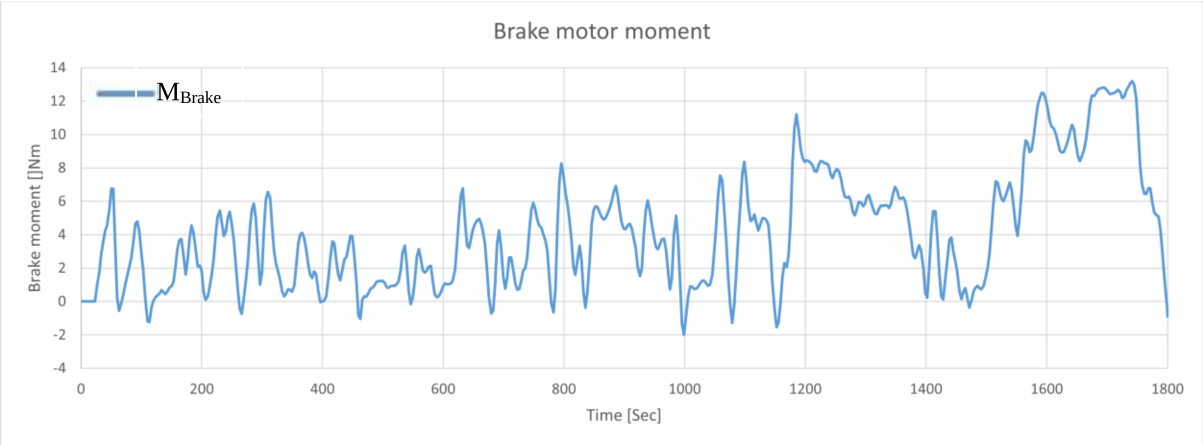

Figure 8. 8 Brake torque measured for WLTC class 3

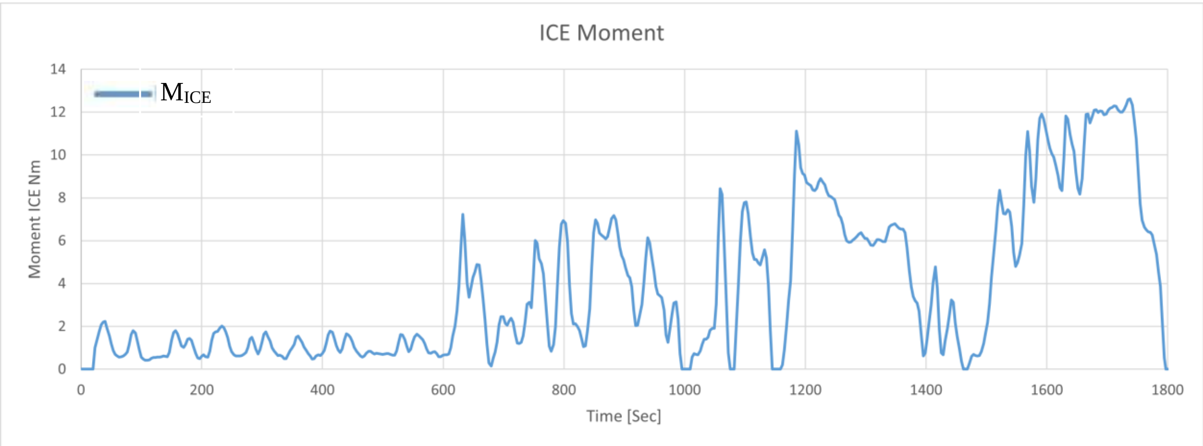

Figure 8. 9 ICE torque measured for WLTC class 3

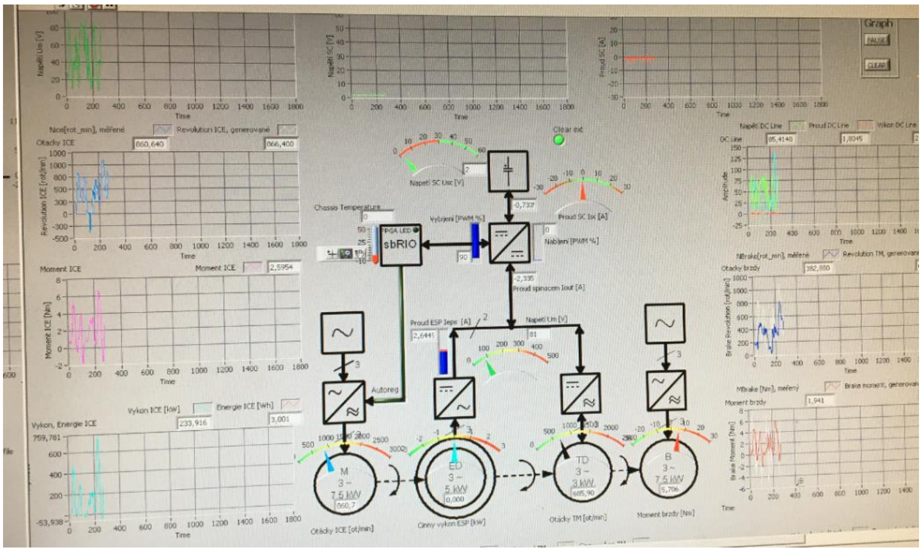

Figure 8. 10 GUI of LabVIEW running WLTC driving cycle being plotted

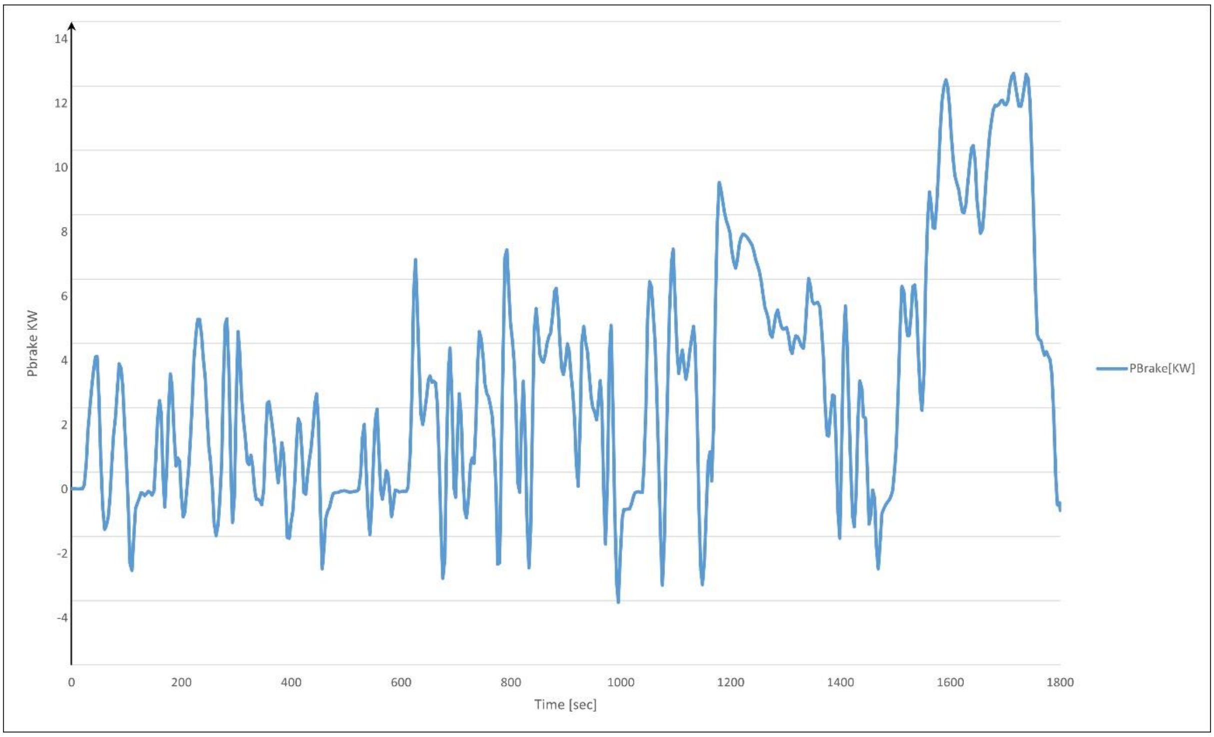

Figure 8. 11 Resistive power supplied as brake power P_{brake}

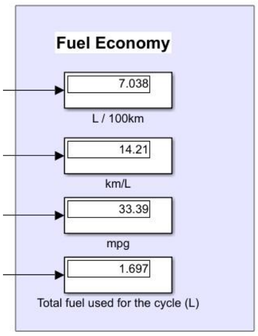

Figure 8. 12 Fuel efficiency of HEV from Simulink simulation

9. Conclusion

This master's thesis is an interdisciplinary work implementing many technical disciplines using high-performance electrical engineering, electric drives, and automation technology process, machine programming, software simulation, measurement technology, vehicle technology. As a result, all these technical areas are implemented synergistically when creating the control algorithm for Hybrid Vehicle. Strategies for specific automotive hybrid systems and vehicle can be tested using HEV test bench. In chapter 1 we have discussed and analyzed the main hybrid electric vehicle systems available, the need and the importance of hybrid-electric technology is justified by the resulting fuel efficiency. This will help improve the quality of environment by lowering the emission and having higher fuel efficiency.

Each segment of the HEV-CVUT system has been carefully and systematically researched and analyzed. This work contributes to the consolidation of all previously realized work with the sublimation of results, the creation of individual conclusions, and the direction of further project development.

Theoretically with a precise mathematical approach kinematic model was developed and simulated in Simulink. The SCADA is a general system for visualizing and controlling complex processes. Use of HEV-SCADA helped making experimental HEV-CVUT performance measurement in Real-time control with feedback simplified and user friendly. Measurement of all important electrical and mechanical quantities and real-time visualization and calculation of values aided in the comparison and monitoring of experiments. Experiments were performed using this HEV SCADA system and the results were shown in the aforementioned graphs. These results and analysis provide an overview of the control strategy for this hybrid vehicle system. This data also helps in confirming the results from MATLAB Simulink results where similar characteristics of graph plotted is observed. The test bench motors and Supercapacitor had low power rating due to which their load levels were modified in accordance with the real-life cycle parameters.

A detailed description of the program structure for simulating the driving style based on Driving cycle is given. A standardized template is used to calculate the vehicle's fuel consumption. Also, a quasi-static approach is used to calculate the kinematic vehicle model numerically.

The complexity of control strategies for HEV-CVUT system can be foreseen as there are numerous energy paths, current transformers, energy sources, and energy transformations, each with specific working behavior and function. The control algorithm also includes strategies that include predictive logic control. Therefore, it was discussed in detail. The calculation of vehicle fuel consumption for the entire driving cycle(WLTC) is done as fuel consumption is a typical indicator of the energy efficiency of the entire vehicle.

Using HEV control strategies, the simulation program created in this work is versatile and it can be adjusted to specific driving cycle, vehicle parameters, and road conditions. One can change the functional parameters according to the needs.

The most important thing is the fuel efficiency of the system as it provides an economic sustainability for possible future commercial implementation. Adopting similar control strategy simulation program for commercial use is possible. HEV-SCADA is upgradeable and can be improved with new options and better controls.

References

[1] J. Kavanagh, “euro-1-to-euro-6-emission-standards--a-comprehensive-guide,” 2021. [Online]. Available: https://www.myvehicle.ie/car-news/euro-1-to-euro-6-emission-standards--a-comprehensive-guide.

[2] H. W. Won's, “researchgate,” Nov 2021. [Online]. Available: https://www.researchgate.net/figure/System-operation-region-division-from-engine-map-for-parallel-HEVs_fig3_356638229.

[3] S. Massey, “MODELING, SIMUL MODELING, SIMULATION AND CON TION AND CONTROL OF H TROL OF HYBRID ELEC YBRID ELECTRIC,” Michigan, 2016.

[4] H. 2. P. release, “hyundai-48-volt-mild-hybrid-system,” 2019. [Online]. Available: https://www.hyundai.news/eu/articles/press-releases/hyundai-48-volt-mild-hybrid-system.html.

[5] U. D. o. Energy, “how-do-hybrid-electric-cars-work,” 2015. [Online]. Available: https://afdc.energy.gov/vehicles/how-do-hybrid-electric-cars-work.

[6] P. M. Dobri Cundev, “European Driving Schedule of Hybrid Electric Vehicle with electric power splitter and super-capacitor,” p. 5, 2008.

[7] P. M. Dobri Cundev, “Driving characterstics for Hybrid Electric Vehicle with Electric Power Splitter and Supercapacitor as Electric Storage Unit,” p. 4, 2007.

[8] CVEL, “Asynchronous AC Motors,” 2010. [Online]. Available: https://cecas.clemson.edu/cvel/auto/actuators/motors-ac-asynchronous.html.

[9] muRata, “muRata mobility electrified,” 2021. [Online]. Available: https://www.murata.com/en-global/apps/mobility/electrified/dcdc.

[10] H. Naunheimer, B. Bertsche and J. Ryborz, Automotive Transmission, Fundamentals, Selection, Design and Application,, Springer, 1999.

[11] D. Čundev, “CONTROL STRATEGY OF CAR HYBRID SYSTEM AND ITS EXPERIMENTAL CONFIRMATION,” 2009.

[12] NI, “Support page,” 2015. [Online]. Available: https://www.ni.com/cs-cz/support/model.usb-6009.html.

[13] D. C. P. M. Zdenek Cerovsky, “Silent operating range of military electrichybrid vehicle using electric power splitter and different electric energy storage,” p. 7, 2009.

[14] P. M. Dobri Cundev, “Design and Development of the Hybrid-electric Vehicle by achieving the Best Operating Performance and Highest Efficiency,” p. 7, 2009.