CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF MECHANICAL ENGINEERING

DEPARTMENT OF AUTOMOTIVE, COMBUSTION AND RAILWAY ENGINEERING

ELECTRIC VEHICLE POWERTRAIN SIMULATION

MASTER'S THESIS

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Branch of Study: Advanced Powertrains

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Declaration

I hereby declare that I am the sole author of the thesis titled “ELECTRIC VEHICLE POWERTRAIN SIMULATION”.
I duly marked out all quotations.
The used literature and sources are stated in the attached list of references.

Place: Prague, Czech Republic
Date:

Acknowledgement:

I hereby wish to express my appreciation and gratitude to the supervisor of my thesis, doc. Ing. Pavel Mindl. CSc., for his continuous support, guidance, patience and understanding as well as for providing crucial information and assistance.

I am utterly grateful to my family and peers for the continuous motivation and meticulous support. I would also like to thank my previous guides, all my course teachers and Mrs. Achtenova for instilling in me immense diligence and the zeal to learn and challenge myself in the field of Automotive.
I would like to thank my friends and acquaintances for providing me working morale, support in hard times and encouragement to perform at the best levels.

MASTER'S THESIS ASSIGNMENT

I. Personal and study details

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Study program: **Master of Automotive Engineering**

II. Master's thesis details

Master's thesis title in English:

Electric Vehicle Powertrain Simulation

Master's thesis title in Czech:

Simulace pohonu elektromobilu

Guidelines:

On the basis of electric vehicles powertrain study create simulation model of electric drive for passenger car.
Main goals of thesis
1. Overview of electric and hybrid vehicles powertrain architectures.
2. Detailed analysis of induction motor (IM) powertrain on the 28 kW level
3. Methods of powertrain controls
4. Model of analysed drive in Matlab Simulink
4. Calibration of simulation model on motor powertrain functional example.

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Name and workplace of master's thesis supervisor:

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Date of master's thesis assignment: **19.10.2022** Deadline for master's thesis submission: **11.01.2022**

Assignment valid until: ____________

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Head of department's signature

doc. Ing. Miroslav Španiel, CSc.
Dean's signature

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

Abstract

The diploma thesis is focused on theoretical and empirical analysis of an electric powertrain drive comprising of an induction motor in different operating regimes. The analysis is done using a culmination of Test data procurement and cross referencing them partially using software simulation. The drive is run on a Dyno Test Bed using manual control for different operating regimes.

Similarly, the simulation is run in MATLAB/Simulink using Field Oriented Control.

The work is focused on the problem of electric drive working regime optimisation. In the branch of electric cars electric drives efficiency is key factor for its range.

Laboratory measurements were performed at the experimental workplace of CTU - VTP in Roztoky. The simulation model is created in the MATLAB - SIMULINK software environment. 2022a

Keywords:

Electric Drives, Three-Phase Induction Motor, Field Oriented Control, MATLAB/SIMULINK, Operating Regimes, Electric Vehicles, Powertrain

Abstrakt: Diplomová práce je zaměřena na empirickou analýzu elektrického pohonu hnacího ústrojí sestávajícího z asynchronního motoru v různých provozních režimech. Analýza se provádí pomocí dat z provedených testů a jejich následným využitím při softwarové simulaci.

Simulace jízdy probíhá na dynamometrickém měřicím systému s manuálním ovládáním pro různé typy scénářů.

Podobně je i prováděna simulace s využitím softwarového vybavení MATLAB/Simulink metodou vektorového řízení (FOC). Práce je zaměřena na problematiku optimalizace pracovního režimu elektrického pohonu. V oblasti elektromobilů je účinnost elektrických pohonů klíčovým faktorem pro dojezd. Laboratorní měření byla provedena na experimentálním pracovišti ČVUT - VTP v Roztokách. Simulační model je vytvořen v softwarovém prostředí MATLAB – SIMULINK. 2022a

Keywords in Czech: Elektrické pohony, třífázový asynchronní motor, vektorové řízení magnetického pole, Matlab-Simulink, provozní režimy, elektromobil, pohon.

Table of Contents

List of Figures

List of symbols

Stator phases	a, b, c
Rotor Phases	A, B,C
Direct axis d, Quadrature axis q windings	d,q
Stator	s
Rotor	r
Magnetizing	m
Mechanical	M (As in Θ_m or ω_m)
Mechanical	mech
Leakage	l
Superscripts *	Reference value
p	Number of poles
Θ	All angles such as Θ_m and the axes orientation are in electrical radians

	equal to p/2 times mechanical radians
ω	All speeds except for ωmech are in electrical radians per sec.
Θmech	Rotor angle is in actual mechanical radians per secodn
s	Slip
Ns	Synchronous Speed
MMF	Magnetomotive force
T	Torque
L	Inductance
R	Resistance
χ	Reactance
i	current
λ	Flux
Ψ or F	Flux linkage
IM	Induction Motor
DTC	Direct Torque Control
J	Inertia
HEV	Hybrid Electric Vehicle
EV	Electric Vehicle

Chapter 1 Introduction

From the medieval ages humankind has always tried to make advancements in the field of both technology and territory. Right from the discovery of the wheel to the autonomous levels now in trend having adequate control with sustainability must be the primary objectives of any technological advancement. The Automotive industry has become one of the most important worldwide industries, not only at economic fronts but also in terms of research and development.

Currently seeking to the dismayed situation of the environment EVs and its development must be the hot topic which needs high profile importance.

For EVs to propel the motor and the source of power which is the battery have to the most crucial elements to attain sufficient acclaims and be able to put up to the challenging demands and trends in the transportation sector. Typical disadvantages would be the low energy density and longer charging time. The Energy Management in the EV is also a crucial aspect as sustainability and economic factors could hold major stakes. For Optimal Energy management in addition to the optimum motor selection and design, selection of proper drive and optimal control strategies are a major factor. The primary goals of a propulsion system in an EV would be high ratio of torque to inertia, power to weight, high maximum torque capability, high speed, high starting torque, less noisy, high efficiency over low and high-speed ranges, high recuperation of energy and minimal sensitivity to acceleration forces.[1]

Well Knit and Managed transportation provides mobility as well as environmental superiority. The road transportation consumes 75% of the total energy spent on transportation. Contrasting to that also most vehicles running on Internal Combustion contribute to 25-30% of the total greenhouse emissions. The parameters, crucial control aspects and to understand the optimisation points for running an efficient electric drive and cater to all the above stated goals would be the primary objective.

1.1 Market Survey and Trends

EV sales volume has increased significantly, especially in recent years, even though the purchase price of electric vehicles is greater when compared to the internal combustion engine version of the same vehicle type. Furthermore, numerous countries are switching to green technology of propulsion and excluding any such fossil fuel usage to sustain the environment. Evidently it can be seen in the Paris Agreement as well that there has been an uprising public interest both vocally and financially to take up such initiatives.

As a matter of fact, all the developed countries are switching to such renewable sources and putting more financial stakes on the research, development, promotion, and awareness generation of the mayhem that might be coming around the end of the decade if the emissions and overexploitation is not given a proper check on.

From a global perspective China is leading the market trends to be the most future driven and electric vehicle adoption enthusiast. It has been deciphered in the Global Report by Mckinsey and Company and can be seen in the Figure 2 [2].

Empirical Studies reveal that the high rising OEMs have started applying what is called design to cost strategy to the Electric Vehicle Powertrain and Body in white, as the contest for range and performance has been out won with flying colours and moreover there have been development of better materials and battery recycling. This trend notably emerges in second-generation EVs. The DTC focus has been mostly on component integration in the powertrain area and efficient use of optimal weight materials in structural parts.[3]

The mass market EVs will keep on converging to the low-end mass market ICE models due to the following reasons as stated in [3]:

- Generational leaps in powertrain technology yield significant weight reductions, which are then directly reinvested into lower-cost structural materials.
- In the manufacturing trends currently going on Batteries hold more significance than lightweight materials
- EVs fall short on external incentives for weight reduction while it is vastly different for ICE vehicles with their emission penalties.

For EVs the OEMs must redefine their logic and business models in order to attain the profits and maintain a good source of reliability to ensure market value remains stagnant or goes better. EVs are less expensive on maintenance and have more constraints on options for the following:

1. The margin or room for differentiation is very minimal in comparison to an ICE model.
2. The higher base prices in the EVs lead to loss of high margin income. The battery is the primary contributor to this variety of options for the base EV configurations.

Figure 1 : Price shares in German Market [3]

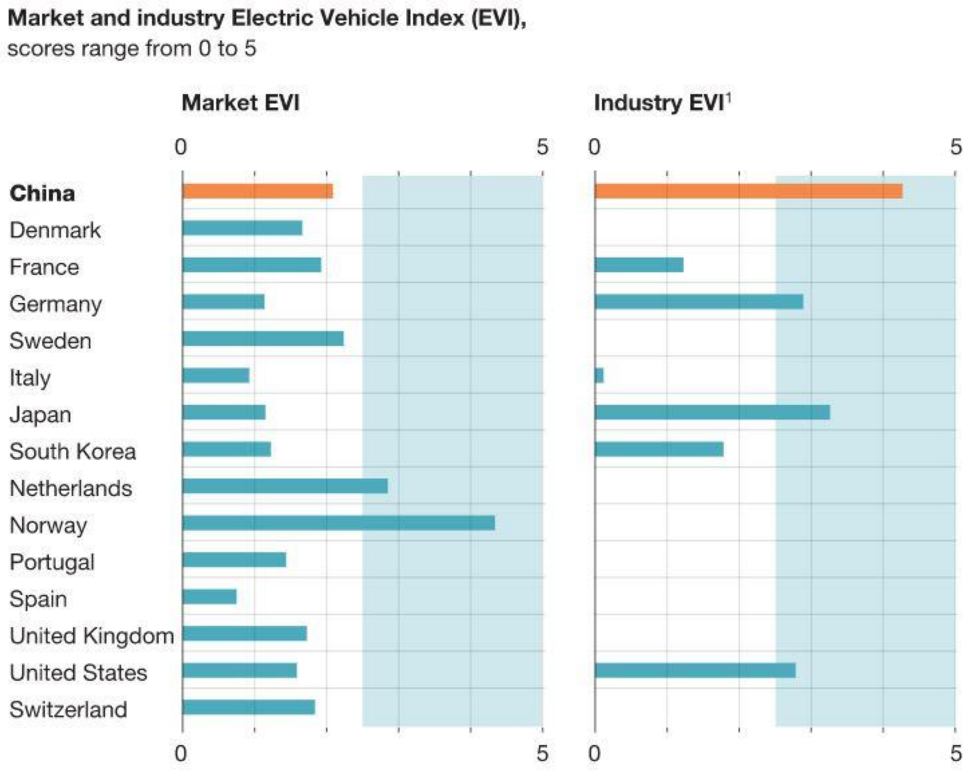

Figure 2 : Market Statistics for EV Adoption [2]

1.2 Literature Review

The Thesis is vastly defined by control methods, simulation and understanding of the electrical machine specifically Induction Machine in their operating ranges and different test conditions, their components, equations and working principle. For understanding the basics as being from a Mechanical Background, I underwent few online courses as follows.

1. https://learning.edx.org/course/course v1:ChalmersX+ChM012x+1T2022/home
Model-Based Automotive Systems Engineering

2. https://learning.edx.org/course/course-v1:DelftX+eCARS2x+3T2019/home
Electric Cars: Technology

3. https://www.udemy.com/course/matlab4b/

MATLAB/Simulink - Simulink Course for Electrical Engineering.

Furthermore, due to the comparison of physical and model-based development, the block-based knowledge from MATHWORKS and their E-Learning platforms provided great impetus.

Primarily I used Explore the Electric Vehicle Reference Application which is an extensive documentation provided my MATHWORKS on the variety of real-world discrepancies and knowledge in the field on Electric Drive Propulsion.

In their book Austin Hughes and Drury B explain elaborately from the generation of torque to the control and modelling of the drives along with their mathematical explanations, "**Electric motors and drives: fundamentals, types and applications"** which turned out to be the primary source of literature review. [4]

Also, **Modern Power Electronic and AC Drives by** Bimal K Bose was of great impetus for reading the different components involved, their equations and the power electronics foundations. [5]
In the book "**AC Motor Control and Electrical Vehicle Applications** by Kwang Hee Nam.[6] there were some specific approaches on IM to EVs.

The Paper entitled "**Modelling, simulation and analysis of induction motor for electric vehicle application"** by Yusof Y, Mat K [1] explained the basic equations, working and modelling aspects of an IM using the various transformations

I also used several notes and documentations from the Josef Bozef Centre of Competencies namely the test stand description provided by the paper "**HIL System for EV Drives testing**" written by Pavel Mindl, Pavel Mňuk, Zdeněk

Čeřovský,Tomáš Haubert of the Faculty of Electrical Engineering in Czech Technical University in Prague.
Lastly also the lessons from my university course in **Hybrid Powertrains** was beneficial to get the head start.

Through my thesis work I would like to amend the research gaps, alleviate the perplexing control issues, and present a potential to bring further development.

1.3 Problem statement

To determine optimal controlling conditions for drives transient states. To compare achieved data for electric drive efficiency and its dynamic behaviour in all revolutions regimes.

The other part of solved problem is to create simulation model of electric drive which can be calibrated emulating the real electric drive. The model is calibrated for static model situation.

1.4 Methodology

1. In the VTP Roztoky[1] test bed different scenarios have been evaluated for both the static and transient performance of the electric drive.
2. The Tested Induction Motor Power Supply with transformers and output filters.
3. The test bed is run, and the control is done using a dynamometer control system software known as the ASMOT M4 and the Power Analyser Yokogawa.
4. The data is recorded for different operating scenarios using a PC for experiment control.

Once for the static state and later by means of scopes in the oscilloscope for the dynamic states.

5. The Dynamic Behaviour is attained using the manual control knob wherein firstly the supplying voltage is change and simultaneously frequency. The sudden skip using both parameters are avoided to not over peak up the currents.

[1] VTP Roztoky – Jozef Bozek Research Centre Lab situated in Prague; Czech Republic as explained in the abstract.

6. The Datasets are recorded in excel sheets are plotted and discussed and further exported for calibration or testing in the simulation models.
7. For the dynamics skips arranged for examining the operating regimes, the oscilloscope plots are also recorded.
8. Finally, the data from both physical calibration and simulation is recorded in form of graphs and used for discussion.
9. The comparison for dynamic data arrangement in the simulation model was a bit complex so it was delegated as a future scope.

1.5 Electric Motors

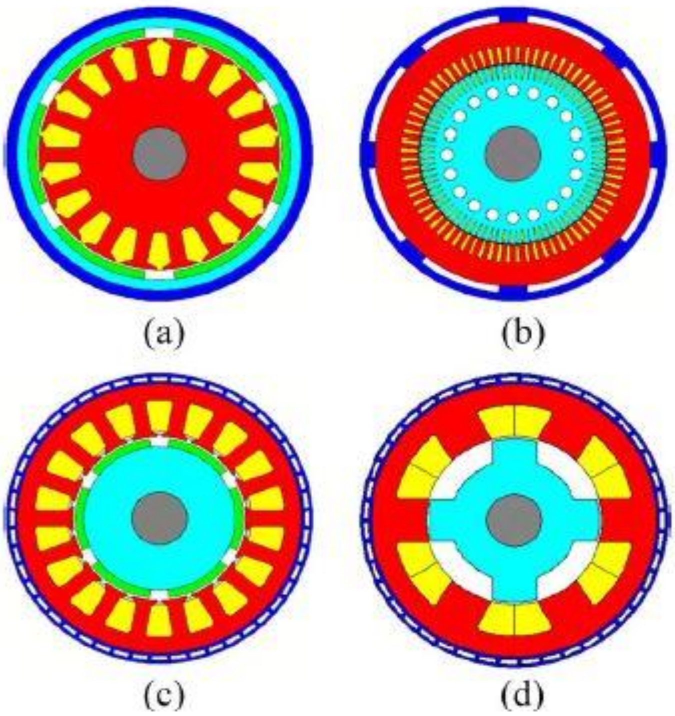

Figure 3 : Industrial and Traction Motors (a) DC Motor. (b) IM. (c) PM Brushless motor. (d)SRM

Electric Motors have a long and meticulous usage history on everyday basis since a long time that we seldom give them a second thought.
Motors basically containing nothing more than arrangements of copper coils and steel laminations are clever energy converters. Exploiting the force which is exerted on a current carrying conductor placed in a magnetic field. The force although is very feeble and keeps the world of motor development wondering on how to make best use of probably an uncompromising effect as

that. Although the magnetic field is essential to the working of the motor, it only acts as a catalyst and all the mechanical output power comes from the electrical supply to the conductors on which the force is developed.[7]
In hindsight through the years it has been discerned that identifying and separating the excitation and energy converting functions is the best way to understand motor types and also to develop it in a drive for enhanced performance and minimal electrical supply.
The choice for electric propulsion systems are further driven by: driver expectations, vehicle constraints and energy sources. With these meticulous objectives to be taken care of the overall operating points are not tightly defined. Therefore, it is a daunting task to select the appropriate motor and drive to cater the EV demands. In the current industrial and automotive point of views include DC motors, Induction Motors (IM), the permanent magnet synchronous motor and the switched reluctance motor. Cross sections are depicted in Figure 3. By altering the magnetic field arrangements and also harnessing material properties there have been more trending type of motors which but have foundations to these four main ones. To sight as an example the Tesla Model 3 vehicle uses the IPM (Interior Permanent Magnet) synchronous reluctance motor making use of both the magnetic and reluctance effects of motors where interaction between induced currents and rotor magnetic fields imposes force on rotor bars and initiates spinning.
Overall as studied in the comparisons made in [8], it is viable to state that IM stands out to be one of the best adapted candidate with its reliability and technological maturity and also caters to crucial factors in energy management of EVs namely extended speed range ability and energy efficiency which are in turn influenced by Vehicle Dynamics and Vehicle System Architecture that are discussed in the next chapter.

Electric vehicles motors have a high torque to volume ratio and a wide speed operation range(O~14000rpm)[9]. The back emf voltage should be low to accommodate a desired torque in a high-speed operation. In relation to the Back EMF Voltage relation, a high-speed motor needs to be designed to have a small inductance, EV motors have a smaller winding number and, being water cooled, have a larger current density than the normal induction motors of the same power rating[10]

Tremendous quicksclae development has been made in inverters and control systems that pair inverters with motors since the 1980s, along with advancements in microelectronics technology and power semiconductor devices. Along with control capabilities that have made it possible to provide motors with operating characteristics customized for certain system applications, it appears likely that the demand for higher energy efficiency has aided in this development. Electric motors are widely utilized as power sources in factories, railways, home appliances, even in cars and data processing equipment. Almost all power generating methods use generators and motors.

History for changes in motor technology skips back to two centuries ago and later being inspired by Faradays electromagnetic induction.[11] While motor topologies have remained relatively unscathed with only the material fields being not typically dormant much over the past century, control techniques have been well harnessed to meet the ever-thriving industrial needs and by comparison have experienced explosive growth. This has been driven in large part by technology advancements in the semiconductor industry. Few primary contributors could be advancements in power electronics, reductions in form factor and more sophisticated control algorithms with future driven targets. The enhancement of materials and design for curbing the motor losses have also made big scale contributions to the motor technology. The ability to study motor noise using coupled electromagnetic force, structure, and fluid analysis has recently been possible because to advancements in coupled analysis techniques including electromagnetic field analysis, structural analysis, and vibration and noise analysis.[11]

1.5.1 Motors and Development

Experimentation through the years has shown that the magnitude of force depends proportionally on the current in the wire and strength of magnetic field with the force being greatest when the magnetic field is perpendicular to the conductor carrying current.

The development, testing and analysis of motors could be carried out for a variety of objectives. The major concerns would be efficiency enhancement, fault detection and continuous torque generation.

The EV motors need to have some specific advances like high efficiency, high power density, volume downsized and less cost of manufacturing. The surge for downsized motor has been experienced recently to have better packaging prowess and improve energy management and power consumption. The viable method to downsize is to enhance the motor speed. The output power is defined by product of torque and rotational speed. The motor needs to have attained significant mechanical and electrical performances, i.e high mechanical strength in the rotor and a reduction is motor losses such as copper loss. The EV development timeline can be seen in Figure 5.

Few of possible trending developments and areas of concern are:

- The modelling of various motor types including synchronous and asynchronous and creation of various levels of fidelity and also provide finite element analysis, thermal loading etc using FEA tools such as Ansys, Maxwell, JMAG and Femtet.
- Model controllers, cascaded loops of control and modulators
- Modelling of power electronics

- Control System Tuning using linear control and also automated default tuning settings.
- Model startup, shutdown, and error modes and design derating and protection logic to ensure safe operation.
- Estimators for rotor position and velocity
- Optimize reference currents to ensure minimal loss in power, operation above the nominal levels and cater to parametric uncertainties.
- Design Digital signal processing.
- Empirical analysis of closed loop simulations for motor and controller
- Generation of C code and other aspects for rapid prototyping and other testing standards.

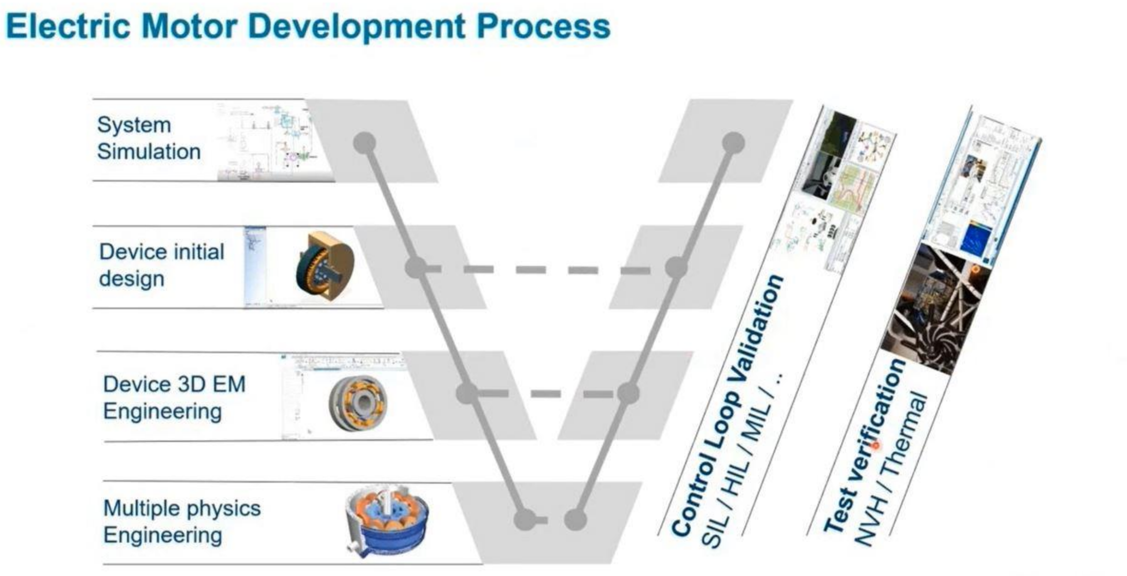

Figure 4 EV Motor Development

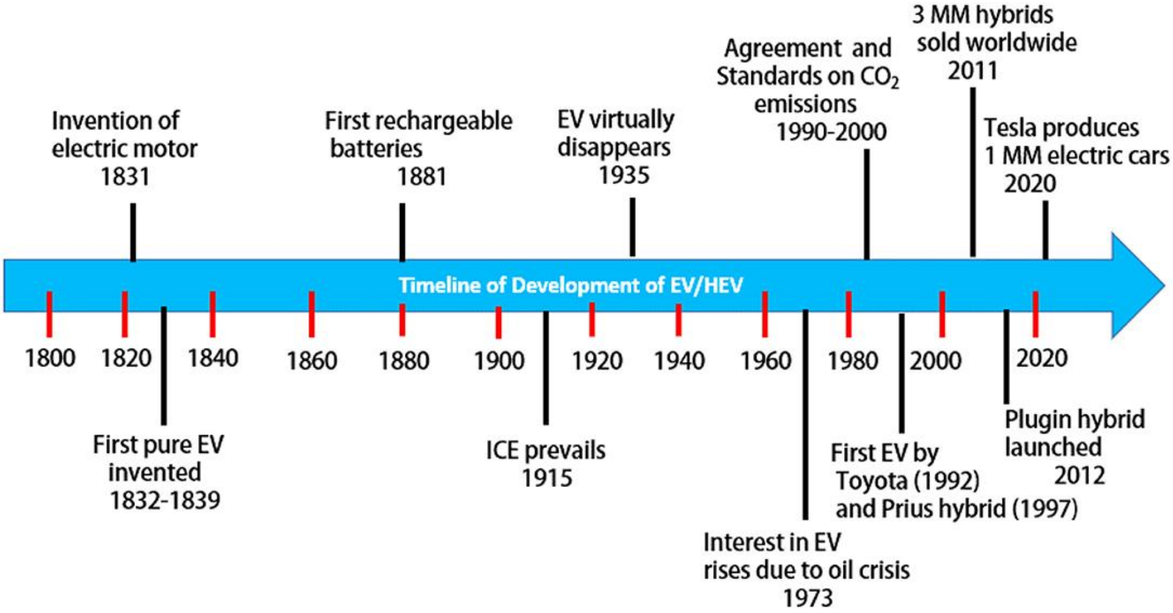

Figure 5 : The EV development timeline

1.6 Electric Drives

Electric Drives are industrial systems that converts electrical energy to motoring energy or vice versa in terms of generator braking. Approximately 50% of electrical energy produced is used in electric drives. Electric Drives run either at constant speed or at variable speed depending on the application and the deliverables it can conjure up. The components include the motor, mechanical coupling, load and a start/stop and protection system.
In variable speed drives everything like this along with a power electronic converter to have certain defined and fast control response. The common ones for power conversion are rectifiers, choppers, inverters and cycloconverters.[12]

A basic architecture for an electric drive is depicted in Figure 6.

While DC brush motors just require changing DC voltage, AC motors also require variable voltage amplitude and frequency for variable speed. In comparison to DC brush motors, AC motors are frequently brushless, have higher torque (power) densities (Nm/kg or kW/kg), and are less expensive to install and maintain. Power Energy Converters (PEC) for reversible speed applications are now priced the same for brushless and DC motors. Even though PEC costs are higher than motor costs, this ratio decreases when power and speed levels increase. Electric Drives are consisting mainly of motor, static power converter, feedback sensors and observers, a motion controller which could be digital or analog. The majority of electric drives still run at a constant speed today 60%–65% of them because speed control is mostly used for starting, stopping, and safety. A 35%-40% subset of applications, though, need varying the torque and speed to account for the mechanical load due to their high annual growth rate.[12] Their basic diagrams have been presented in Figure 7, Figure 8.

The Electric Drives used in EVs are somewhat contrasting to the ones used for industrial purposes which are mostly running on constant speed and have large power capacities. A brief comparison is being shown in

	Motor Drives in Industry	Motor Drives in Electric Vehicles
	Inverter	
Power Supply	Three phase supply is rectified	Battery voltage
Voltage range	380 V, 400 V, 690 V AC input for rectifier For 380-400 V AC supply; typically 513-540 V DC input for inverter	In passenger cars and light commercial vehicles; considering rated DC design voltage of EM, typically 250-400 V DC input for inverter
Switching frequency	1.5-16 kHz adjustable setting. Dependent on power range 2- 8 kHz typically used as factory setting	fsw>=10 kHz ▪ reduces acoustic noise ▪ reduces current ripple for low inductance motors ▪ enables use of smaller DC bus capacitor
DC-Link capacitors	Electrolytic or film capacitors are used	Film capacitors are commonly used. They provide: ▪ smaller size ▪ less capacitance loss at negative temperatures ▪ longer life and reliable
	Functionalities in Control System	
Control method	Scalar, FOC or DTC with or without speed/position sensor	FOC or DTC with speed/position sensor
Control mode	Speed control mode is used commonly. Motor drive receives the speed reference. Torque control mode is used in special applications. For example, mechanically coupled two motors run as master-slave control, master drive runs in speed and slave drive runs in torque control mode	Torque control mode is used as in combustion engine control. Torque reference is received via Electric Vehicle Control Unit.
Self commissioning	Supplier of motor and drive unit can be different. Self-commissioning is needed in order to estimate the electrical parameters of electrical machine and tuning of speed controller.	Supplier of motor and drive unit is typically the same. Therefore, electrical parameters of electrical machine and rotor inertia are known.
Regenerative braking	Regenerative energy can be controlled in several ways: - DC bus over voltage controller extends the ramp down time - DC bus resistor - Active front end rectifiers return the regenerative energy to the supply - Increasing the losses of the motor	Regenerative energy is used to charge the battery. It can be controlled as follows: - Electric vehicle control unit should coordinate the regenerative energy between the mechanical brakes and battery. - Efficiency of EM can be controlled in limit conditions.
DC Bus discharging at power shutdown	- DC bus discharging at power shutdown is performed typically for service/maintenance.	- DC bus discharging at power shutdown is an obligatory homologation requirement.
Communication protocol	Profibus or CAN bus	CAN bus

Figure 9.

The Primary aspects to be significant when considering choosing electric drives are:

1. High Power density which could cater to the variable load demands in the ever-challenging control methods. Instant Power Generation with less transient time is also highly upheld.
2. At starting the EV, there must be high torque and also for incline runs and at higher speeds, higher power for cruising.
3. Very widely spread range of performance including constant torque areas and also constant power regions.
4. Blink of an eye torque response. Even in HEVs it is beneficial for obtaining a highly efficient driving cycle.
5. The Driving Efficiency should be high over wide speed and torque ranges.
6. During Recuperation of energy there should be minimal loss and maintain linearity.
7. Highly Sturdy, Reliable and Robust system especially for terrains and temperatures variance.
8. The cost of manufacturing and flexibility with the altering demands is also crucial. [13]

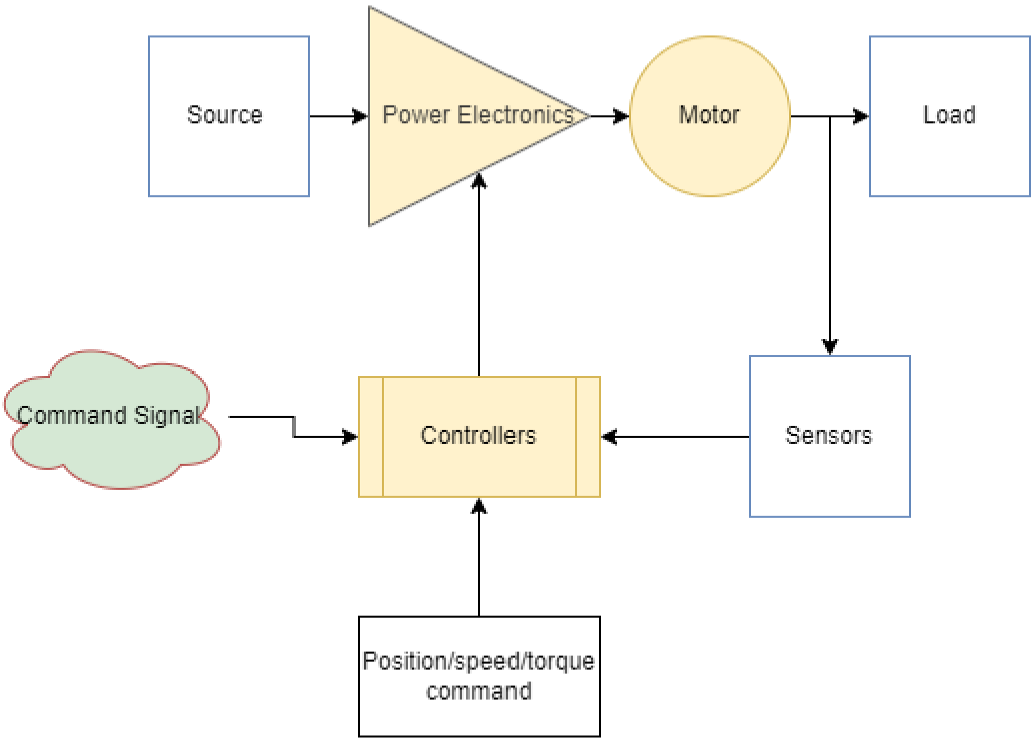

Figure 6 : Electric Drive Architecture

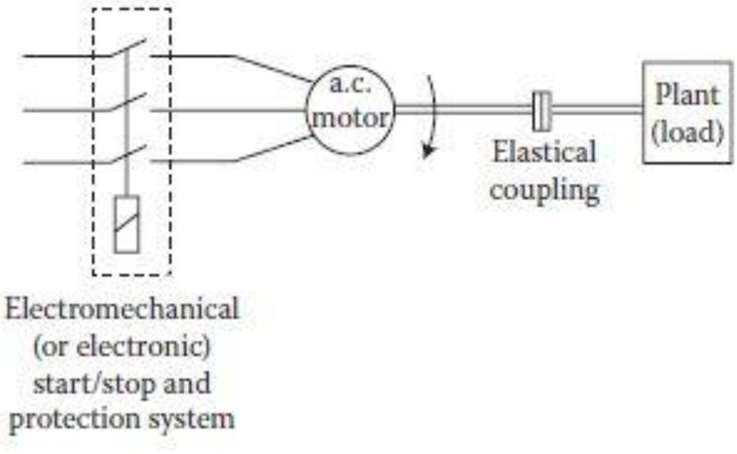

Figure 7 : Constant Speed Drive[12]

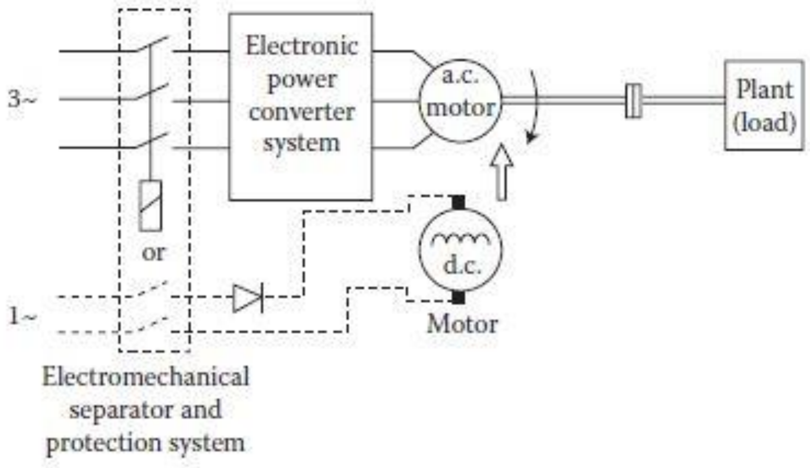

Figure 8 : Variable Speed Drive.[12]

	Motor Drives in Industry	Motor Drives in Electric Vehicles
	Inverter	
Power Supply	Three phase supply is rectified	Battery voltage
Voltage range	380 V, 400 V, 690 V AC input for rectifier For 380-400 V AC supply; typically 513-540 V DC input for inverter	In passenger cars and light commercial vehicles; considering rated DC design voltage of EM, typically 250-400 V DC input for inverter
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DC Bus discharging at power shutdown	- DC bus discharging at power shutdown is performed typically for service/maintenance.	- DC bus discharging at power shutdown is an obligatory homologation requirement.
Communication protocol	Profibus or CAN bus	CAN bus

Figure 9 : Comparative study for EV Drives [14]
[2]

[2] Few of the terms used are defined and explained in the later part of the thesis.[2]

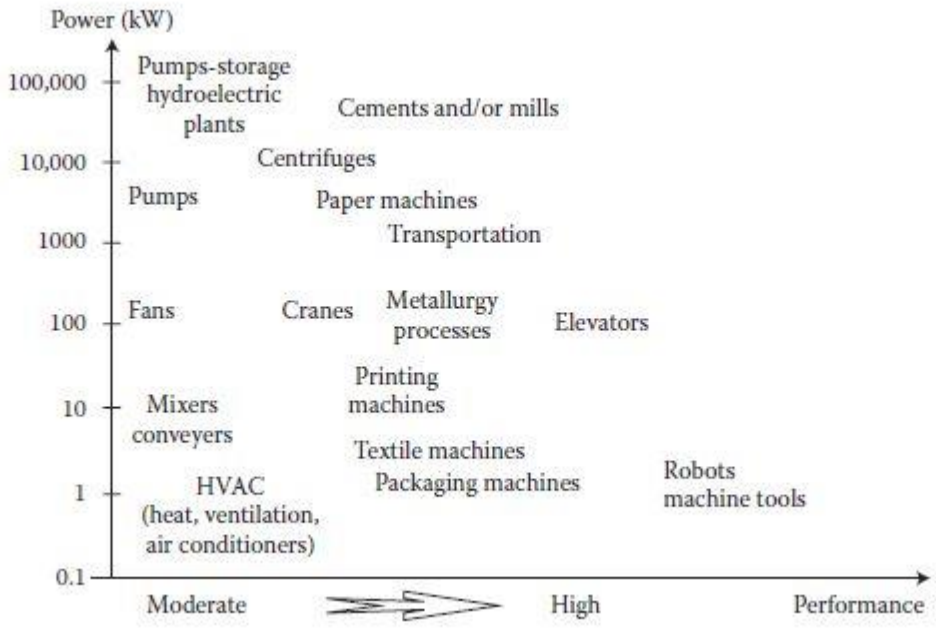

Figure 10: Applications of Electric Drive[12]

Chapter 2 EV HEV Powertrain Architecture

This chapter deals with the primary definition of the thesis i.e., powertrain simulation for which we need to know the architecture, the components and the power flow which is taking place among the various configurations of powertrains, and which is the primary sources of energy production and propulsion.

Powertrain architecture is a basic framework used to evince the several components in a vehicle powertrain and to analyse the power flow from the energy source through the conversion elements and determine if there is any recuperation in the system which leads to reverting the energy back for positive usage.

The source of propulsion of the vehicle defines its powertrain architecture and alignment. Electrification of conventional vehicles is the most hyperactive trend in the automotive industry pertaining to the strict emissions standards and uncanny issues. Adding supplemental energy storage and energy converters allow the OEMs to harness the peak of energy and have a judicious energy management strategy. Different degrees of electrification and the topologies compete in a highly engaging market.

Comparing to conventional ICE vehicles having optimum fuel efficiency in the middle speed or high torque region but the efficiency is low in the low speed/low torque.

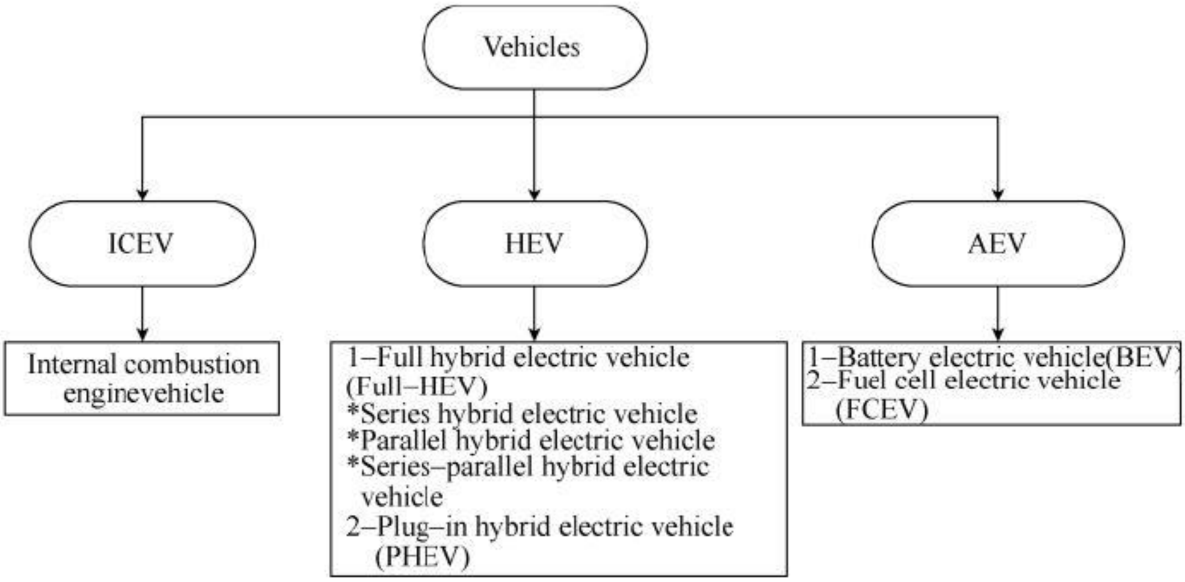

Figure 11: Classification of vehicle powertrains[15]

Characteristics	ICEVs	BEVs	HEVs	PHEVs	FCEVs
Propulsion System	ICE based	Electric motor based	Electric motor & ICE	Electric motor & ICE	Electric motor based
Energy storage	Fuel tank	Battery Ultra capacitor Flywheel	Fuel tank Battery Ultra capacitor Flywheel	Fuel tank Battery Ultra capacitor Flywheel	Fuel cell Battery Ultra capacitor
Energy source infrastructure	Refueling station	Electric charging facility	Electric power Refueling station	Electric charging station Refueling station	Hydrogen cylinder Hydrogen refiner & refueling station
Advantages	Fully commercialized Matured technology Better performance Simple operation Reliable	Zero emission Quite Smooth operation Energy efficient Independency from petroleum product Commercialized	Low emission Higher fuel economy Long driving range Reliable Commercialized Durability	High fuel efficient Lower emission Extended electric driving range V2G or G2V capability Quite and smooth operation	Ultra low emission Competent driving range Highly efficient Independency from petroleum products Reliable Durable High cost
Drawbacks	Less efficient Harmful emission Poor fuel economy Comparatively bulky	Limited driving range Poor dynamic response High recharging time	Complex system Costly Bulky Increased component	High complexity Higher initial cost Battery technology Impact on grid	Slow dynamic response Not commercialized Sophisticated electronic controller
Major issues	Harmful emissions Fuel economy Dependency on petroleum products	Size & weight of battery pack Infrastructure for charging station	Size & weight of battery pack & ICE Integration of components	Charging station infrastructure Size & weight of battery pack & ICE Impact on grid	Cost of fuel cell Infrastructure for hydrogen conditioning, storage and refilling system

Table 1: Different characteristics of vehicle configurations

2.1 Electric Vehicles (EV) –

The first EV was proposed in 1834. During the 19th century the harness of even more sophisticated technology to propel the power of electric vehicle was being researched especially in America, Britain, and France. 1930s saw the plummeting of the EVs due to battery development limitations and further enhancement of the ICE. By the beginning of the 21st century, intense interest in zero-emission vehicles (ZEVs) resulted in renewed interest in EVs. Several EV research projects; products and awareness has been generated since then.[16]

In the near future it is out of question to abide by the ZEVs to satisfy the ACEA 2020 commission target level of 95gCO2/km. Hydrogen powered vehicles and Battery Driven Vehicles are regarded as viable options, but Hydrogen ones have some flaws in their infrastructure for creating, distributing, and storage of hydrogen. The Hydrogen seems to yet be a far-sighted option and would need more sturdy development and assured infrastructure.

The Key concerns for BEV on the other hand are harnessing battery, its production, life span and the recycling prowess it needs to have to cater to the sustainable goals both economically and environmentally.

Range anxiety and the battery energy density are also inevitable factors which need to be taken notice of and the charging infrastructure availability as well which in turn again reinstates the fact of having commendable range in the single charge.

The EV Powertrain architecture primarily consists of the workhorse, which is the electric traction motor, the power electronics comprising of also the converters, the energy storage systems (ESS) and the powertrain controller [17]. The energy storage system is the heart of the EV architecture which can be combination of electrochemical battery, fuel cell or less prominently used nowadays being flywheel. The control systems are also an important link in the architecture and is a monitor to the functioning and maintenance of the EV. The ESS is defined by the amount of energy and the amount of power it can store defined in units of MWh and MW.

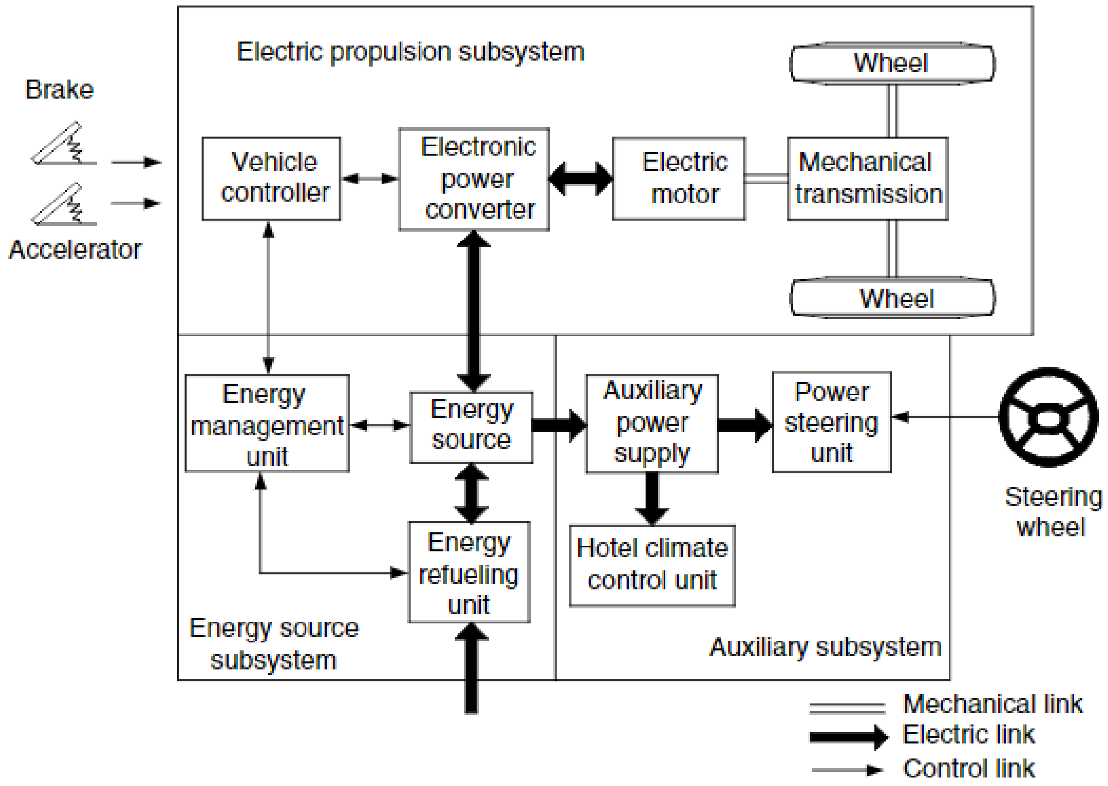

Figure 12 : Conceptual EV configuration[17]

The primary power electronics would be defined by DC-DC converters and dc-ac converters. The converters are used to interface and control the power forms inside the voltage bus of the EV system. The functions of these converters in dc-dc mode are similar to that of transformers in AC systems but in contrast to transformers the ratio of the input to the output can be varied continuously and ratios can be manipulated around unity value. The dc-dc converters are merely electronic switches combines and also include inductive/capacitive components inorder to smoother the peaks or ripples and finally also followed by low pass filters.

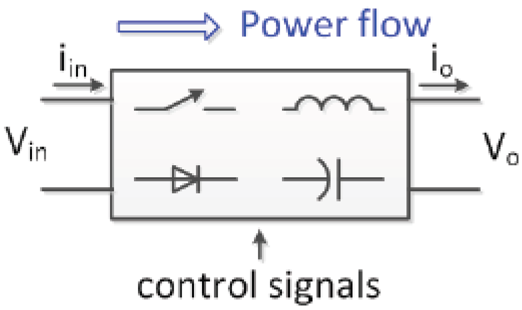

Figure 13 : Basic DC-DC Converter

In EVs there is a crucial phenomenon which allows EVs to be energy efficient and it is known as regenerative braking. It is basically conversion of vehicles kinetic energy stored into the chemical energy which is stored in the ESS and can later be used to propel the vehicle. It is braking as it serves to slow down the vehicle in turn gathering up recuperative energy.
The most significant power processing converter used for the battery converters of an EV is a boost and buck converter, shown in

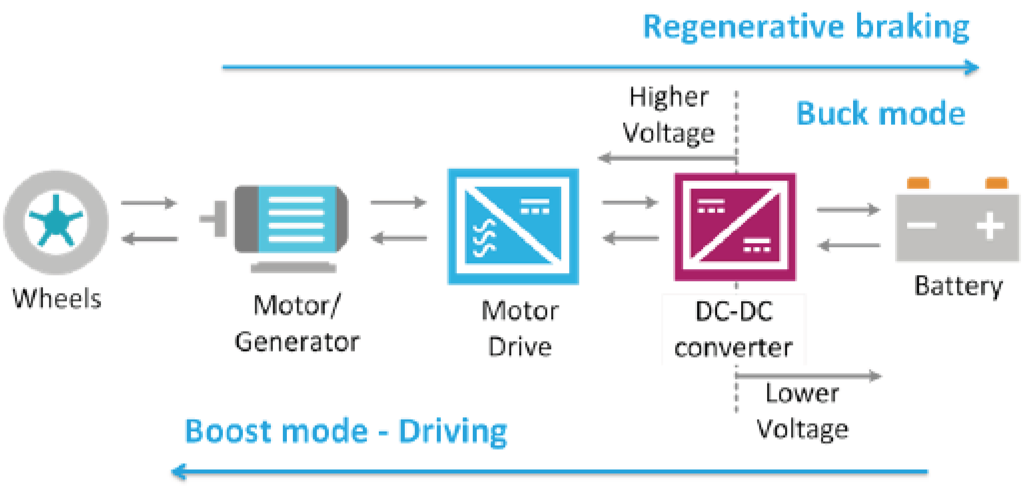

Figure 14. When recovering the kinetic energy from the vehicle, the device operates in buck mode, where the voltage level is decreased to a level that is within the safe voltage range of the battery. When propelling the vehicle, the device operates in boost mode and the DC voltage is regulated to output a higher voltage level for the electric motor drive and motor. Bidirectional

power flow is required in automotive energy management due to charging and discharging during the drive whilst the voltages do not change polarity.

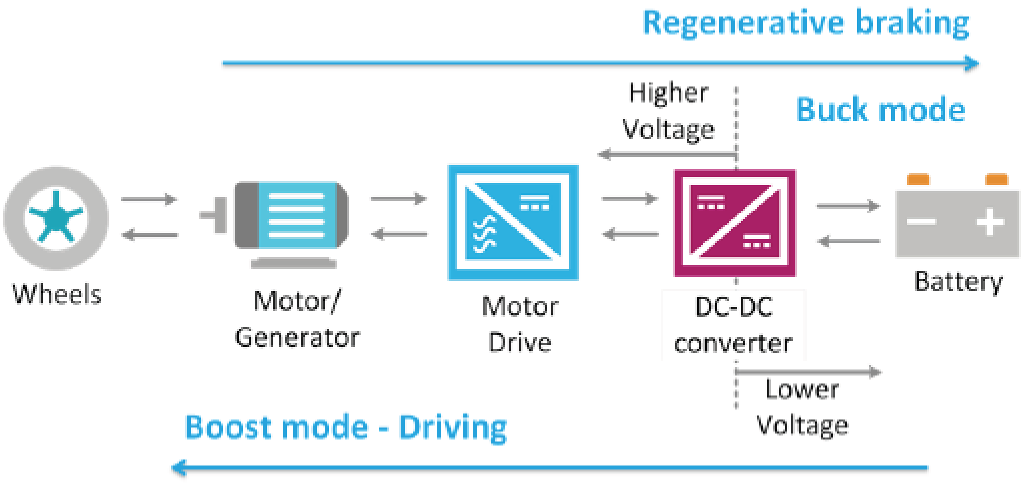

Figure 14 : Buck Boost Converter

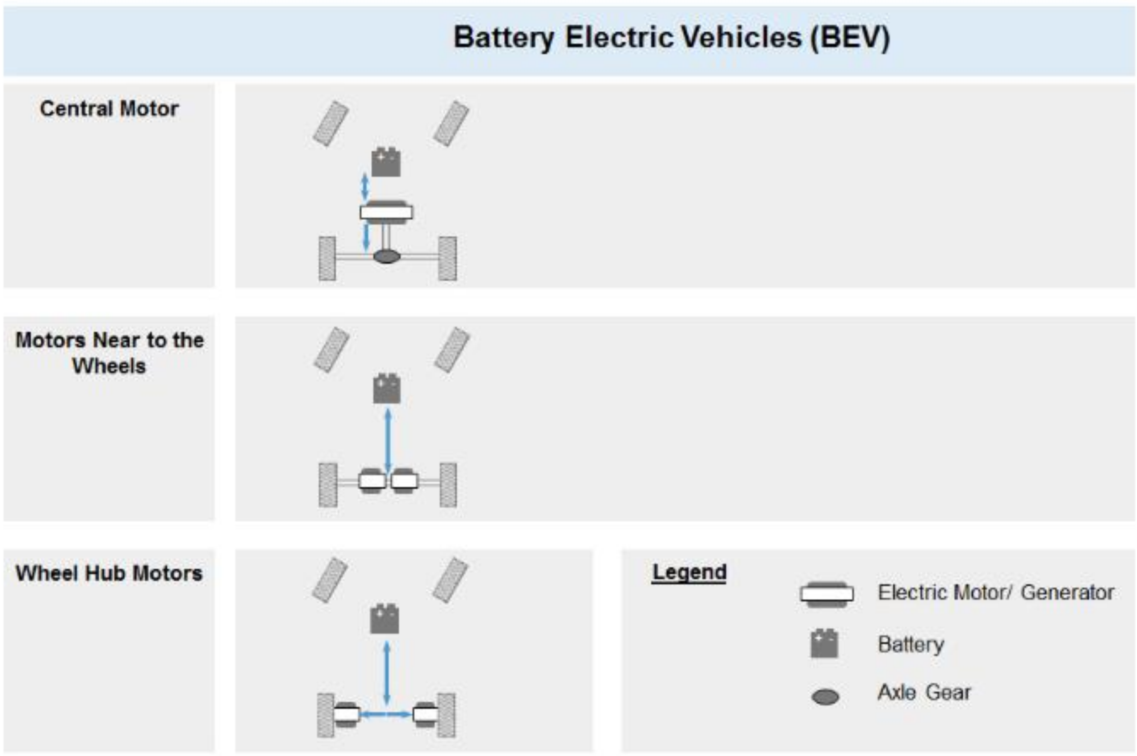

Figure 15 : EV Architecture [18]

For Electric Vehicles, the architecture depends majorly on the power to weight aspects of the vehicle and in turn enhancing the efficiency of the vehicle. The different options including the layout of the relevant systems and components can be realized. The placement of the motor and the power

circulation among the wheels are a point of discussion and could henceforth generate several architectures for the EVs. Electrical Machines could be placed in the propeller axle adjacent to the wheels and when using this majorly two motors are used, one for the front and other for the rear axles. Another more recent and thought of way in the EV Architecture is by placing the motors in the wheel hub of the more sides of the wheel. This can further lead to some complex control systems known as torque vectoring, which is analysing instantaneously on how much power to be sent to each wheel at a moment of time. However, compared to central motor architectures, this way of placing the motor leads to increased unsprung mass and eventually lead to reducing driving dynamics and at times passenger comfort.
Like the electric machines placement shown in (Figure 17), the battery or the ESS of the EV placement could also alter the configuration of the EV by a certain extent. The Battery Packaging is defined by certain factors like thermal heat release, ease of replacement and charging ease. Below in the (Figure 18) it has been enumerated on how the placement of batteries vary.[18]

In a broader aspect the EV configurations can be further classified in terms of their electric propulsion characteristics and energy sources.
In the Figure 16 (a) there is replacement of ICE by Motor and the gearbox is separated from the motor using a clutch which can be utilised to disconnect the power. The gearbox helps to modify the speed-power scenarios and could also be replaced by automatic transmissions. Next to simplify the drivetrain in Figure 16 (b) a fixed gearing could replace multispeed, and it is useful for constant power motors. For Figure 16 (c) the assembly could be unified and used on a single axle as well making it compact.
Further in Figure 16 (d) the differential is eliminated, and two motors are utilised in the wheels. Above that in Figure 16 (e) the EM can also be placed

inside the wheel, and it is manipulated by planetary gear sets to reduce speed and enhance torque. Finally, in Figure 16 (f) a high starting torque based motor could be placed in the wheels eliminating any kind of driveline issues

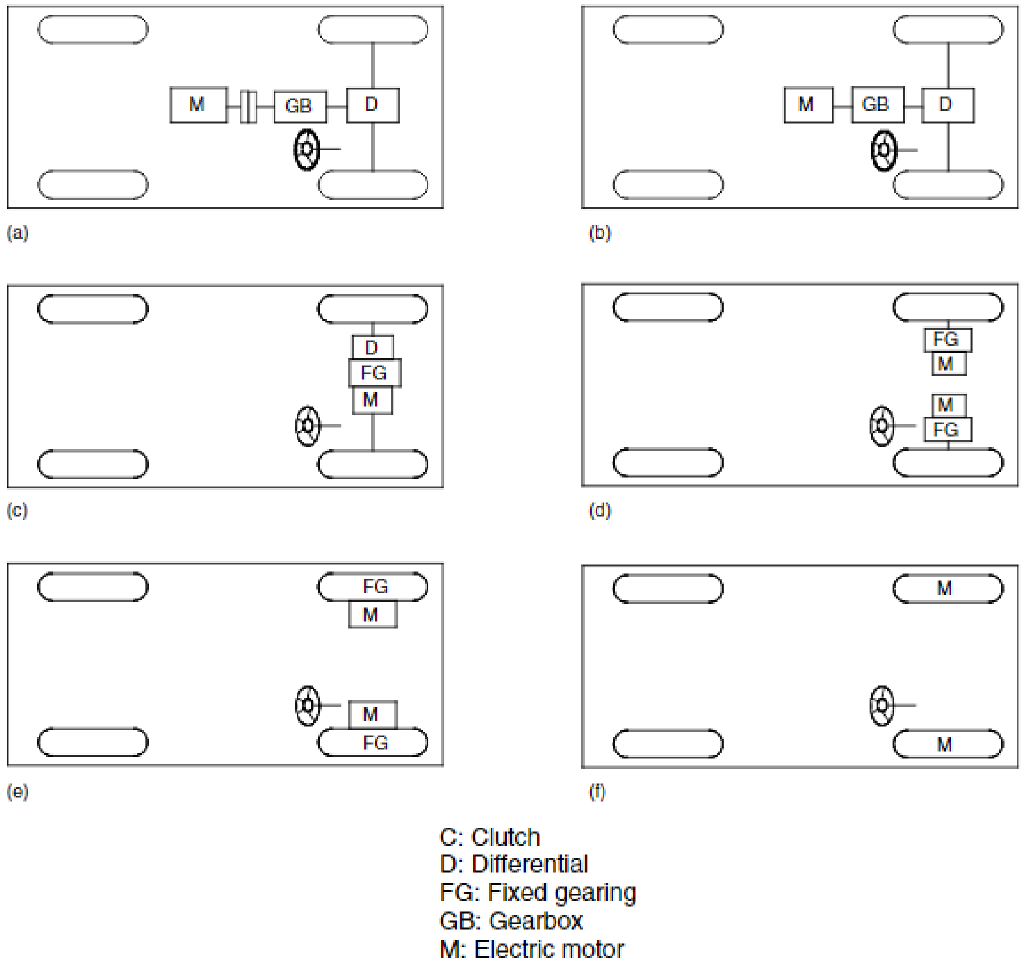

Figure 16 : Broader EV Classification in terms of gearing as well [17]

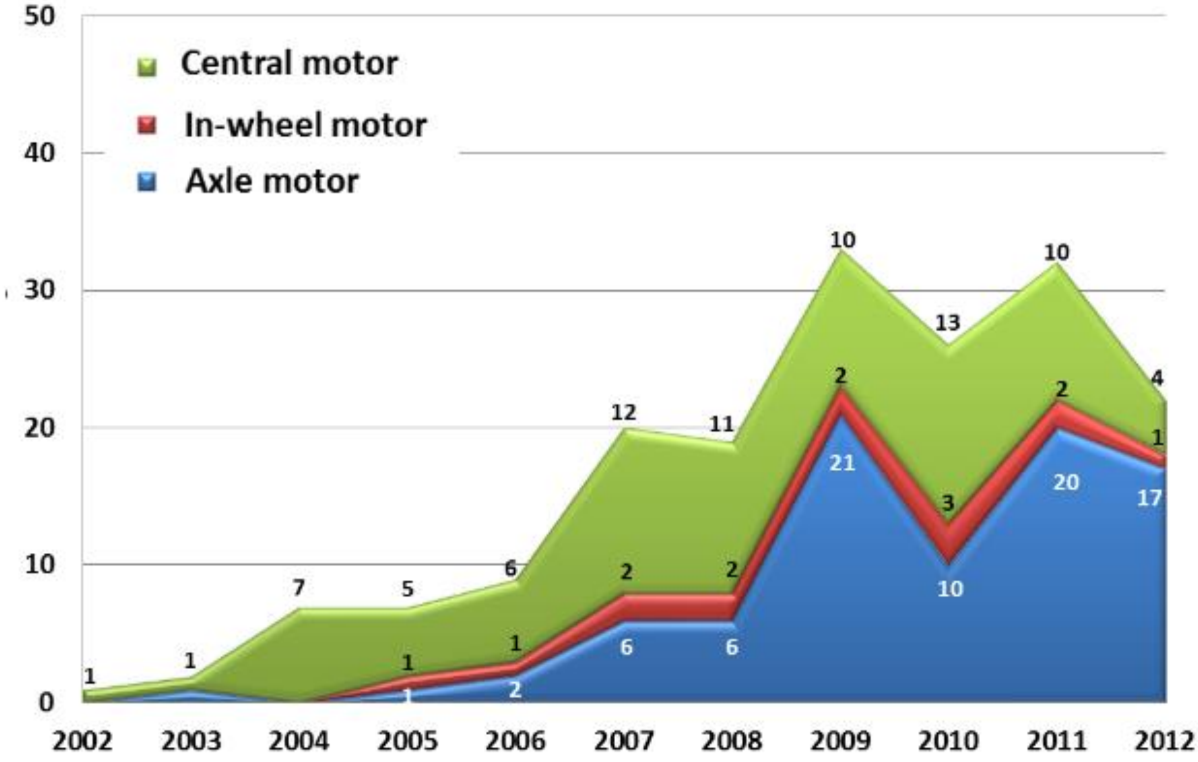

Figure 17: Electrical Machines Placement

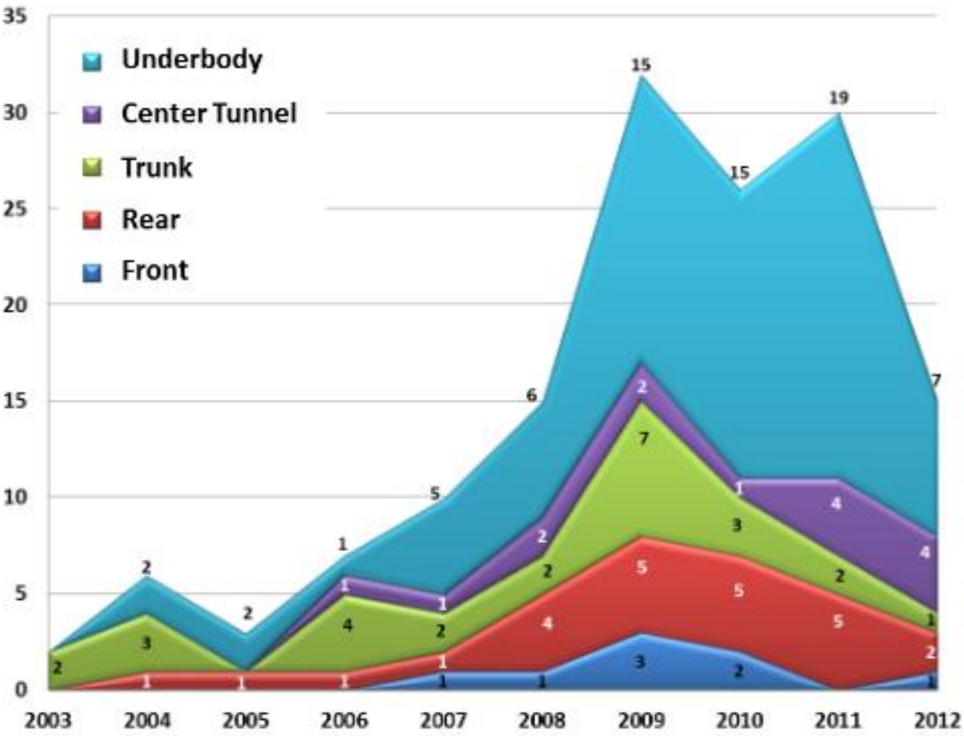

Figure 18 : Use of Battery Installation Places in EVs

There are two steps towards to EVs: hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs). There are many different potential HEV and PHEV configurations, but in general, an (P)HEV has an electric drivetrain that can recharge batteries with the card, or the charging infrastructures placed in vicinity which even includes the home ac supply.
HEVs and PHEVs are quite popular because:

1. Their range is not limited by the battery
2. They save a lot of fuel compared to ICE vehicles
3. They require less maintenance on the powertrain and brakes. This is since the fuel engine is supported by the electric motor.

The European Union Reports tend to present the transport sector is responsible for around 28% of the total hydrocarbon emissions.
The authorities from the developed countries correctly to avoid the concentrations of air pollutants and eventual choking. [19]
The points which propel EV to some extra points over traditional systems.

2.2 Hybrid Electric Vehicles (HEV)

Hybrid vehicles as the name suggest has multiple ways to source power from. An electric power source is additionally added to the ICE values of the power. A hybrid drivetrain can supply its power to the load by a selective power train. Going back to 1898, German Dr. Ferdinand Porsche fabricated the Lohner Electric Chaise. He used the ICE to drive the generator that gave the traction power and could even record distances as far as 40 mi.[16]

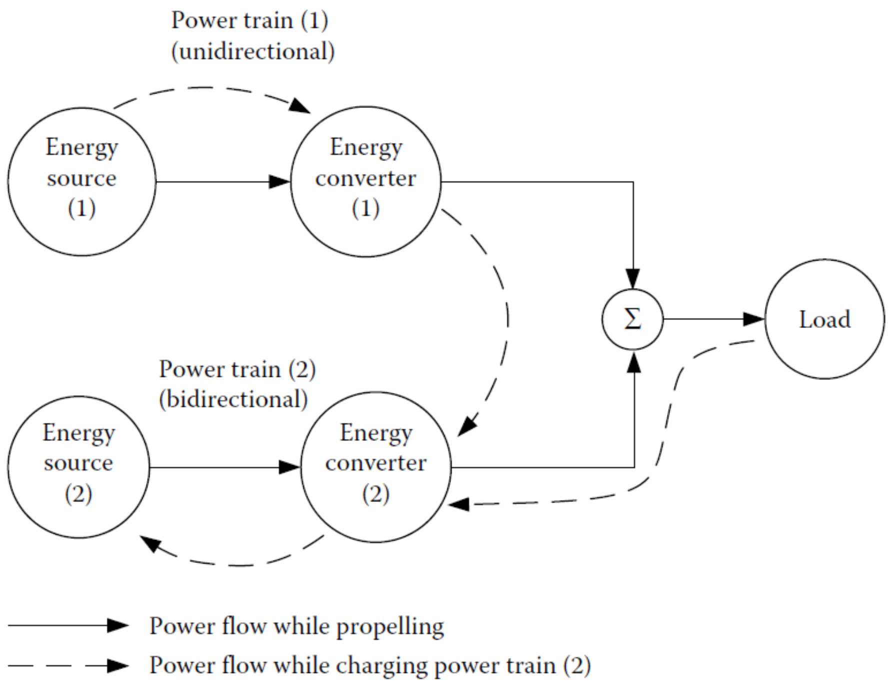

Figure 19:Schematic for Hybrid electric Drivetrain

The advantage of an HEV is that the fuel-burning engine, in general, is most efficient in only a small range of operating conditions (speed and load). Also, at this most efficient operating point, the fuel-burning engine usually produces its lowest levels of emissions. Unfortunately, while driving, the engine in the car must run under a wide range of speeds and loads, and thus it is far less efficient and produces much greater emissions than it would if it could run at its most efficient point all the time. Electric drivetrains are also most efficient at only one point, but the reduction in efficiency for other speeds and loads is far less. Therefore, an HEV can run the fuel-burning engine at its most efficient point for battery charging and can use the electric drivetrain to take up all the slack under other conditions.
This way, emissions are much less than for the fuel-burning engine driving the car by itself, and fuel economy can be significantly improved. Hybrid technologies extend the usable range of EVs beyond what an all-electric vehicle can achieve with batteries only. Being a hybrid or plug-in hybrid would allow the vehicle to operate on only batteries within an urban/polluted area, and then switch to its engine outside the urban area.

The HEV powertrain architecture consists of two or more power plants. Comprising of both the ICE and EM, the Primary driving source is the ICE for long range driving and producing bulk of the energy while the EM being the auxiliary source is required for short bursts, high power demand and the efficiency of the ICE. The EM is crucial to charge the batteries from the excess power from ICE when not needed by the vehicle and from the Kinetic Energy Recuperation.

The different configurations of hybrid powertrains are possible, depending on the layout of the hybrid system and the layout of the several components which make up the HEV. Broadly it is classified into Series, Parallel and Combined. Typical driving patterns for HEVs include:

1. Start (EM + Engine)
2. Acceleration/incline (EM + Engine)
3. Cruise (Engine)
4. Decline (Motor (Regen))
5. Deceleration/Stop (Motor)

The HEVs are classified also according to the degree of electrification wherein the ICE comes as zero % and the BEV becomes 100% and the remaining types like PHEV/HEV occupy the central position. The Major Design objectives of the HEV are

1. Optimal Fuel Usage
2. Minimal Emissions
3. Minimum system costs
4. Better Driving Performance[6]

Description of the different architectures.

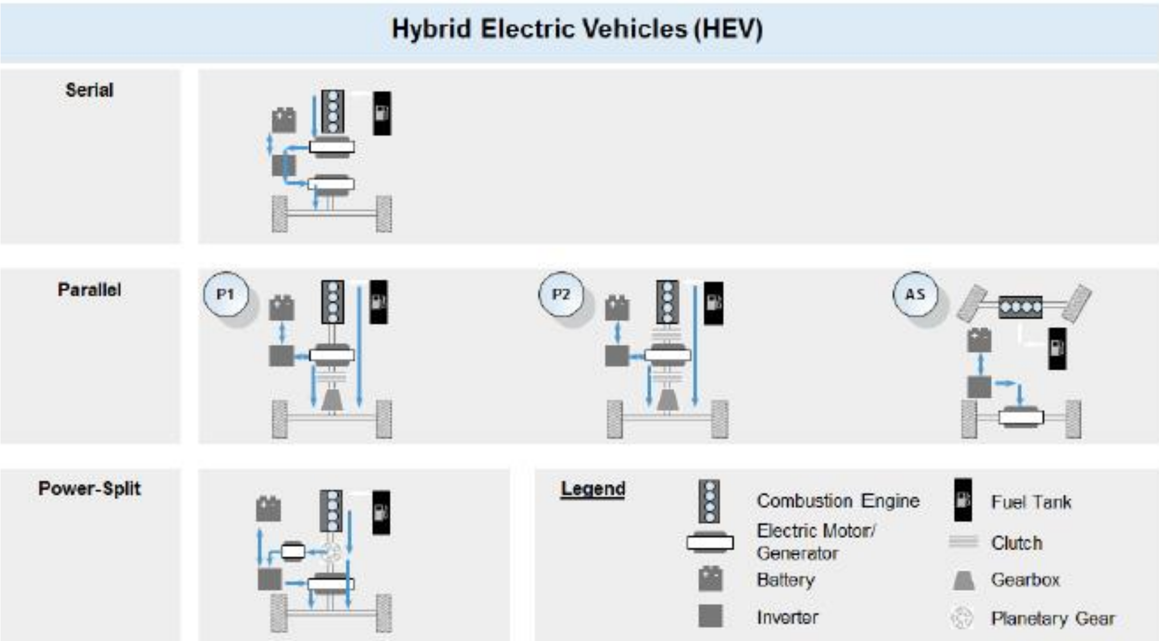

Figure 20 : HEV Architecture[18]

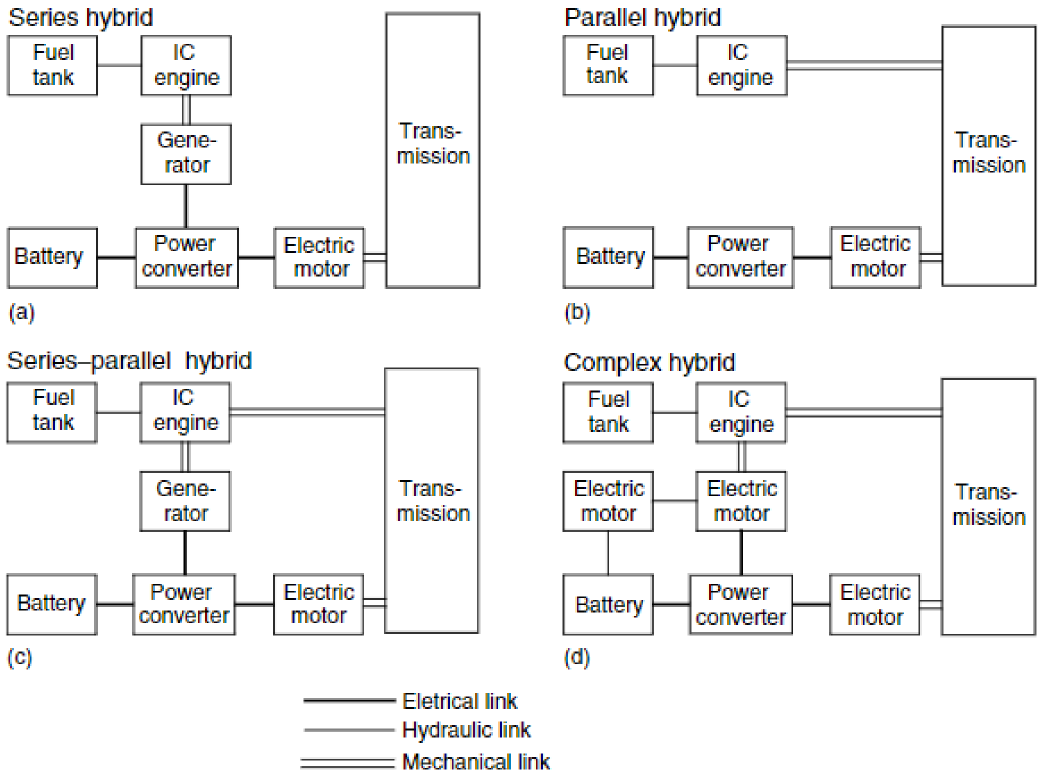

Figure 21 : Hybrid Classification[17]

2.2.2 Series Hybrid:

The series hybrid consists of the motor/generator unit directly coupled to the conventional ICE. The ICE does not play major role in the propulsion and instead the generator on board is used to convert energy to either maintain power flow to the electrical machine or is used to redirect power flow back to the ESS where it is stored for future usage. The advantage of this system is that the ICE can be downsized to a greater extent and operated only in charging the battery.[18]

This in turn also helps in reduction of the emissions and there can be optimal driving points and high efficiency. Due to no mechanical connection between engine and the driven wheels the engine can be operated at any point of speed-torque map and higher efficiency strategies. Due to presence of ideal torque-speed profile the drivetrain is very simplified. But a drawback is that due to multiple power conversion steps, the drivetrain efficiency is very low. Operation modes of the series power train are branched as engine on-off mode and blended mode. In the engine on-off or the EV mode until the SOC (State of charge) in battery depletes highly there is no engine intervention. For the latter one the engine covers up peak load situations and assists the motor.

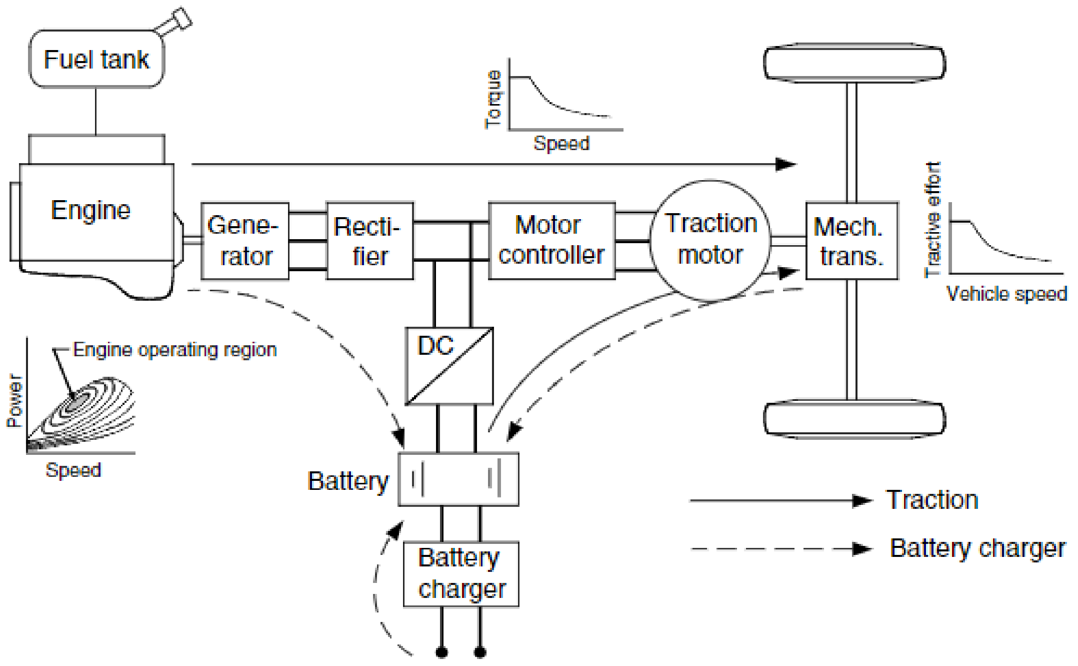

Figure 22: Series Hybrid configuration[17]

Some Operating modes include

1. Pure Electric Mode: Powered by only the battery
2. Pure Engine Mode: Powered only by the Engine-Generator
3. Hybrid Mode: Powered by both ICE and EM
4. Engine Traction and Battery Charging Mode: Powered by Engine Generator which in turn charges the battery to propel
5. Regenerative Mode: Powered by the EM and the generator is used to replenish the batteries
6. Battery Charging Mode: No Power to EM but generator charges batteries

7. Hybrid Battery Charging Mode: Both the ICE-generator and EM charge batteries due to lowering of the SOC.

2.2.3 Parallel Hybrid:

It is a configuration which can use both the conventional ICE and the EM. The EM works as a single Motor Generator Unit and can be used depending on the need of power. Parallel Hybrid allow the utilisation of torque from both the sources, but the ICE cannot be operated in the most effective operating point for long time. The placement of components along the parallel driveline also further divides these kinds of hybrids into P0, P1, P2 and axle split.

A hybrid vehicle drive train usually consists of only upto 2 power sources More than two power train configurations will complicate the system. For the purpose of replenishing part of the braking energy that is distributed in the form of thermal energy in the conventional ICE vehicles. The sources of energy are bidirectional and similar for the converters. Propulsion power to wheels may be supplied from engine, motor, or both. Speed ratio of motor and engine are fixed hence the roles of motor are limited. The parallel assist strategy can be summarized as:[6]

Furthermore, the Parallel hybrid are also redefined using the type of coupling they have with the

1. Motor Propulsion with engine off in low speed
2. Motor assistance when large torque requirement
3. Motor charging batteries
4. Low SOC leading to engine charging on the battery

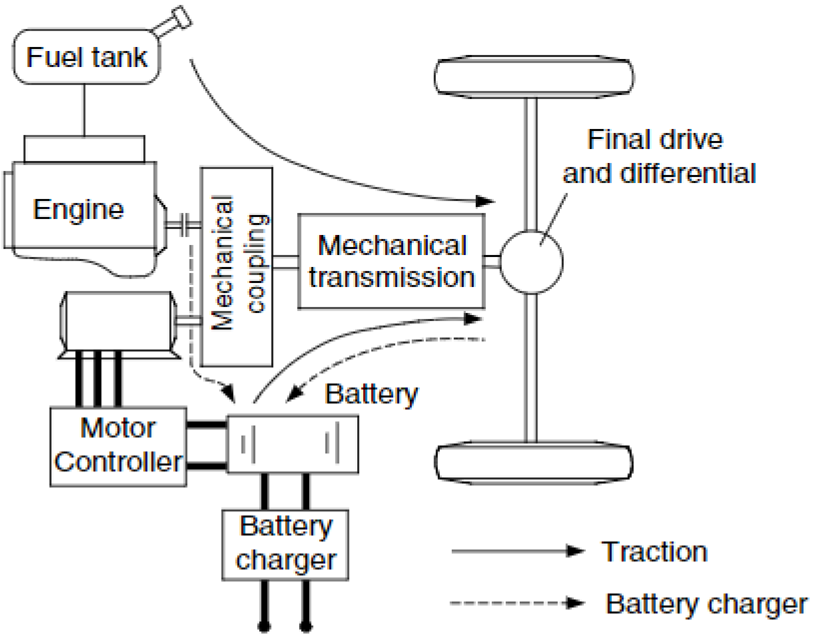

Figure 23 : Parallel Hybrid configuration[17]

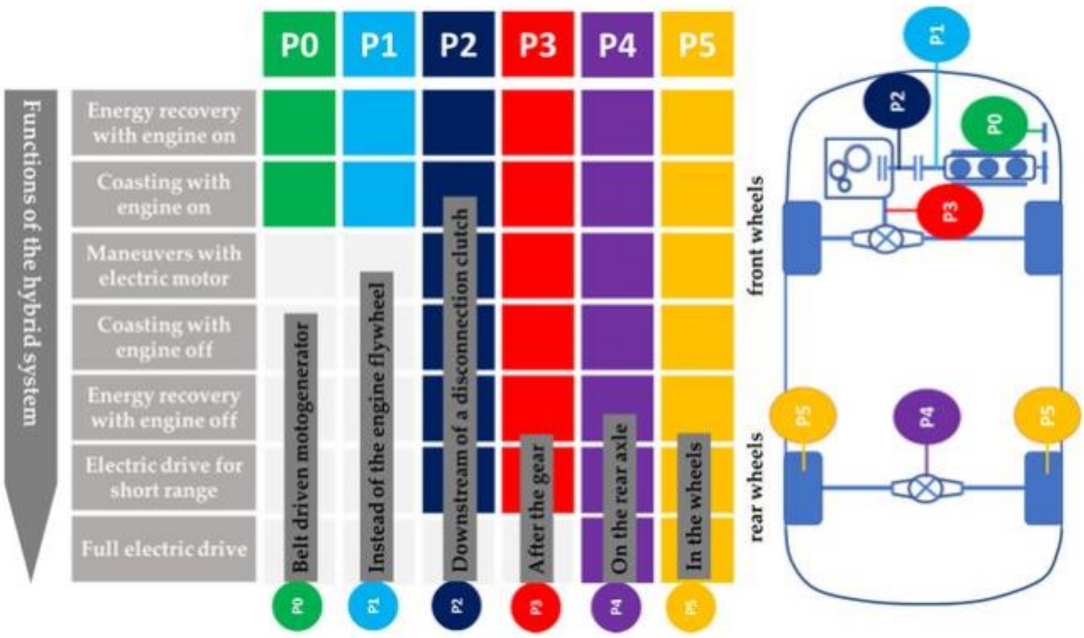

Figure 24: Hybrid configurations in terms of Hybridization and placement of the motor

The major advantages of the parallel hybrid drive train over the series one is the following:

1. Both the ICE and the Electric Traction Motor directly supply torques to the driven wheels and no energy form conversion occurs, thus the energy loss may be less.
2. It is compact because there is no need for an additional generator and the traction motor is smaller than in the series powertrain.

The mechanical combination of the engine and electric motor also opens room for other configurations which are defined based on the coupling they have among their power flow. The mechanical couplings could be a torque or a speed coupling. Torque coupling splits the torque into either propelling or battery charging. Furthermore, this coupling could be in terms of two or one shaft designs. Depending on tractive requirements the transmission placement can be manipulated.

Torque couplers can be used to constitute hybrid drivetrains with many different configurations. Based on the torque coupler used, a two- or one-shaft configuration may be constituted. In each, the transmission may be placed in different positions with different gears, resulting in various tractive characteristics. A good design depends mostly on the tractive requirements, engine size, motor size, and motor speed-torque characteristics.

Figure 25 shows a two-shaft configuration, in which two transmissions are used. One is placed between the engine and the torque coupler and the other between the motor and the torque coupler. Both transmissions may be single-gear or multi-gear.

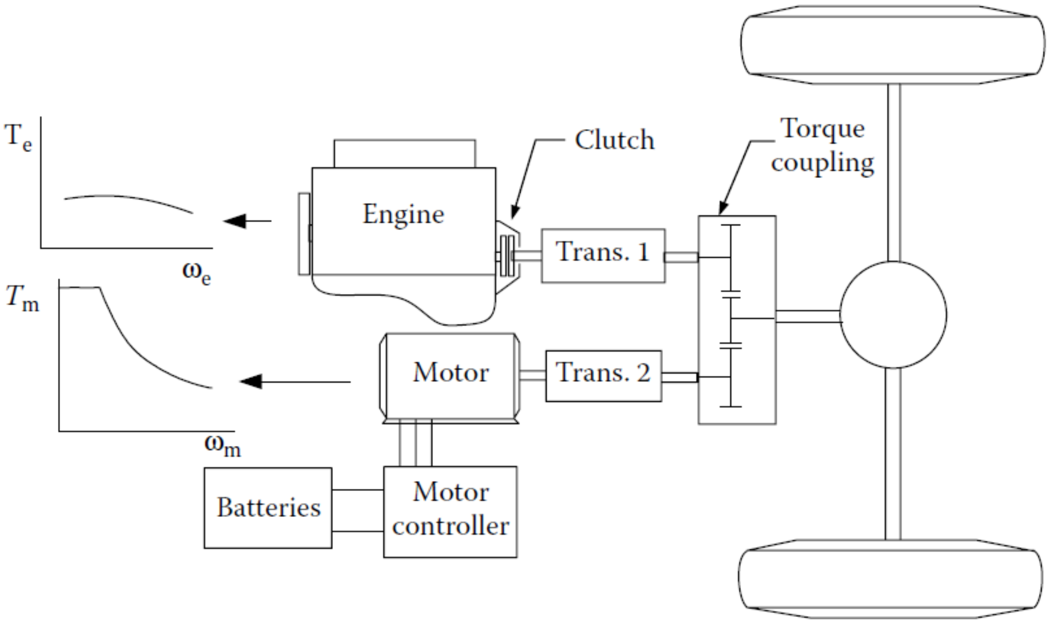

Figure 25: Two shaft configuration[17]

In the pretransmission configuration, as shown in Figure 26, the torques of both the engine and the motor are modified by the transmission. However, the engine and the motor are required to have the same speed range. This configuration is usually used in the case of a small motor, referred to as a mild hybrid drivetrain, in which the electric motor functions as an engine starter, an electrical generator, an engine power assistant, and for regenerative braking.

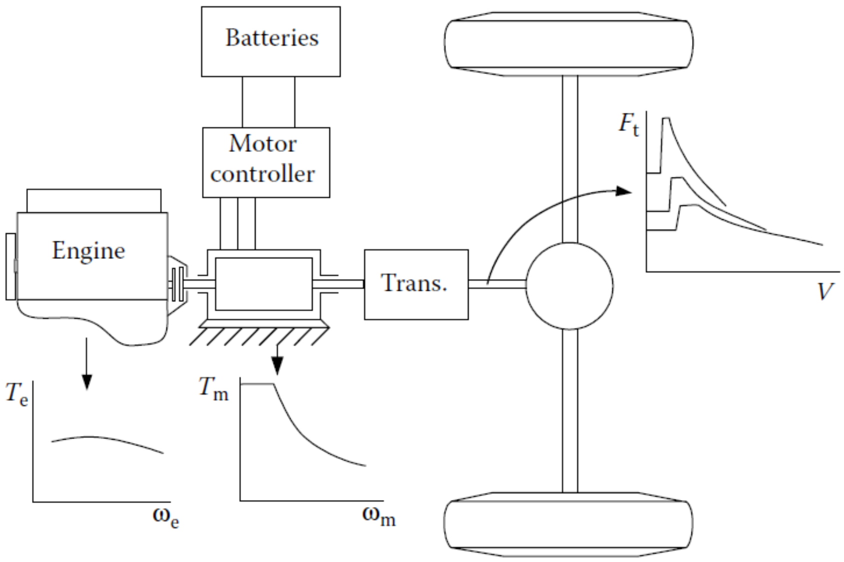

Figure 26: Pretransmission single shaft torque combination[17]

Similar to the torque-coupling device, speed-coupling units can be used to constitute various hybrid drivetrains. (Figure 27) the engine supplies its power to the sun gear through a clutch and transmission. The transmission is used to modify the speed-torque profile of the engine to match the traction requirements. The transmission may be multi-gear or single-gear based on the engine speed–torque profile. The electric motor supplies its power to the ring gear through a pair of gears. Lock 1 and lock 2 are used to lock the sun gear and the ring gear to the stationary frame of the vehicle to implement different operation modes

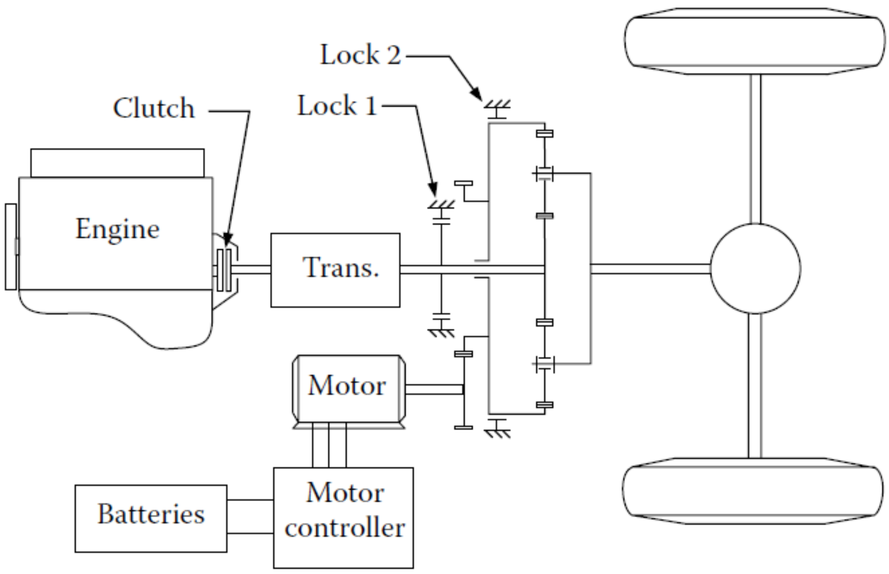

Figure 27 : Speed Coupled Hybrid Configuration[17]

2.2.4 Combined Hybrid

The combined hybrid is generally referred or defined in terms of the power split it does through its transmission among the power sources. It is served by an essential feature where in a planetary gear set serves as a transmission device. The power generated by ICE is split into electrical and mechanical pathways. Electrical path in turn transfers energy to another electrical machine coupled to motor shaft and apparently converting into Mechanical Power. There is flexibility also to choose power couple mode in terms of Torque or Speed.

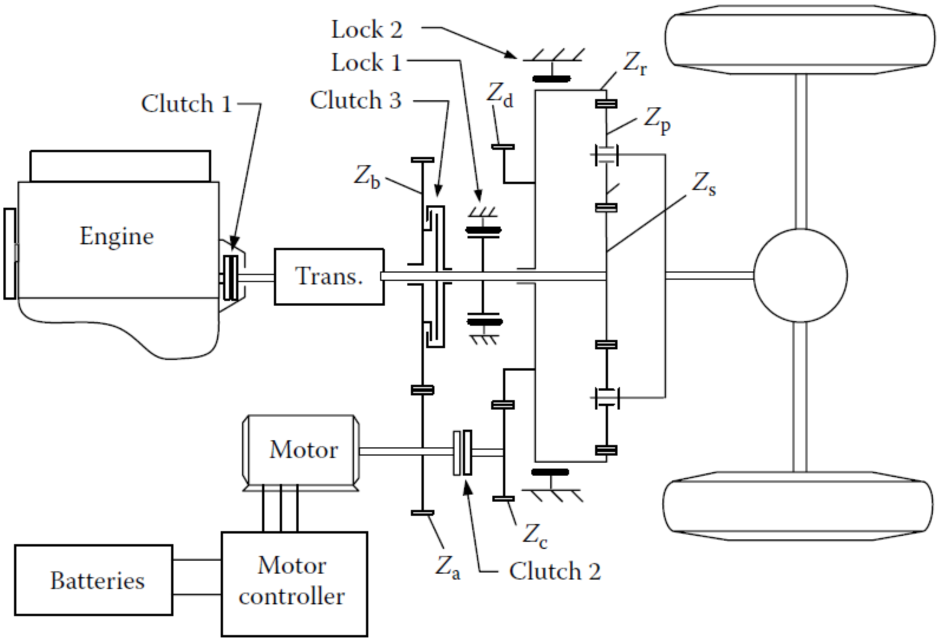

Figure 28: Combined Hybrid Configuration[17]

2.3 Why do we need to model the electric vehicle powertrain?

The major objective is to understand the influence of parameters and consider building the accurate simulation models for different case study scenarios. It is very complex and challenging to understand the dependencies and variables influencing the performance. If not, it becomes very extensive to design an EV with multiple driving types and demands for the powertrain. The nominal regions of the operation of the motor needs to be kept at high stakes as it defines the efficiency and consumption of the battery energy and indirectly maintain the energy regeneration goals. The powertrain energy consumption is also influenced by the driver behaviour along with the drive cycle definitions. The energy consumption impacts the motor torque and current attributes as well and it is highly cardinal to discern such effects with the help of powertrain modelling.

In certain extreme weather countries like India, Middle East it is also important to discuss and study the influence of temperatures on the energy consumption and eventually the functioning of the powertrain.

End goal of Simulation

1. Component Sizing
2. Influence of real time parameters which can influence energy consumption
3. Component Sizing Optimization
4. Achieve lowest W/km
5. Scalability & Modularity

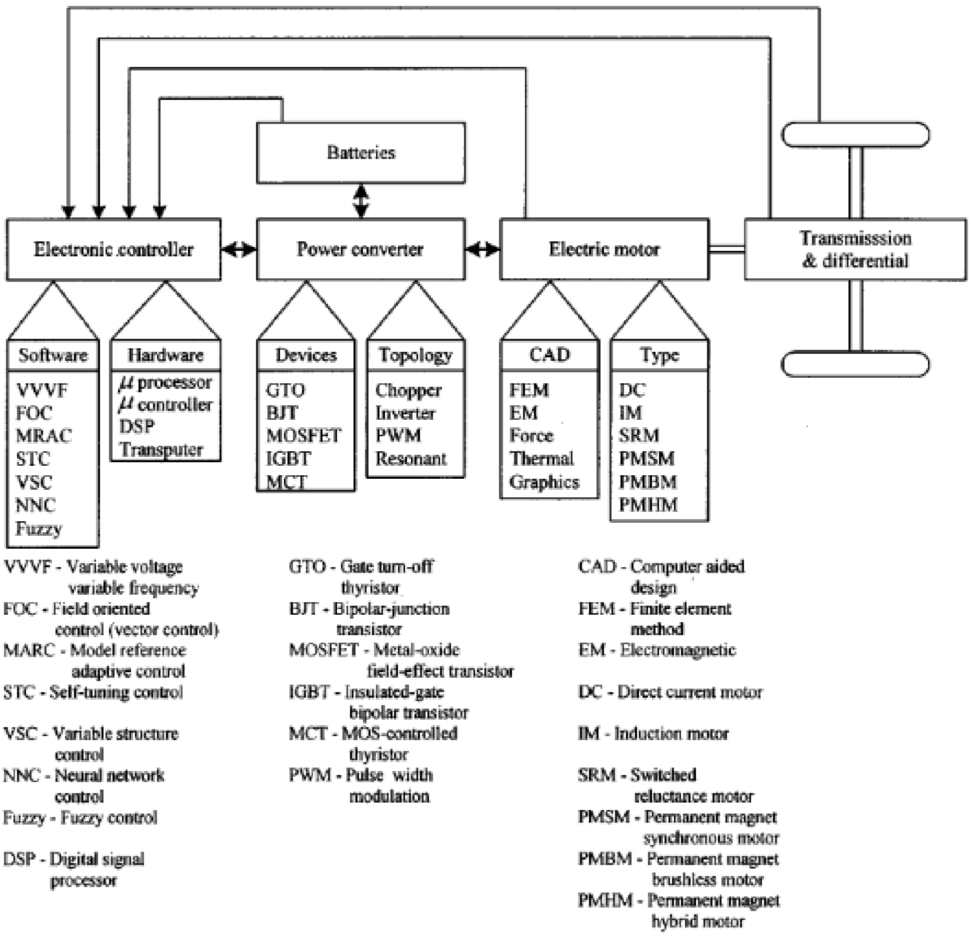

Figure 29: EV Propulsion System Design Workflow[13]

Chapter 3 Analysis of 28kw Induction Motor

This chapter would be guiding through the fundamentals of an Induction Motor and the parameters, constants, design, and other details of the specific motor used in the thesis and the Hardware in Loop system used for the Drives Testing.[20] Lastly, we also look at some of the performance factors or faults

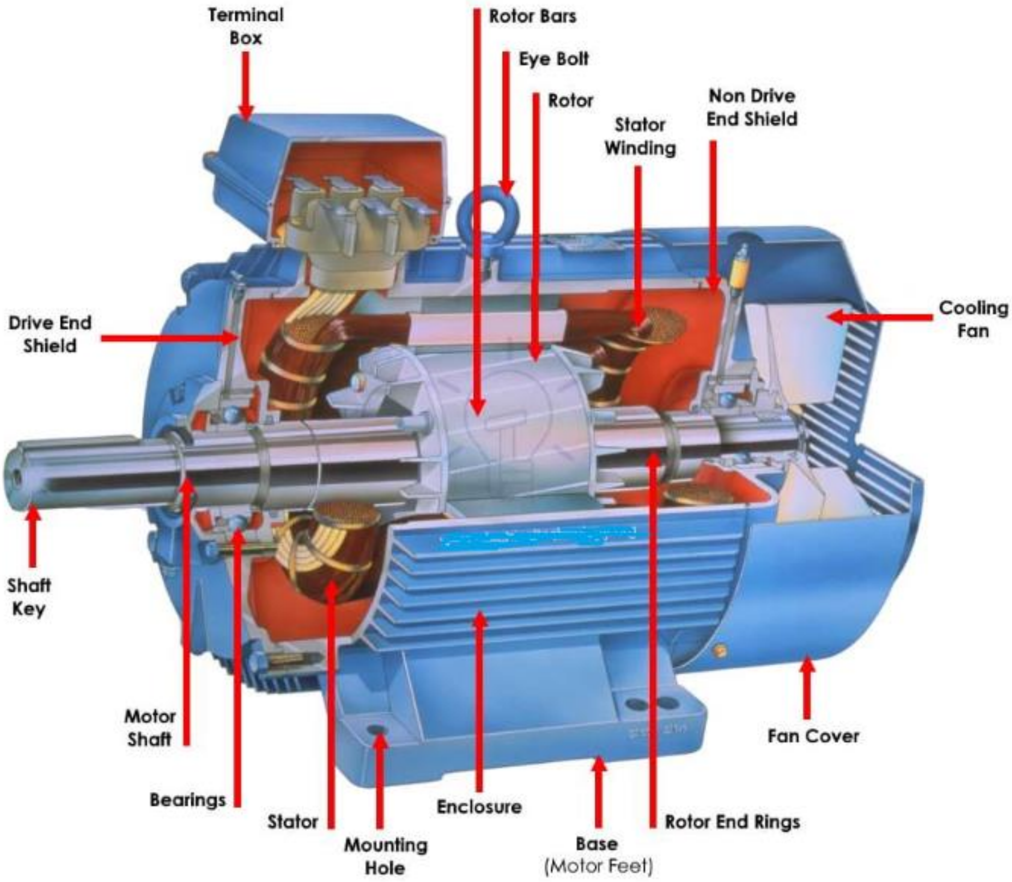

Figure 30 : Induction Motor Cross Section

3.1 Working Principle.

The simplest way or physics behind the IM would be that induction makes forces; Forces make torque and the Back Emf is a form of a drag to the system. The simplest circuit to represent a motor would be inclusive of an inductor, resistor and a back emf based load. Magnetic field lines produced link with stator windings and generate EMF there, this is known as back emf, and it is a form of reverse voltage to the supply voltage. The Resistor represents all the losses while the inductor represents energy storage and magnetic field induced. Due to inductor current can't change instantaneously.

Analogously mass would correspond to inductance, force to voltage and velocity to current in laymen terms of physics. This inductor resistor circuit acts as a low pass filter between voltage we apply and current through system.

$$V_L = L\frac{di}{dt}$$ *Equation 1*

Starting with a small contrast to DC Machine operation wherein we need to give double excitation or supply, one to stator and other to rotor through brushed commutation and for BLDC it is required to energise two coils or connect free ends of stator coil together (separately energized) but it isn't any of the cases in the IM where electromagnetic induction takes place.

Laws that govern the IM functionality: [21]

1. Faradays Law – stating that current will be induced in a conductor which is exposed to a changing magnetic field.
2. Lenz's Law – stating direction of induced current will be such that the magnetic field created by induced current always opposes the initial changing magnetic field which produced it. Fleming's right-hand rule is used to determine direction of current flow.

The stator of the motor consists of overlapping winding offset by an electrical angle of 120^oWhen phase supply is given to the windings of the stator, a rotating magnetic field is produced which rotates with some speed known as synchronous speed $N_{s,}$ the rotating flux passes through the air gap and cuts the rotors bars at rest. The rotor bars are short circuited using the end rings; therefore, the current will flow in the rotor bars due to induced emf and a magnetic field is generated. As stated above due to the Lenz's Law the speed of the rotor will always be less than the stator in general operating conditions. The difference in speed between the rotor and stator is termed as slip. The magnetic field or stator flux has the uniform strength and rotates at the frequency which is equal to stator frequency.

The Synchronous speed is given by

$$N_s = \frac{120 * f}{P} \qquad \textit{Equation 2}$$

Here f is defined as the frequency of the power supply and P denotes number of poles of the stator.

$$S = \frac{Ns - Nr}{Ns} = \frac{\omega e - \omega r}{\omega e} = \frac{\omega sl}{Ns} \qquad \textit{Equation 3}$$

Here S is the slip and the Nr denotes rotor speed.

The magnetic field cuts the rotor with relative speed N_s - N_r. For a rotating speed of ω_r and its current waveforms moving at a speed of ω_{sl} relative to rotor, the magnetomotive force of the rotor is same as the airgap flux wave. The Torque generated is given as

$$Te = \pi \left(\frac{p}{2}\right) l_a\ (ra) BpFpsin\delta \qquad \textit{Equation 4}$$

l_a is axial length, ra is radius and Bp is peak air gap flux density, Fp peak value of rotor mmf, δ torque angle give by π/2 + Θr

The primary factors which determine the torque production in a three-phase induction machine are as follows

1. Magnitude of rotor current I_r
2. Flux producing emf and interacting with rotor
3. Power Factor which is the phase angle between voltage and current (cosφ)

   Therefore, torque equation is given as

$$T \propto \Phi I cos\varphi \qquad \textit{Equation 5}$$

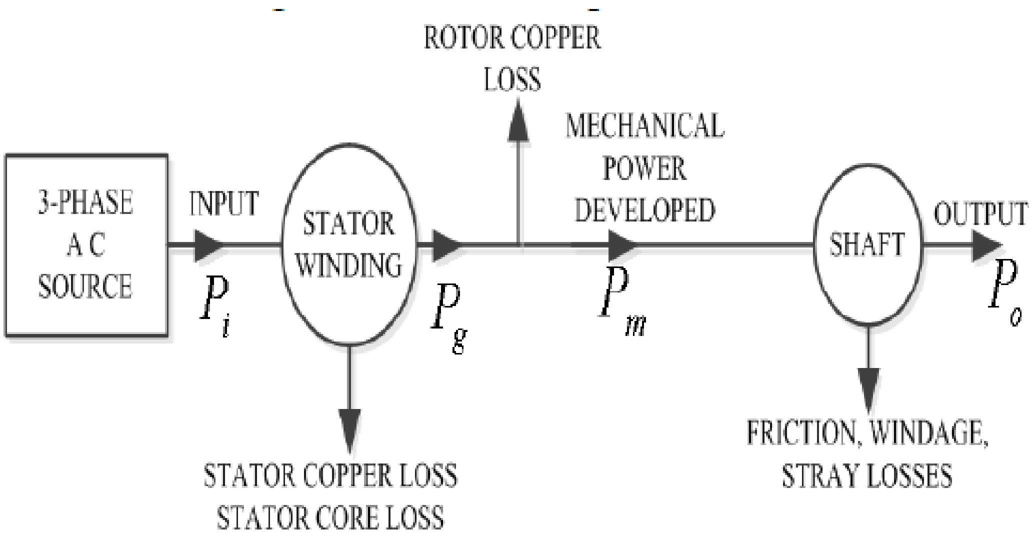

Figure 31: Power Flow in 3 phase IM[22]

The Power flow diagram outlines the losses and the input/outputs. The inputs into the induction motor are three phase voltages and currents.

The Input power drawn in by the induction motor is expressed as

$$P = \sqrt{3} * V_L * I_l * cos\varphi \qquad \textit{Equation 6}$$

Also $\frac{V_L}{\sqrt{3}} = V_{P,rms}$

Where V_L *is line voltage*, I_l *is Line Current and* $cos\varphi$ *is power factor*

3.1.2 Characteristics

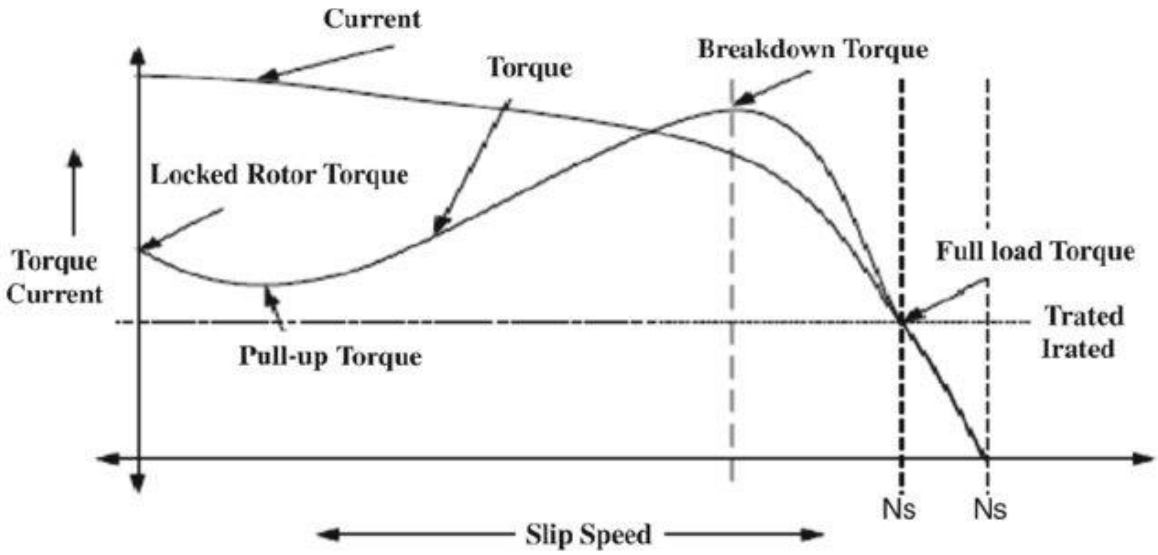

Figure 32 Torque variations with speed

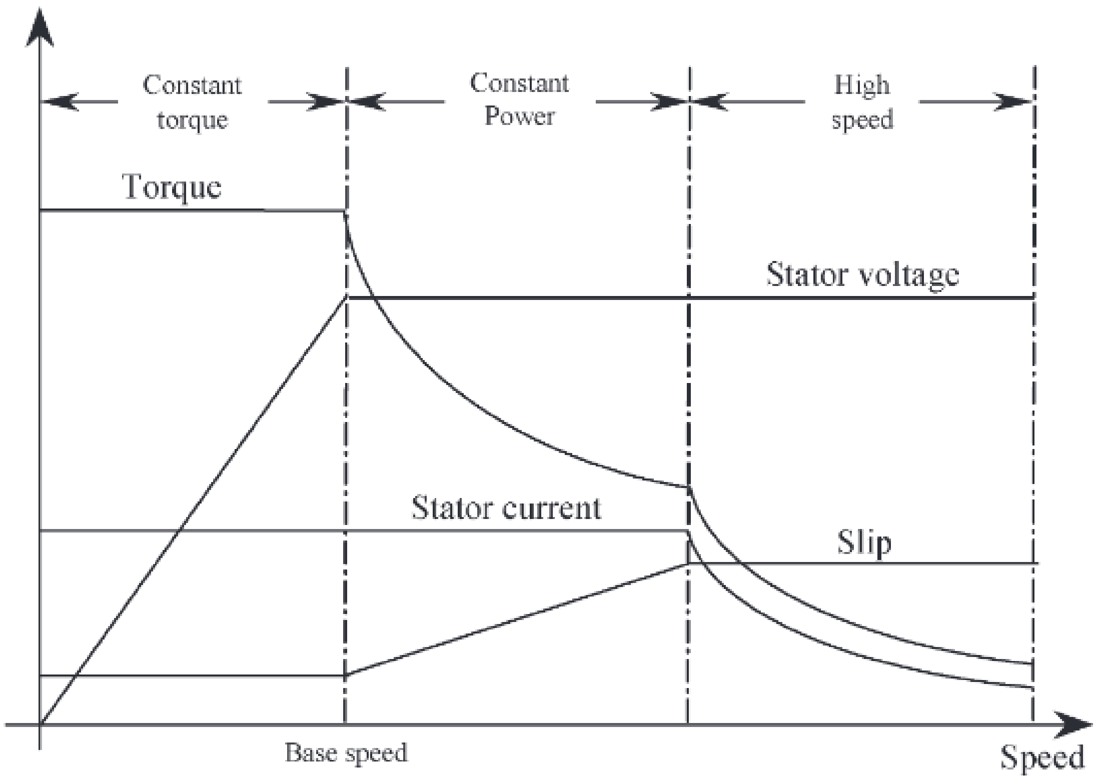

Figure 33 : Induction Motor Characteristics[8]

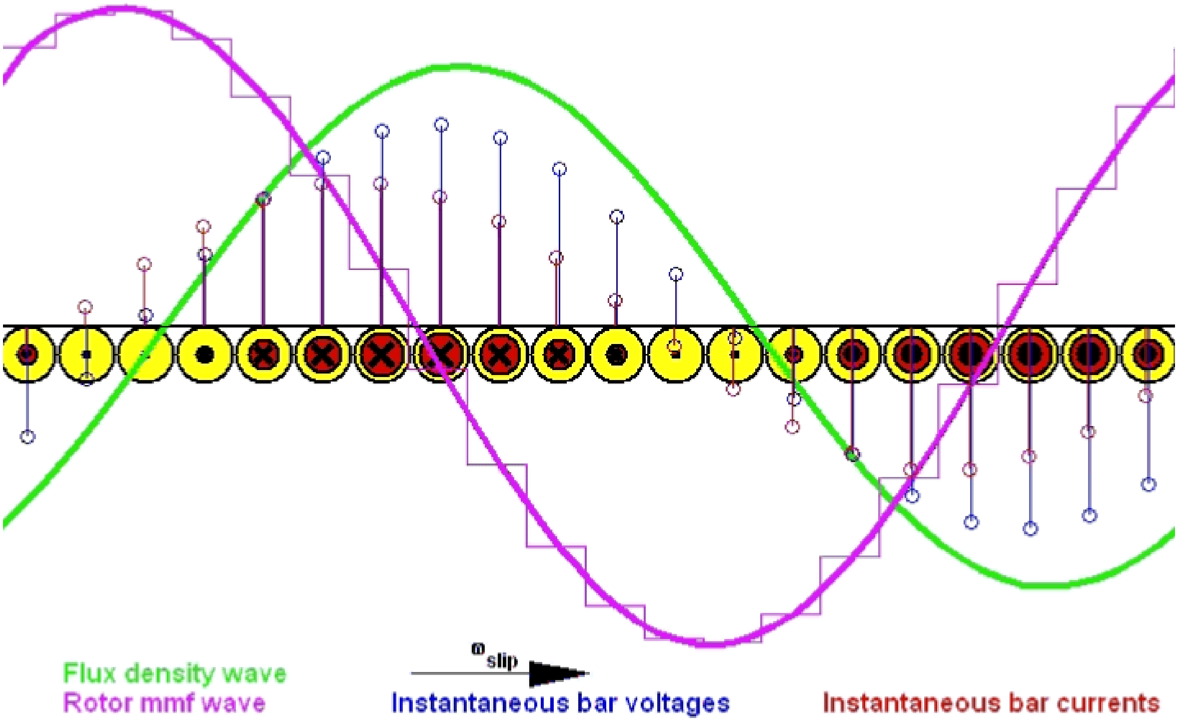

Figure 34:Squirrel Cage Phase Simulation

3.1.3 Torque- Speed Characteristics

Shows how speed torque varies through the stages of its operation. Starting Torque is the amount of torque an induction motor produces as it ramps up from a standstill which is generally observed to be around 150% of the rated torque. Pull Up torque is the torque which is reached when the motor is approaching its rated speed generally observed as 125%.

The next form is the breakdown torque which is the greatest amount of torque a motor can generate. When the motor has reached its rated speed, the motor must be producing around 80-100% torque.[23]

As the load is increased and amount of speed decreases there is also simultaneous increase of Torque. Torque and Current are proportional to each other which justifies why an induction motor draws more current on a sharp increase of load. Overload relay switches are used to withstand sharp increases in load beyond the breakdown torque region. In no-load condition, the value of slip will be very less due to the comparative (relative) motion among the rotor and the stator fields is very less and the frequency of the rotor will also have less value.

Due to the sturdiness and low maintenance squirrel cage motors are perfect for traction. The Torque and Flux Field is easily controlled by vector control methods to be discussed in the next chapter. But reducing the flux, speed may be increased. Due to rotor winding and copper losses efficiency is also reduced. They also have low power factor, the angle between the phase voltage and current which is very crucial to measure the power management in the motor. The constant power region may be enhanced using dual inverters and doubly fed IMs can produce efficient results by reduction of rotor losses at low speeds. [8]

3.1.4 The major components of the induction motor are

1. Stator
2. Rotor
3. Air Gap

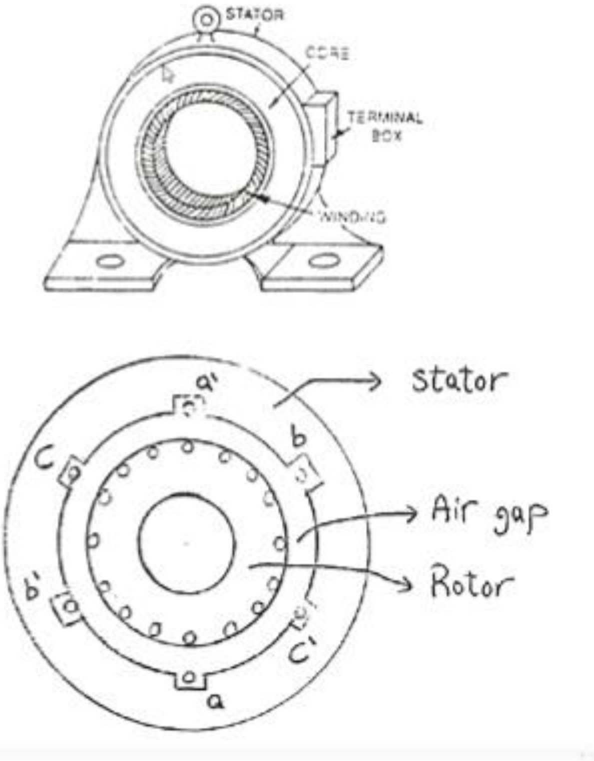

Figure 35 : IM Cross section

Stator is the static part of the motor of a cylindrical shape. Stator frame has stator and stator windings. The stator in designed is such a way where it could be piled up with the stator windings which is shifted by 120 degrees electrical in space in the slots carved between the series of iron slices. These iron slices are stacked, insulated, and compressed form of iron. We use stacking system to avoid the electrical losses in the system.

The rotor is centrally located within the stator and made of iron core and laminated slices. The rotor has conducting end caps and conducting bars positioned in a skewed manner shaping like a cage and hence the name squirrel cage. Bearings support the motor shaft allowing shaft and roller to rotate and remain centrally positioned within the stator enclosure. The shaft transports the mechanical energy created from the rotor to the load and there is an air gap between stator and rotor to eliminate any physical contact. The interiors rotational components and magnetic field producing areas are protected by the enclosure and the end bells which allow rotor shaft to turn freely on its axis.

Air space between rotor and stator allows clearance for the rotation and also provide reactance between them without brushing. There is also no heating and frictional damage.

Functional Regimes and Construction wise categorised

- With respect to energy flow – Induction Motor, Generator and Brake
- With respect to no of supply phase – single and three
- With respect to construction – squirrel cage, wound rotor, and special rotor (Figure 36)(Figure 37)
- With respect to machine movement – rotating and translating

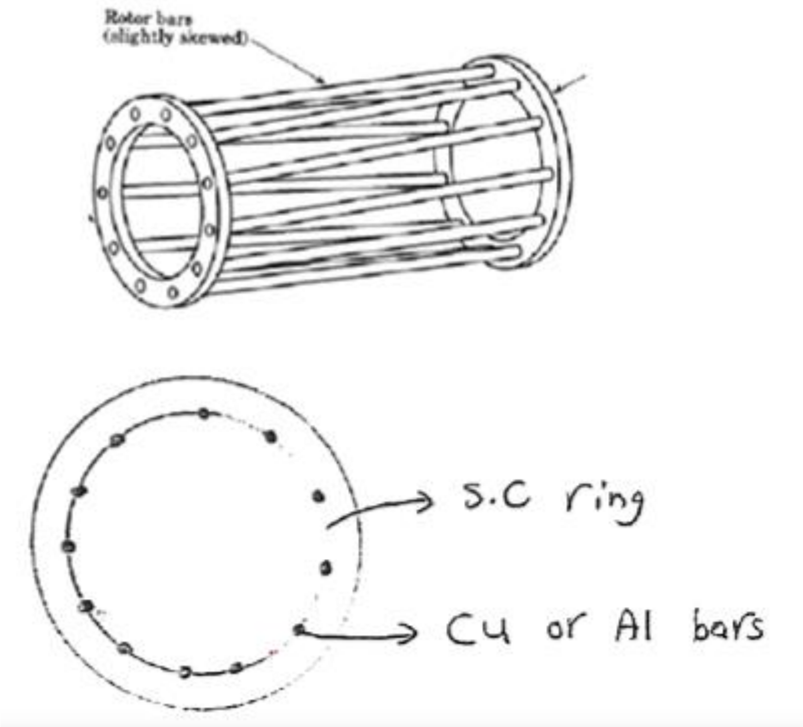

Figure 36: Squirrel Cage

In Squirrel cage conducting bars made of Copper or Aluminium are placed in the rotor slots and they are short circuited by end rings. Figure 36

The number of poles is usually similar or less than stator poles and due to low leakage reactance, there is resulting low starting torque. The bars of the cage are hence skewed to provide torque and reduce motor noise. The skew causes the length of rotor to increase in turn increasing the resistance and eventually the high starting torque.

1. The wound rotor has the same components but consists of a slotted armature. Insulated conductors are put in the slots & connected to form a

three-phase double layer distributed winding like the stator winding. Windings of the rotor are connected in a star arrangement. The open end of the start circuit is brought outside the rotor and connected to the insulated slip rings. There are slip rings which are mounted on the shaft with brushes strung onto them. The brushes are connected to three phase variable resistors connected in star. Their sole purpose is to allow external connection of resistors and which in turn helps in the speed control and starting of the machine. [https://www.udemy.com/course/matlab4b/]

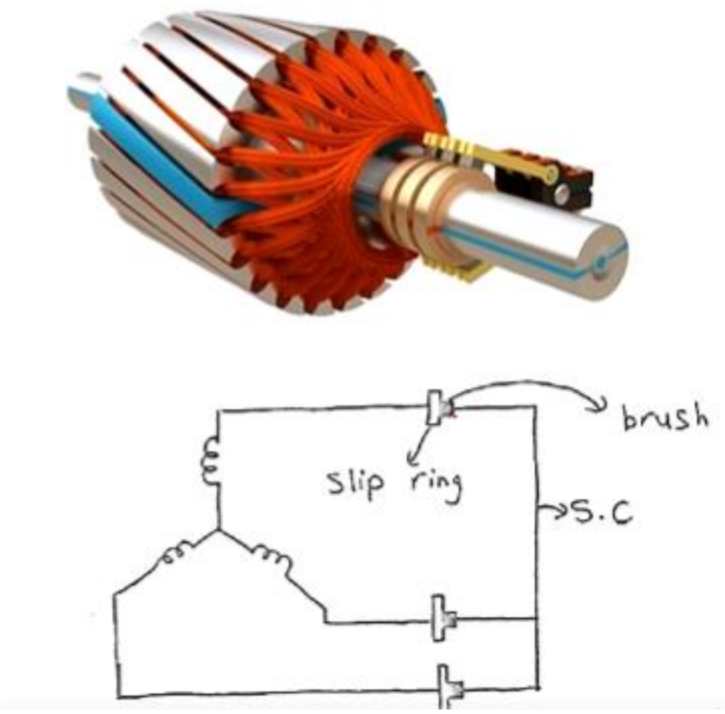

Figure 37: Wound Rotor IM

3.2 IM analysis

An IM can be analogous to a three-phase transformer. IMs have likely primary and secondary windings, and iron cores for flux linkages. Reluctance is the property of material by virtue of which is tends to provide defiance to flux going through it. The amount of opposition by a material of change of current is inductive reactance and voltage is capacitive reactance.

$$R=\frac{MMF}{\Phi} \qquad \textit{Equation 7}$$

Also,

$$R = \frac{L}{\mu A}$$ *Equation 8*

Hence combining them

$$\Phi = MMF\left(\frac{\mu A}{L}\right)$$ *Equation 9*

Here

$\mu =$ Permeability of material, L = Length of air gap, Φ = flux in air gap,

MMF = Magnetomotive force, R = Reluctance

Hence from Equation 9 it can be observed that MMF depends on flux density and air gap length. The increase in reluctance with air gap leads to additional MMF and eventually demand of current increases.

But with few differences in comparison to transformer as follows:

1. IMs are consisting of air gaps having large reluctance causing large leakage fields.
2. Due to voltage drop which comes with the leakage field it leads to a low power factor as well.
3. The Secondary winding is always shortened
4. The Secondary Winding is allowed rotation.

Magnetizing current is dependent on the magnetic loading and air gap length of the machine. A high gap leads to peaks in current and a very low power factor.
The Analysis of the losses and power flow is necessary for the understanding the equivalent circuits and the functioning of IM, the descriptive diagram is presented in Figure 38[3]

$$P_{SCL} = 3 * I_s^2 R_s$$ *Equation 10*

$$P_{core} = 3 * E_s^2 / R_C$$ *Equation 11*

$$P_{Ag} = 3I_r^2\left(\frac{R_r}{s}\right)$$ *Equation 12*

[3] Here P_{SCL} = Stator core losses; P_{core} = core losses; P_{Ag} = air gap; P_{RCL} = Rotor Copper Losses; P_{conv} = conversion losses.
S = slip, subscript r = rotor; s = stator R_c= Core Loss Resistance

$$P_{RCL} = 3I_r^2 R_r \quad \text{Equation 13}$$

$$P_{conv} = P_{Ag} - P_{RCL} = 3I_r^2[\frac{R_r(1-S)}{S}] \quad \text{Equation 14}$$

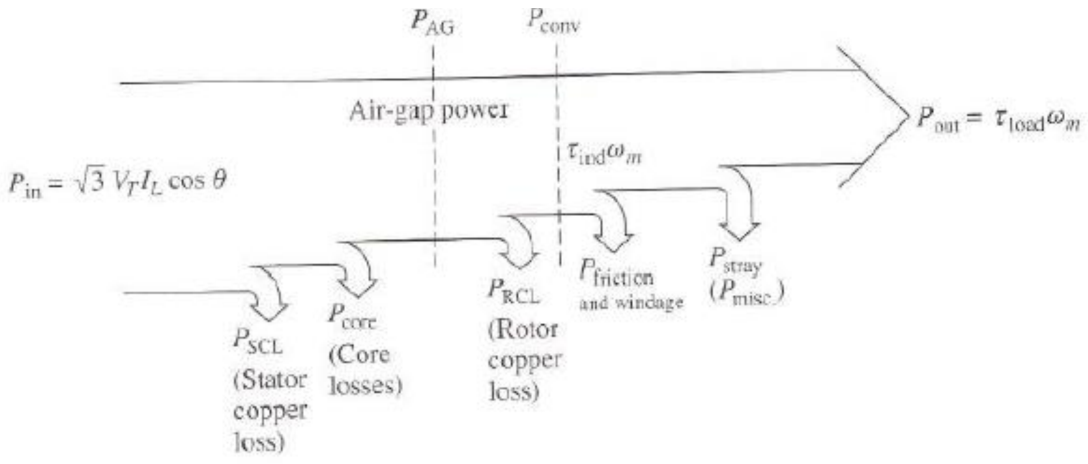

Figure 38 : Power Flow in IMs

3.3 Circuits, Transformations and Equations.

On describing the AC IM dynamics in a synchronous reference frame, they resemble DC dynamics which is simpler and easier to decipher. As we had seen in the torque speed graphs discussion the variations in torque with the slip speeds now, we need to go through the simplified representation of the IM using circuit in SRF and equations which help model the machine and understand the dynamics. The voltage vectors are crucial parts to be controlled and prior to that we look are few more parameters. There are few assumptions in developing the IM model as stated in [1].

- Linear magnetic circuit
- Negligible iron losses
- Negligible mechanical losses, the ones which were discussed above in the previous chapter.

In AC machine torque are shown as outer product of flux and current vectors so for maximization they need to be orthogonal to each other while in DC orthogonality is provided by brush and commutators. The balanced three phase systems have two DOFs and they are allocated to flux regulation and torque control. This role ordering in very dismayed in the stationary reference frame hence the roles are shifted to SRF, and dynamics are a resemblance of separately excited DC machine.

An electrical sub-model to implement the three-axis to two-axis (3/2) transformation of stator voltage and current calculation, a torque sum-model to calculate the developed electromagnetic torque (T_{em}), and a mechanical sub-model to produce the rotor speed (ω) make up a generalized dynamic model of the induction motor.

The per phase equivalent circuit of the IM is only valid in steady conditions but for controls dynamically d-q axes or the direct and quadrature axis are crucial step. It is the primary objective of the field-oriented control method which is discussed in the next chapter. Transformation is based on Altercations and formulas that transform a three-phase time and speed dependent system into a two coordinate (d and q coordinates) time invariant system as in Figure 39

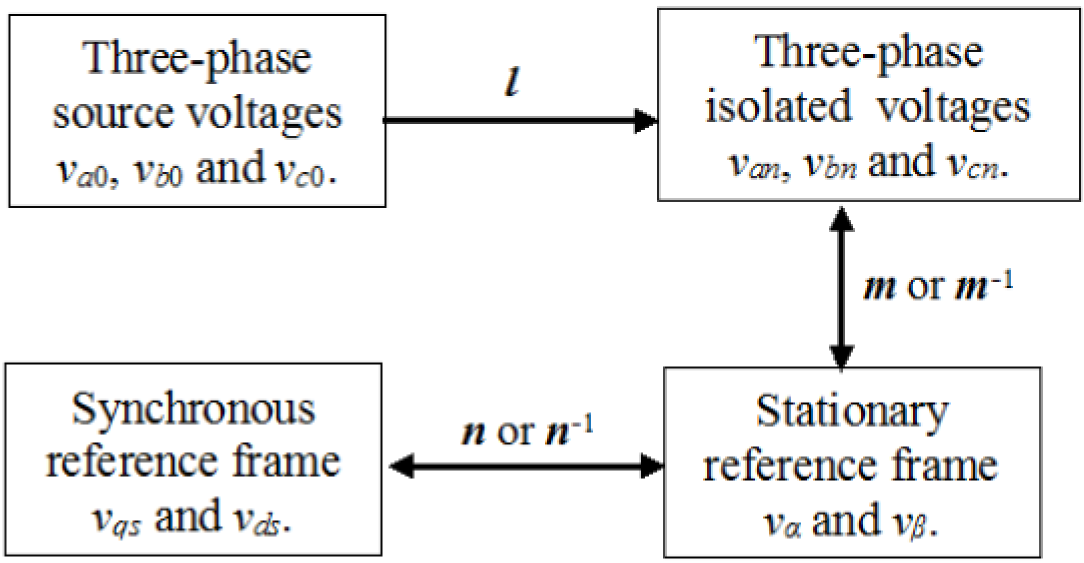

Figure 39 : Voltage Transformation[1]

The vector forms are as follows

Equation 15

$$\boldsymbol{v_{sn}} = \begin{bmatrix} V_m \sin \omega t \\ V_m \sin(\omega t - 2\pi/3) \\ V_m \sin(\omega t + 2\pi/3) \end{bmatrix}$$

Equation 16

$$\boldsymbol{l} = \begin{bmatrix} 2/3 & -1/3 & -1/3 \\ -1/3 & 2/3 & -1/3 \\ -1/3 & -1/3 & 2/3 \end{bmatrix}$$

Equation 17

$$\boldsymbol{m} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1/\sqrt{3} & 1/\sqrt{3} \end{bmatrix}$$

Equation 18

$$\boldsymbol{n} = \begin{bmatrix} \cos\theta_e & -\sin\theta_e \\ \sin\theta_e & \cos\theta_e \end{bmatrix}$$

Here m: clarke transformation; n: park transformation.

Induction machine equations in SRF where the frame is obtained by speed set, ω_e *and* $(\omega_b = 2\pi f)$ *is the motor electrical angular base frequency*:

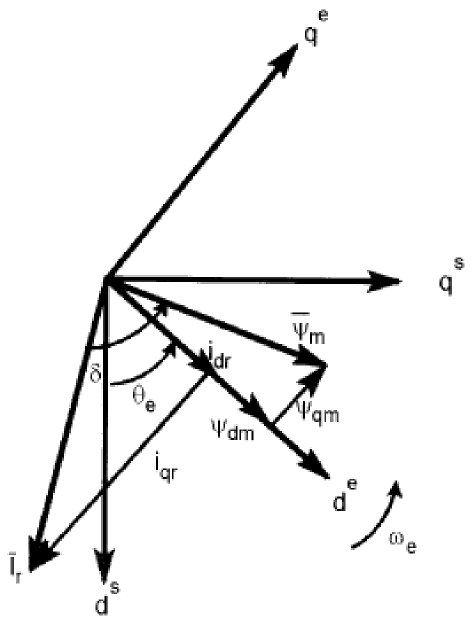

Figure 40 : Flux and current vectors in SRF

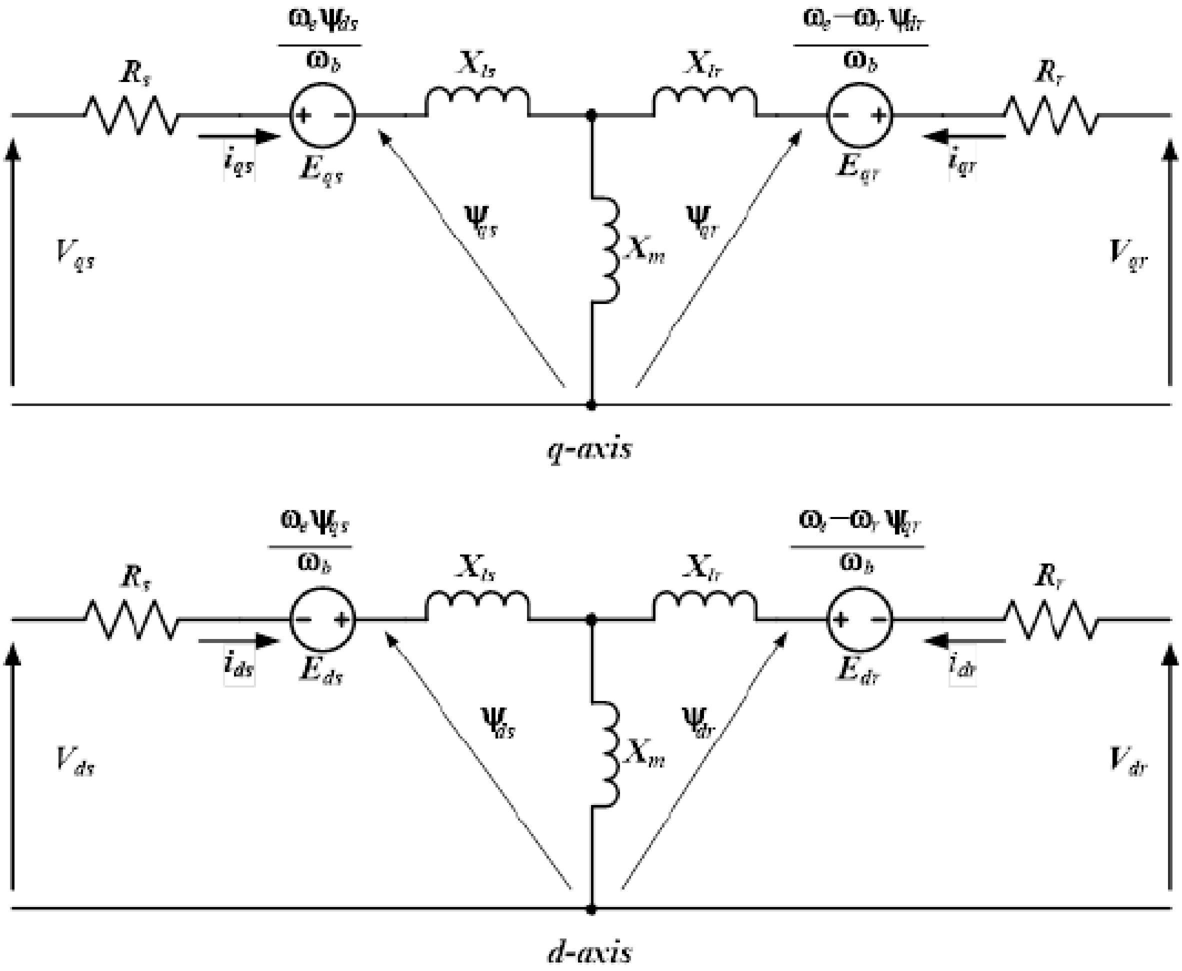

Figure 41 :State Equation of IM [4][1]

Voltage equations are:

$$v_{qs} = \frac{p}{\omega_b} F_{qs} + \frac{\omega_e}{\omega_b} F_{ds} + r_s i_{qs}$$ *Equation 19*

$$v_{ds} = \frac{p}{\omega_b} F_{ds} + \frac{\omega_e}{\omega_b} F_{qs} + r_s i_{ds}$$ *Equation 20*

$$v_{qr} = \frac{p}{\omega_b} F_{qr} + \frac{\omega_e - \omega_r}{\omega_b} F_{dr} + r_r i_{qr}$$ *Equation 21*

$$v_{dr} = \frac{p}{\omega_b} F_{dr} + \frac{\omega_e - \omega_r}{\omega_b} F_{qr} + r_r i_{dr}$$ *Equation 22*

Current Equations are:

[4] E means here Electromotive force.

$$i_{ds} = \frac{1}{\chi_{ls}}(\lambda_{ds} - \lambda_{md})$$ *Equation 23*

$$i_{qs} = \frac{1}{\chi_{ls}}(\lambda_{qs} - \lambda_{mq})$$ *Equation 24*

$$i_{dr} = \frac{1}{\chi_{ls}}(\lambda_{dr} - \lambda_{md}) \quad Rotor$$ *Equation 25*

$$i_{qr} = \frac{1}{\chi_{ls}}(\lambda_{qr} - \lambda_{mq})$$ *Equation 26*

Flux Linkage equations are:

$$\begin{bmatrix} F_{qs} \\ F_{ds} \\ F_{0s} \\ F_{qr} \\ F_{dr} \\ F_{0r} \end{bmatrix} = \begin{bmatrix} \chi_{ls} + \chi_m & 0 & 0 & \chi_m & 0 & 0 \\ 0 & \chi_{ls} + \chi_m & 0 & 0 & \chi_m & 0 \\ 0 & 0 & \chi_{ls} & 0 & 0 & 0 \\ \chi_m & 0 & 0 & \chi_{lr} + \chi_m & 0 & 0 \\ 0 & \chi_m & 0 & 0 & \chi_{lr} + \chi_m & 0 \\ 0 & 0 & 0 & 0 & 0 & \chi_{lr} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{0s} \\ i_{qr} \\ i_{dr} \\ i_{0r} \end{bmatrix}$$ *Equation 27*

Torque Equations are:

$$T_{em} = \frac{3}{2}\frac{P}{2\omega_b}(F_{qr}i_{dr} - F_{dr}i_{qr})$$ *Equation 28*

$$T_{em} = \frac{3}{2}\frac{P}{2\omega_b}(F_{ds}i_{qs} - F_{qs}i_{ds})$$ *Equation 29*

Equation 30

$$T_{em} = \frac{3}{2}\frac{P}{2\omega_b}\chi_m(i_{dr}i_{qs} - i_{qr}i_{ds})$$

Finally, the relation between flux and flux linkage is given by (Ψ)[5] = $\omega_b\lambda$. In terms of Reactance's can be rewritten as $\chi = \omega_b L$

$$\frac{d\omega_r}{dt} = \frac{2J}{p}(T_{em} - T_l)$$ *Equation 20*

For computing powers

5

F *can also be written as* Ψ *meaning the flux linkages where* F_{qs} *would mean q axis stator flux linkages.*

$$P_i = 3V_{s,rms}I_{s,rms}cos\Theta_e \qquad \textit{Equation 21}$$

$$P_o = T_{em}\omega_r\ (W) \qquad \textit{Equation 22}$$

$$\eta = \frac{\omega_r}{P_i} \qquad \textit{Equation 23}$$

Where $\cos\Theta_e$ represents the power factor.[1]

Chapter 4 Methods of Powertrain Controls

This chapter is about going through the need and the why, how's of Powertrain Control which in our case is conceived as Motor Controls and more concerned to IM Drives.

While motor topologies have remained relatively unscathed with only the material fields being not typically dormant much over the past century, control techniques have been well harnessed to meet the ever-thriving industrial needs and by comparison have experienced explosive growth. This has been driven in large part by technology advancements in the semiconductor industry. Few primary contributors could be advancements in power electronics, reductions in form factor and more sophisticated control algorithms with future driven targets. With the advent of numerous control techniques which are to be discussed like the Vector Control, there has been significant alleviation of control issues in the adjustable speed drives. The only point stands are that it is difficult to develop mathematical models for unknown load variations and parameter variations due to variations in external elements like temperatures, disturbances around and in the system and few saturation effects.

In an EV, the IM is interfaced between the power sources which are stacks of batteries and the car's body via the motor controller. The motor controller in brief is comprising of the inverter circuit for pulse generation to motor and a control unit which basically can be based on any viable algorithms as per requirements. The IM is modelled based on its equation for single phase or multiple phases. The basic flowchart of the Motor Control workflow is presented in Figure 42

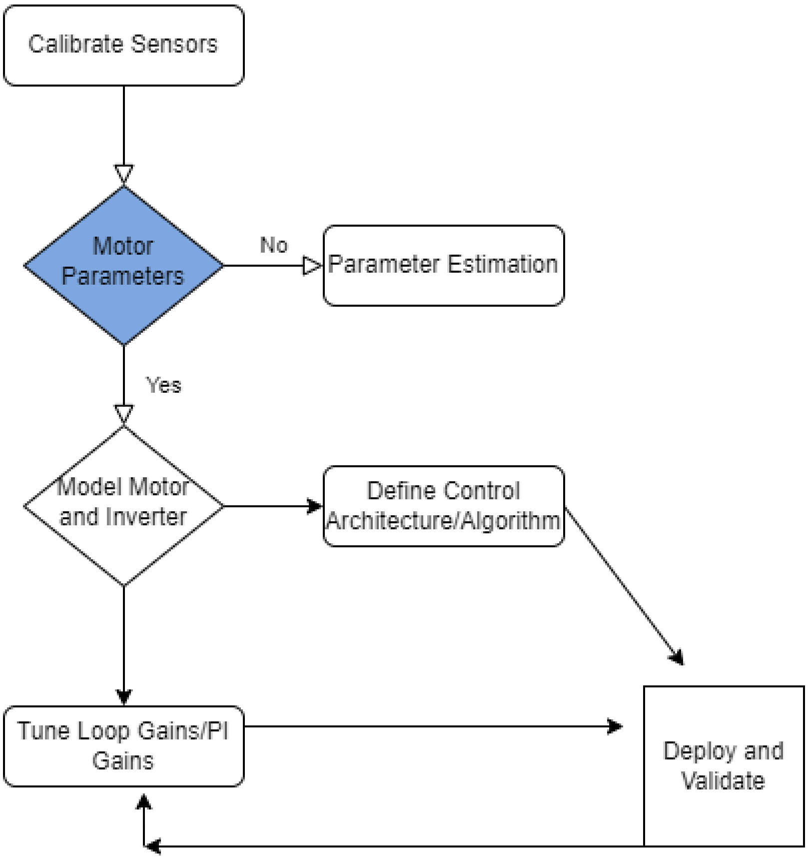

Figure 42 : Motor Control Workflow

4.1 What is the kind of control needed?

What you want should be equal to what we want. Feed forward works when we know the system and there are no exterior perturbations. The Process is unadjustable and unpredictable. To enable quick (regenerative) braking in both directions and forward and reverse motion, an electric drive may be necessary. Torque in the direction of motion is implied by motor action. Regenerative braking involves reversing the direction of the motor's electric power flow as well as the torque (negative). The operation is known as Multiquadrant operation as shown in Figure 43.

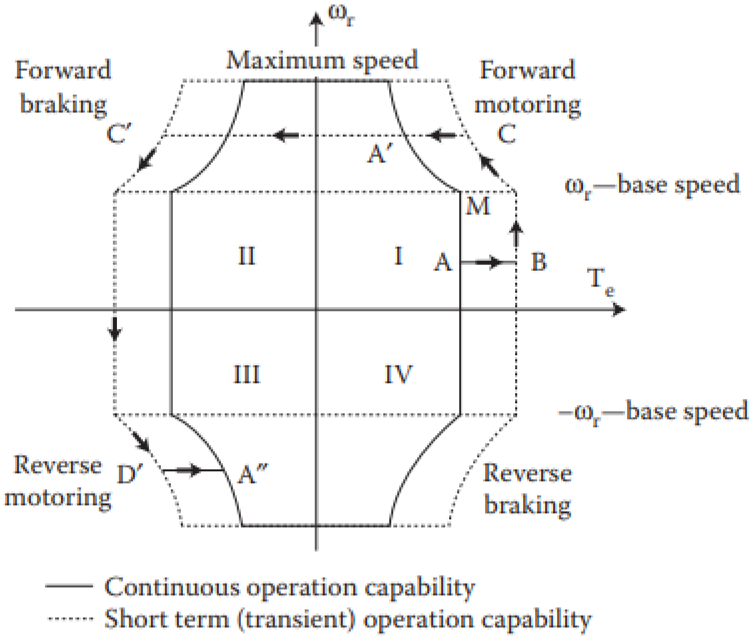

Figure 43:Multiquadrant Operation of IM [12]

As Laplace has famously stated "If we know the initial velocities of all the particles in nature, we can predict the future".

When there are some unknown and undefined disturbances then there must be some feedback put into some comparators to witness the error or the difference for the non-linearity. In many cases both feedback and feedforward are used in tandem. In low frequency feedback systems sometimes used without stability issues. The higher the gain is theoretically a mastered answer for a better control system, but it isn't the case when considered with the dynamics of the systems and other constraints. Every gain is a function of frequency, any natural system will also have a frequency response where there is one more pole than there are zeros.

In simple terms the frequency response is going to roll off at some point. Phase delay is introduced, and signals have phase shifts causing problems or eventually oscillations. We need to find ways to stabilize the system.

Feedback is good for disturbance rejection while feedforward for better handling stability issues and trajectory tracking but also requires system dynamics knowledge. Feedforward is best with known simple trajectory.

Important measures on designing a control system for IM Drive.

1. The Drive must be emulated into a mathematical model and thereafter evaluation and analysis take ground.
2. When disturbances from the external is coming, through optimal regulator the response of the system is obtained.[24]

4.2 Converters

As we can see at the EV System workflow in Figure 29 the final input to the motor is through the converters after which energy is directly put out for propulsion. The Power energy converters (PEC) generally work in form of battery (DC) form the vehicles energy source or from conventional utility supply 50Hz. The prime job of converter is to draw electrical energy from supply as commanded by reference and supply to motor at whatever voltage or frequency necessary to achieve desired mechanical outputs. The parts of a converter are namely the power stage which takes care of the flow to the motor and the control unit which monitors and calibrates the amount of flow into the motor. The quantity that is to be regulated is measured and given back to the controller so that action can be done if the two signals do not coincide. This makes the system clearly a speed control system closed loop because the signal indicating the demand or reference quantity is speed. Power converters have less storage capacity and hence prone to voltage spike leading to enforced delay. Measurements of the motor's location and speed are sent to the controller, and the motor's currents are monitored. And fed back to the drive through measurement. The drive effectively closes the current loop. According to recent industrial trends the AC drives convert AC power into DC and invert DC into variable voltage and frequency three-phase AC power[25].

The inverters are broadly classified as Voltage source inverters (VSI) and Current Source Inverters (CSI) which respectively sends PWM voltage and current waveforms to the load which is the motor.to control the mean output.

For switching control, the drives are inducted with choppers or switching regulators which chops off battery supply on and off. During chopper switch on, there is current flow, but voltage is zero and hence power is zero but due to the high frequency the problem is solved and inductance of motor causes current to be smooth and the mechanical inertia of motor cleans up torque ripples. The switches commonly in use are the bipolar junction transistor (bjt), Insulated gate bipolar transistor (IGBT) and also metal oxide field effective transistors (MOSFET).

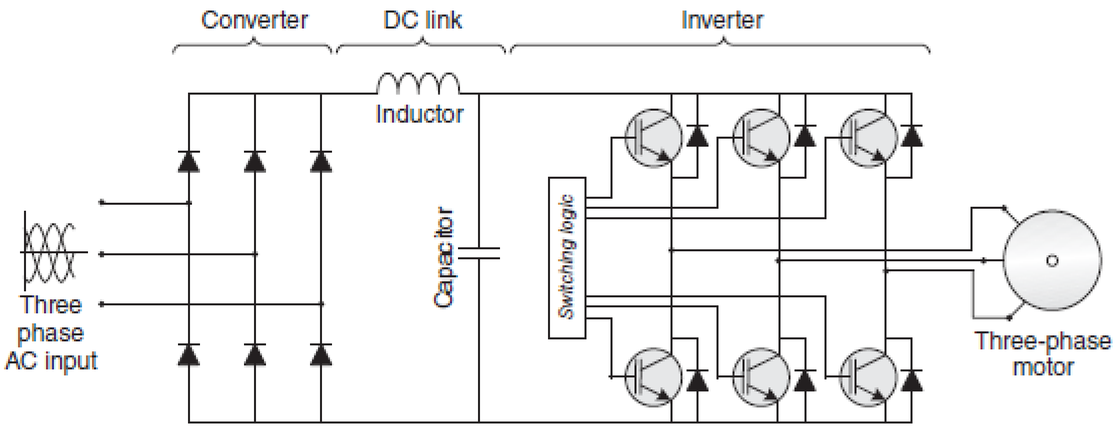

Figure 44 : Converter Block Diagram with PWM[25]

PWM is suited for inertial loads as motors which are not highly succumbed to discrete switching. The resultant waveform grasped by the load must be as smooth as possible. PWM technique is advantageous because power loss in the switching devices is very low when compared to other comparable methods. Power loss is classically the product of voltage and current and thus in both cases of switching on/off, it is zero. PWM also suffices well with digital controls which because of their on/off nature, can be easily harnessed to set the required duty cycle. To simulate switching frequency in Simulink, a sawtooth comparator is used, and frequency is considered equivalent. To convert square waves from inverters a time averaging is used to generate sinusoidal waveforms of voltage. [25]

Simply switching patterns leads to switching performance. The percentage of time the FETs or Switches are turned or written high is known as the duty cycle percentage. We control current between zero Amperes to

(V_{supply}/Resistance) Amperes. The switching is classified again as hard, soft, and complimentary and the current decay rate is highest in the hard one.

The most important points to be considered while initiating PWM is to understand the range up to which voltage control is linear, the switching frequency and also the output harmonics. The numerous PWM techniques in use now namely the sinusoidal, space vector, hysteresis band current control etc. By varying the duration of square wave, a variable output is achieved.

Duty cycle $D = \frac{Ton}{T} * 100$

Sinusoidal PWM

Sinusoidal PWM is the most general technique used in the drives. To generate a PWM signal a reference and a triangular carrier are used as control signals as seen in Figure 45 While the reference signal's voltage and frequency can be adjusted, the carrier signal's voltage and frequency are fixed. The magnitudes of the signals are compared to one another at every instant. The PWM signal is set to 1 (switch closed) if the reference signal's strength is greater than the carrier. If not, it is set to 0. (Switch open). The voltage utilization is given by Modulation Index: $\frac{Vpeak}{\frac{Vdc}{2}}$

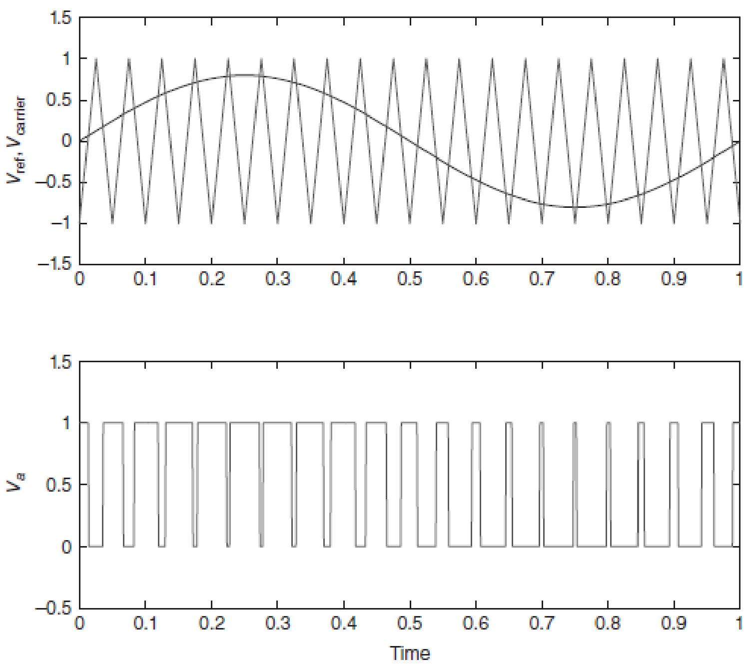

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Figure 45: Sinusoidal PWM

In Sinusoidal PWM, the reference amplitude must be less than the carrier wave for voltages to be linearly modulated. This PWM technique is also known as a carrier based PWM technique since it needs a very high carrier frequency.

Space Vector PWM

Voltage of any angle and magnitude should have to be generated. PWMs control the phase voltages, 120-degree offsets between A, B, C.

SVM creates 6 voltage vector possibilities and 2 null vector state. Sinusoidal operation occurs when a reference vector (V_{ref}) rotates around the d-q axis. To generate voltage vector of any random angle we need to use intervals of respective weightage between the two adjacent vector state. To calibrate the amplitude of the vector we need to use the null states and is determined by the ON states between both the adjacent vectors and the null vectors. Motor only responds to line-to-line voltages and hence the sinusoidal waveforms are given out. In SVM there is 33.3% reduction of switching losses as during null vector one of the phases is not modulating/switching.

The most popular one is the null-alternate reverse sequence where it is alternatively switching between null 0 and null 7. The space vector frequencies are twice that of PWM frequencies. SVM can be generated using Centre Aligned PWM. Another advantage is creation of sine waves with 15% greater amplitude than what we get from Sinusoidal modulation alone. It also depends on the bus size. Out of SV modulation we get Vd and Vq which are the lovely. SVM works well with Volts per Hertz system with magnitude and angle, or it works very well with PWM where rectangular coordinate representation is used. As a rule of thumb PWM signals are greater than 20kHz to avoid audible range

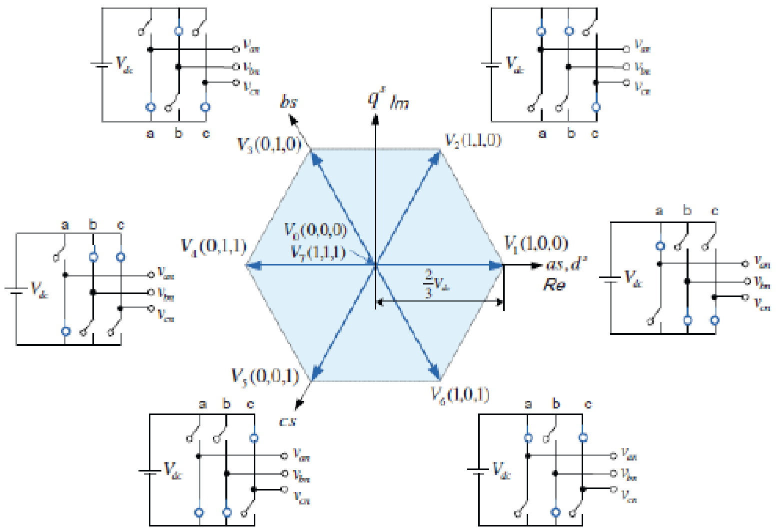


Figure 46 :SVPWM

Overmodulation

The range of linear control of the output fundamental component can be increased by a factor of 1.15 from $V_I = V_{dc}$ to VI = (2/sqrt3) Vdc = 1.15Vdc by either adding a third-harmonic component to natural or regular sampling PWM or by using the space vector modulation technique. Furthermore, the output fundamental voltage for a six-step square-wave controlled inverter is VI = (4/π) Vdc = 1.273 V_{dc}. Entering the nonlinear region of overmodulation, where the modulation controller gain (the ratio between the target reference and the actual inverter output voltage) decreases from 1 to 0 as switched pulses gradually vanish, allows an inverter controlled by PWM to increase its output voltage from 1.15Vdc to its maximum of 1.273Vdc.

In sinusoidal PWM if the carrier peak is lower than the reference and in SVPWM the vector is extruding out of the hexagon then there is nonlinear increase in the variables which is basically overmodulation. The output waveforms include lows frequency harmonics of the fundamental component. There is drop in pulses from the output waveform. In Sinusoidal 78.5% and SVPWM 90.7% the overmodulation region begins.

4.3 Controllers – PID and Cascading Loops

Motion control regimes require quantized control of velocity and position. The most common ones are:[25]

1. Cascaded Velocity and Position loops
2. Single loop PID position control
3. Cascaded with feedforward

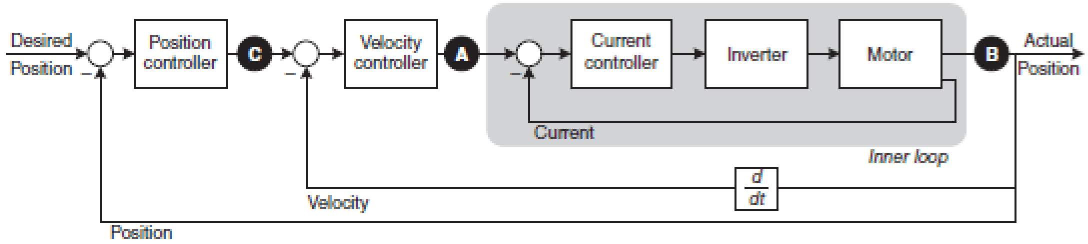


Figure 47Cascaded loop[25]

PID

The proportional. Integral and derivative controller is the most used industrial controller that can a flexible range of control capability and it very reliable. They are the leading control algorithm due to their functional simplicity, which enables engineers to use them in an easy, uncomplicated manner, and to their strong performance in a wide range of operating circumstances.

A mathematical approach to a wide variety of output control scenarios is PID control. PID approaches provide a convenient place to start when implementing a solution whenever a system wants to tune its output based on some input value. From a purely theoretical perspective, a variable (such as pressure, velocity, position, etc.) might be used to define the issue. The process variable (or PV) is the input that is read each period. The SetPoint is the value that we want our control system to achieve and maintain for this variable (or SP). It is helpful to think about the current error at any given time, denoted by the difference between the SetPoint and the process variable, e(t) = SP-PV.

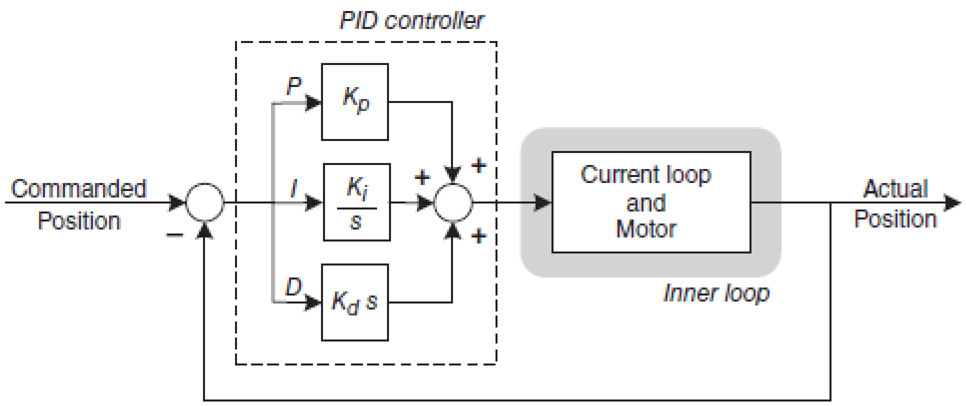


Figure 48 PID Controller[25]

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_p \frac{de}{dx}$$ *Equation 24*

The PID general equation.

In our case and in most of motor control we use the PI controller. The integral component ("I") drives the error to zero, while the proportional gain ("P") provides high-frequency responsiveness and the stability of the loop. We do not use Derivative terms mostly in motor control due to cascaded design techniques. Parallel PI is the most familiar and intuitive one with a integrator and steady state gain. Controller zero is function of both Kp and Ki and there must be achievement of pole zero cancellation in the closed loop frequency response. Due to independent shifting of the Kp, Ki there could be shifting of zero and throw off the frequency. In contrast to this the series PI controller is used where there is recombination of signals from two steady gains. Series PI is better as there is independent control over the controller zero.

When Series PI is used in cascaded current control, loops embedded within themselves. D term isn't required since motor winding has only one pole that is R/L time constant. There is 90 degree of phase shift and there is no requirement for phase lead. The Torque loop is embedded inside of the Velocity/speed loop which is influenced by separate PI controller. The stability analysis is done from the interior loop and further moved onto the exterior ones. The bandwidth is set to be highest gradually from the innermost loop, i.e., the Torque loop. For designing a speed loop, we embed the torque loop inside of speed loop. Feedback is giving the measured velocity to the comparator and is compared to the commanded velocity to generate error signal. Cascaded loop is useful for stability analysis as the closed loop transfer function from the inner loop is used for the open loop expression for the outer loop. Furthermore, the output of the speed loop is the commanded current for the torque loop (current signals) which in turn helps to generate more torque in situations of less speed. Position loop in then further cascaded as the outermost loop with another feedback from the motor signal presenting the measured position. Position control loop without cascaded loop can be attained by the PID. The differentiator allows the system to respond to changes in the error signal, which enhances system stability. We would not want to use a D term as synthesizing it could turn up to be very noisy in the process especially with digital control systems.

D is implemented with the 1/T being on the output and almost like the integrator. The bandwidth of the innermost loop must be highest as it needs to operate with the highest frequency. The bandwidth, also known as response time, of the system is a measure of how rapidly response is seen to the changing input command. This is because the things impacting the current loop are related to the poles of the plant or the motor setup which are typically the R/L time constant is going to higher than the mechanical poles. The things effecting the velocity loop are inertia, torque on the motor. The velocity and position loop are run at same sampling frequency but with lower bandwidth. The mechanical poles of the system are much lower and hence can suffice to the lower frequency. The electrical poles or time constant is higher in comparison to the mechanical ones hence there is less bandwidth. When there is pole zero cancellation, we end up with a first order system. When we end up with complex poles there is peaky resonant effect.

Current PI Controller Coefficients

Tuning a PI Loop for motor control system can be deterministic. Damping factor in ranges of 3-10 give out good response and there is no oscillator formation, then it eventually leads to a good response. There is also sometimes wind-up effect leading from the integrator in the PI control loop. It analogously referred with the winding out of a compressed spring and due to inertia moving back and forth. It is caused due to very high frequency transience.

We can deal with wind-up by using something called as integrator switching which leads to getting rid of steady state error. Steady state error is a problem only when we start getting closer to the trajectory. Hence, we can only use it as the landing lights. We need to be careful with the discontinuities. More preferred technique is the integrator clamping where there are upper and lower limits provided for the integrator. More commonly the saturation limits are taken. While the system follows sinusoidal inputs with frequencies below the bandwidth frequency quite effectively, inputs over the bandwidth frequency are muted by a factor of 1/10 or more.

Basic PI tuning as stated in [25]:

1. Set Kp to 0, Ki to 0, and Kd to low.

2. As an input instruction, use a square wave to move to the desired place.

The theoretical step input is expressed by a square wave.

3. Gradually raise Kp until the result reaches the square wave input target without oscillations and with a 10% overshoot.

4. Increase Kd to as close to or to a critically damped response by removing the overshoot as much as possible.

5. Maintain the critically damped response while gradually building up Ki. Keep overshoot under 15% if it is noticed.

It is tricky to tune the integral gain since it can overshoot even with little Ki inputs. Integrator saturation will provide a large integral signal that will cause oscillations or a large overshoot.

Therefore, it's crucial to avoid integrator saturation.

4.4 Variable Frequency Drive

The primary control for AC drives/IM drive is the variable frequency drive. It is used to run the motor in variable speeds or let them ramp up their speed to give them a smooth start-up. They give us wide range of control, save energy, and also reduce maintenance. The VFDs could also be called an inverter or adjustable speed drives. They are used to control and monitor AC Motors in their full range of working and diminish changes of faulty performance leading to stalling. VFDs completely help to eliminate mechanical speed flow and pressure control systems which may pose a threat as failure points and are also difficult to regulate.

The energy savings for the drive is also possible in terms of the affinity laws.

1a. Flow is proportional to shaft speed.

1b. Pressure or Head is proportional to the square of shaft speed.

1c. Power is proportional to cube of shaft speed.

The motor rotational speed is function of the motor frequency. The incoming electrical frequency is a constant which in Europe is 50Hz. The component in the drive comprises of rectifiers which allows electricity flow and converts AC to DC, generally operated by unidirectional diodes. The next is the DC bus which is the carrier or the common communication pathway where capacitors are imbibed to filter ripples and produce smooth voltage waveforms and finally before the corrected voltages go into the motor, they are inverted using switches like IGBT (Insulated gate bipolar transistor) and the direction along with the frequency of output is controlled. Charged DC Bus Capacitors also act a storage tank for the drive. Capacitors store electrical energy in the form of voltage. There is also a DC link choke at times. IGBTs also allow current flow in regenerative situations in the opposite way of the general current flow. Next there are also the DCCT (Direct Current Current Transformers) which monitor the output current going to the three phases going to the motor. IGBTs work on PWM and defining duty cycle. The rate at which IGBT switching occurs is known as the carrier frequency and this can be adjusted if needed to be done to have cleaner and more sinusoidal waveform. The motor will henceforth generate less crumbling noise but at the cost of higher heat generation in the IGBTs. The striking reason of extra noise when motor is connected to drive rather than a line is due to the carrier frequency calibrations.

In laymen language IMs are basically elaborate inductors and they care about current, wanting to smoothen current waveforms.

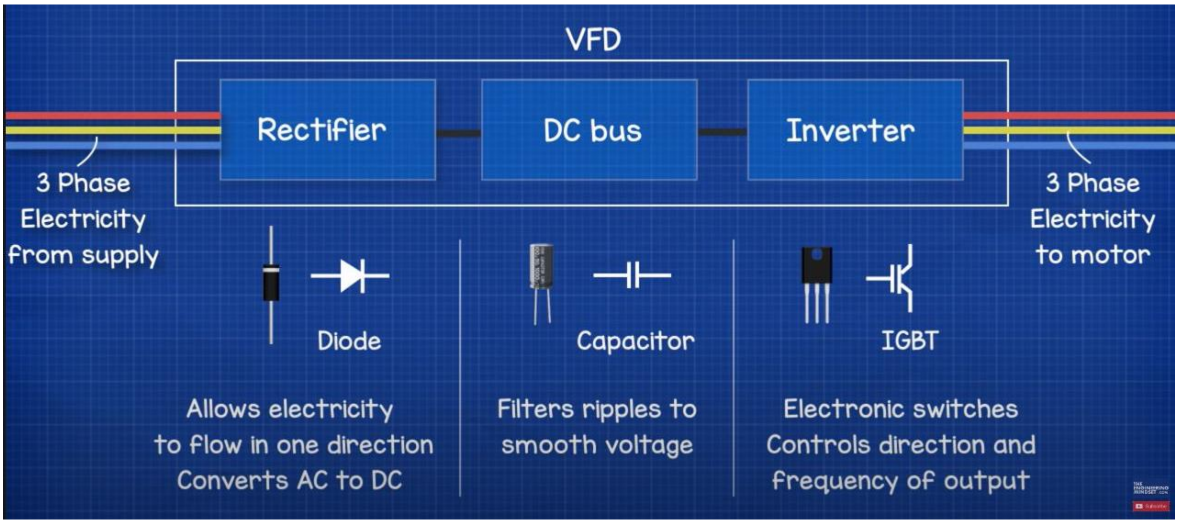


Figure 49: Variable Frequency Drive [6]

4.5 Types of Control

On discussing the control applied to AC Drives. We can now see the control methods for the powertrain drives. The elaborate classification can be found in Figure 50.

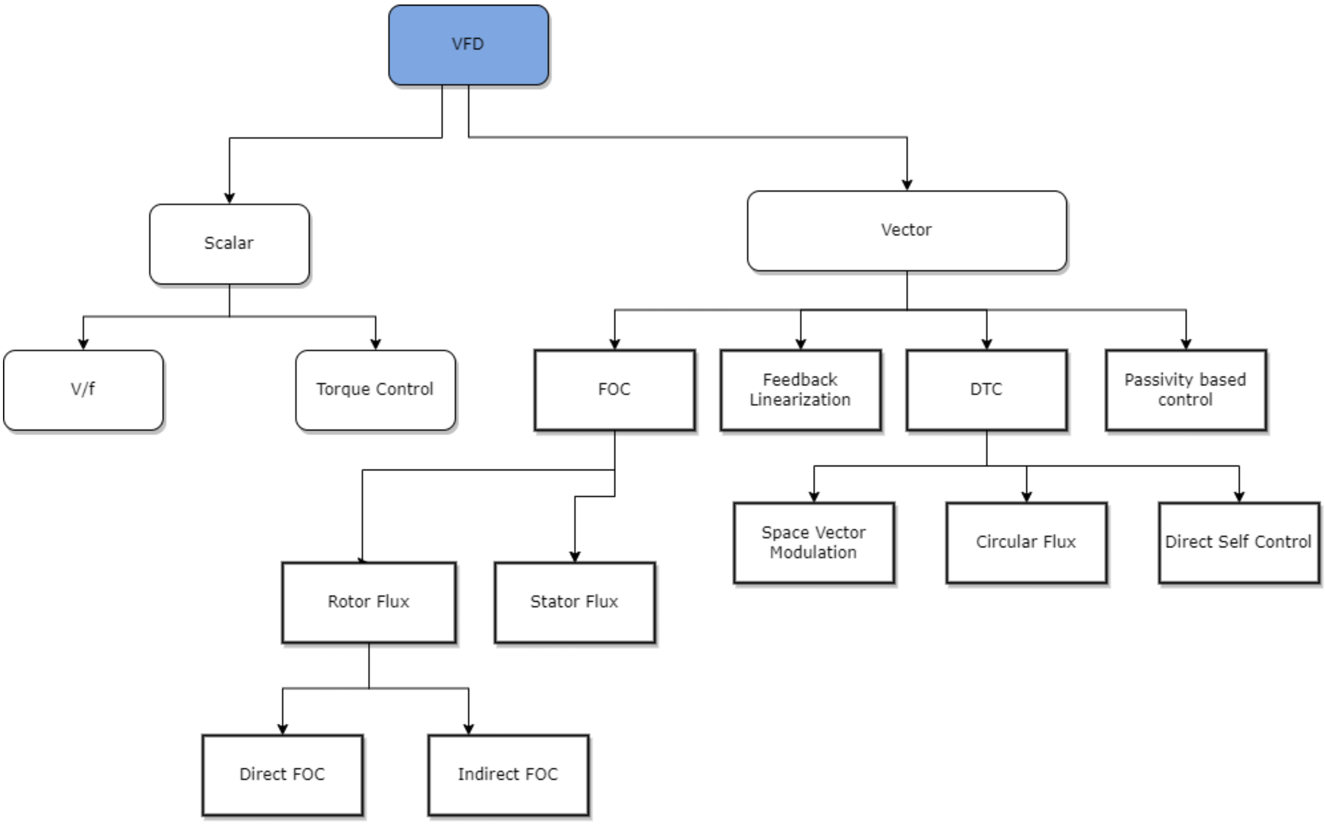


Figure 50:Types of Control[26]

[6] Taken from video: https://www.youtube.com/watch?v=yEPe7RDtkgo

The classification is based on two primary divisions which are Scalar and Vector Control. The most prominent ones being Field Oriented Control and Direct Torque Control with general usages of V/f open loop as well at times.

Not all the methods are to be discussed in detail, but the basic understanding are to be presented. The Induction motor behaviour is considered steady state when supply voltage and frequency are constant.

4.5.1 Scalar Control

The magnitude of the flux wave (B_m[7]) is proportional to the winding m.m.f and is thus proportional to each phase current I_m. But the primary objective stands to be knowing the flux density dependency on the supply voltage and frequency since we can initiate control over these. We know that the pole numbers are inversely proportional to the field rotation speed. Now if we represent the induction motor as a simple equivalent circuit as shown in Figure 51, we see applied alternating voltage V and an alternating EMF E is induced which is opposing the applied voltage.

Applying Kirchoff's Voltage Law

$$V = I_m R + E \qquad \textit{Equation 25}$$

ImR represents the winding resistance and is negligible and hence

$$V \propto E \qquad \textit{Equation 26}$$

But again, EMF proportional to Bm hence $B_m f \propto E$ *Equation 27*

And finally combining them $B_m = k\frac{V}{f}$, and this forms the basic for the scalar V/f control when in simple words voltage sets the flux. The constant k depends on the number of turns per coil, number of coils per phase and distribution of the coils.[4]In order to improve the control on the scalar system the open loop can be turned into a closed loop by using controllers to measure the rotor slip speed which can again in turn be added to feedback speed and eventually reference frequency attained is input to voltage controller which sends corrected voltage to inverter. It follows that if we set

[7] m denote magnetizing

up the voltage supplied by the inverter to vary in direct proportion to the frequency, the flux wave will have a constant amplitude because the amplitude of the flux wave is inversely proportional to the frequency and proportionate to the supply voltage. This straightforward mode of operation, in which the V/f ratio is constant, served as the foundation for the control technique used with the majority of inverter-fed induction motors for a long time, and it is still used in a few commercial products today.

Conventional wisdom holds that the inverter should be able to keep the "V/f ratio," or rather the flux, constant up to the base speed (often 50 or 60 Hz), but that at higher frequencies it should be expected that the voltage would remain constant at its highest value. Accordingly, the flux is maintained constant up to base speed, but once passed that point, the flux decreases inversely with frequency. As we will see, the performance above base speed is obviously negatively impacted.

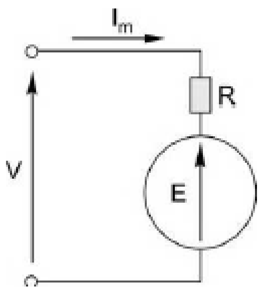


Figure 51:Simple Representation of Induction Motor[4]

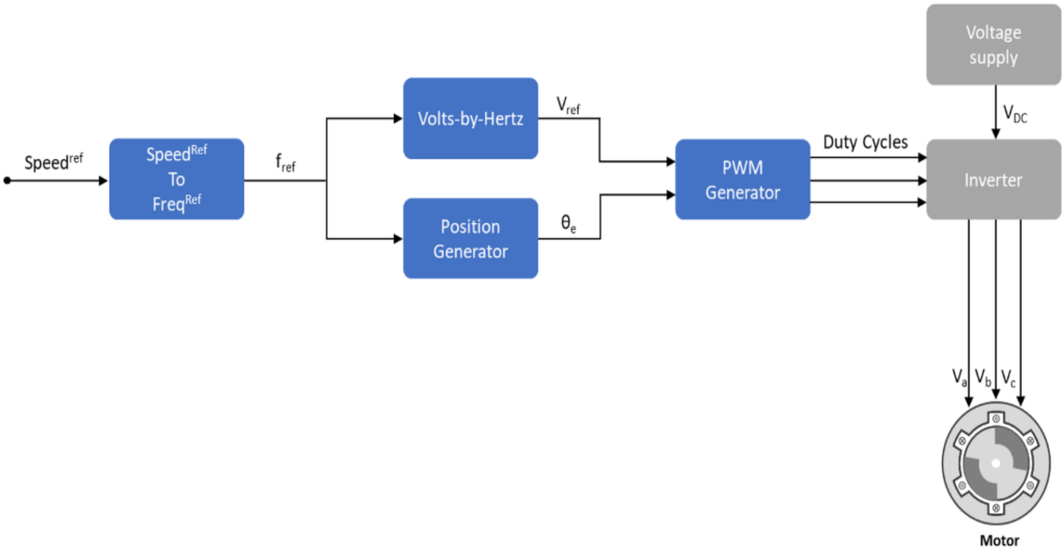


Figure 52 : V/f control scheme

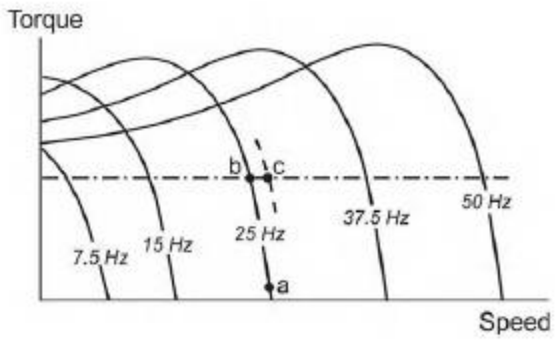


Figure 53 : V/f-controlled Torque-speed [4]

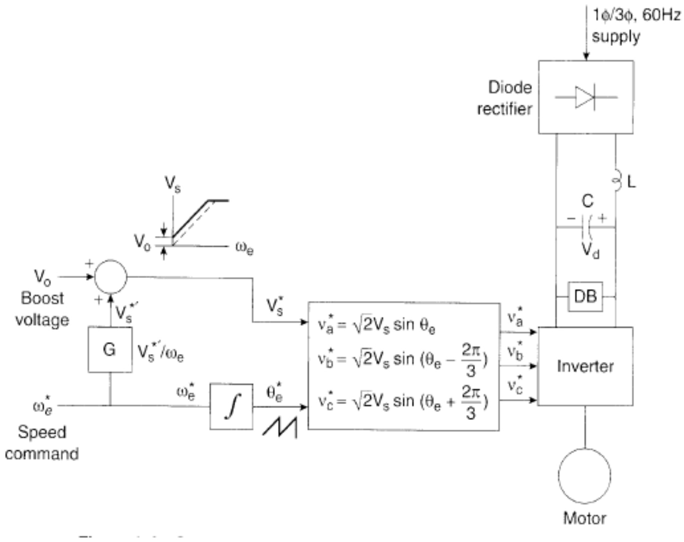


Figure 54 Open loop V/f speed control with voltage-fed inverter[5]

We also observe that, except for low frequencies, where the voltage drops over the stator resistance becomes extremely significant as the applied voltage is decreased, the pull-out torque and the torque stiffness (i.e., the slope of the torque-speed curve in the normal operating region) are essentially the same at all points below base speed. Therefore, a simple V/f control system would experience dramatically decreased flux and consequently, less torque at low speeds. A method known as voltage boost is described in [4] which is used to improve low frequency performance by increasing v/f to regain flux. For induction motors, the scalar control method causes oscillations in the output torque. Consequently, a better control strategy is required for induction motors in order to obtain greater dynamic performance. Hence Scalar control as is self-explanatory by its name is due to variation of control variables only and eliminates coupling effect of the Induction Motor. Summarising it voltage defines flux and frequency/slip defines torque[5] Furthermore, we now discuss the most talked about and general control method the Field Oriented Control and the Vector Control Modes.

4.5.2 Vector Control

Whilst Scalar control was good enough for steady state response. When turning to the transient states which we have tried to emulate in the thesis, the scalar v/f control is inadequate. Hence for good precision and dynamics, vector control was proposed for closed loop feedback controls at the beginning of the 1970s initially for IMs and then for synchronous machines as well. The discovery that an induction motor can be controlled as a separately excited DC motor has led to a rebirth in the high performance of induction motors. The two types of FOC are Direct or Feedback FOC and Indirect or Feed Forward FOC proposed by F.Blaschke and Hasse respectively. [27]

As it is self-explanatory in the name if we orient the fields in the motor all kinds of magical and crucial things could happen in turn leading to motor functioning to its best possible ways. Blaschke harnessed the idea of using rotating synchronous frames to have the control over the AC Induction Motors. Prior to this crucial intervention in the field of motor control the sine waves had to be self-generated in stationary frame and find relation on how the sine waves relate to the flux of the motor.

The FOC comprises of vector-based control of the stator currents. This control is based on projections that change a three-phase, speed- and time-dependent system into a two-coordinate, time-invariant system (d and q coordinates). These projections result in a structure resembling a control structure for a DC machine. The torque component (aligned with the q coordinate) and the flux component are required as two constants as input references for FOC machines (aligned with d coordinate). The control mechanism manages immediate electrical quantities because FOC is just based on projections as in Figure 55. As a result, the control is precise in all working operations (steady state and transient) and is not dependent on the mathematical model with a finite bandwidth. As a result, the FOC resolves the issues with the conventional schemes:

1. The provision of getting constant reference in the torque and flux components of stator current.

2. It is easier to apply direct torque control with regards to the reference form.

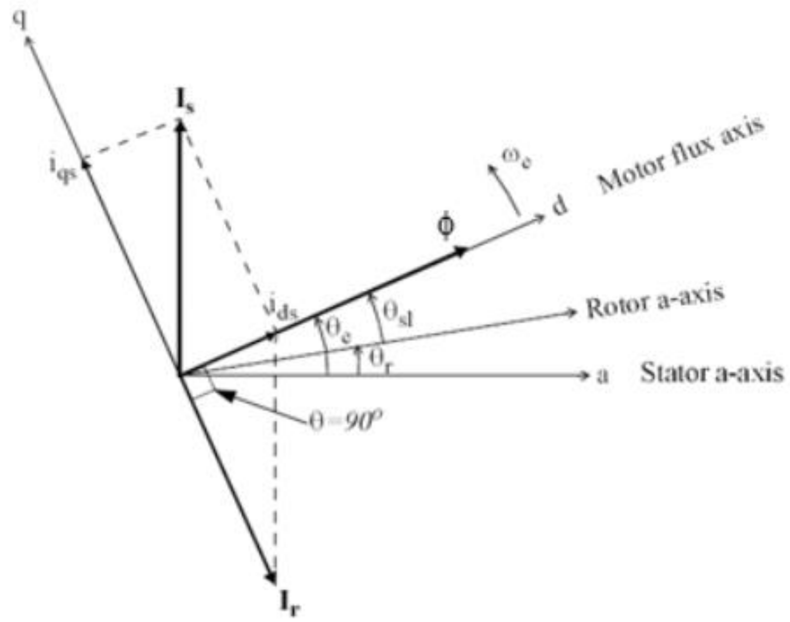


Figure 55 Vector Control Diagram for FOC[28]

There are some drawbacks to FOC as mentioned in [27] which are requirement of coordinate transformations, parameter variations cause issues, current controllers, PWM modulators[8], switching frequency losses, rotor position measurement etc. We sample our currents in the stationary reference frame and generate phase c from negative of a and b. Lump all transforms. We end up with vector representation of current waveforms with a component directly aligned with rotor flux and another which is quadrature to the rotor flux. Those are regulated to generate correction voltages and then reverse park Clarke[9] and 3 phase stationary frame voltages which is applied to motor windings. Resolution of rotor flux angle measure should be under 3-5 degree.

DFOC

In DFOC the field angle or flux is determined by feedback that is calculated by using terminal voltages and currents or flux sensing windings and rotor speed. Unit Vectors are generated by stator voltages and currents using model estimators. There are few drawbacks that it is dependent on rotor resistance value and computational delay and processor requirements due to estimator loops and transformations. Using a hall-effect sensor, a search coil, or other measurement methods, the direct FOC establishes the orientation of the air-

[8] As discussed in the previous chapter
[9] As discussed in the previous chapter

gap flux. However, utilizing sensors is costly since unique motor modifications are needed to install the flux sensors. In addition, the rotor flux cannot be directly sensed. Due to the stator resistance voltage drop's dominance in the stator voltage equation and fluctuations in flux level and temperature, computing the rotor flux from a directly detected signal may be inaccurate at low speeds.[27][24][5]

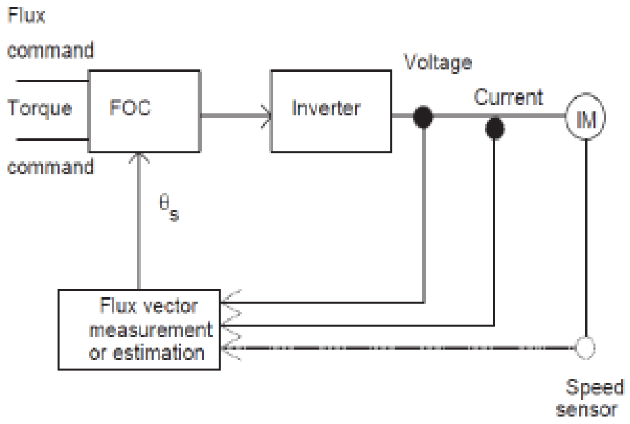


Figure 56Direct FOC [29]

IFOC

Indirect FOC is also pretty laymen and is similar to Open Loop V/f wherein only adding d-q current feedback and vector block turns it to IFOC. The IFOC technique rotor flux angle is obtained by using rotor position measurement and machine’s parameter estimation. For managing ac devices like induction motors and synchronous motors powered by inverters, field orientation has become a potent instrument. Complex field-oriented control functions are carried out by intelligent controllers using microcontrollers or digital signal processors (DSP), considerably lowering the amount of control hardware required. Making the motor parameters in the field-oriented controller match the actual motor parameters is a crucial step in obtaining effective control performance. In Indirect FOC there are two control loops namely outer and inner control loop. The outer control loop is the speed control loop, and it sets a required torque setpoint and this torque setpoint is taken as the reference value for one of the inner control loops which controls the current Iq. The precision of the control gains, which in turn significantly rely on the motor parameters assumed in the feed forward control algorithm, is the fundamental shortcoming of the indirect technique, even though it can get close to the performance of the direct measurement scheme. [24] [27][29]

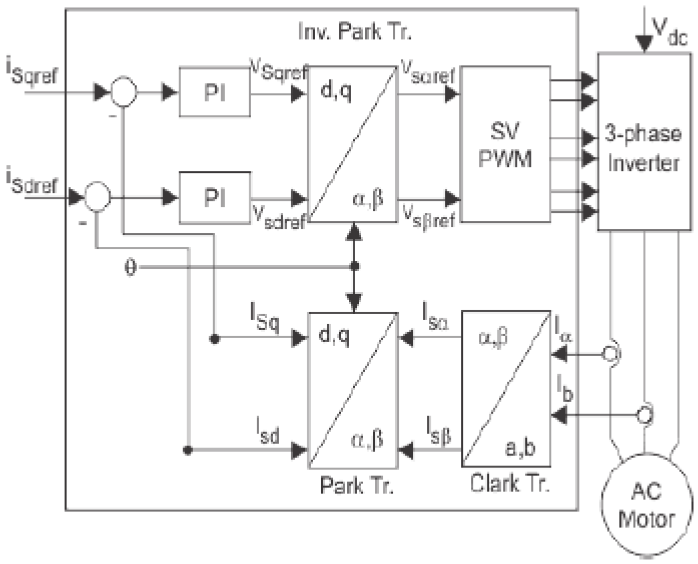


Figure 57: Indirect FOC [29]

Direct Torque Control

Many academics have been interested in "induction motor control techniques" in recent years to discover various approaches for induction motor control that have the qualities of precise and quick torque response, as well as a reduction in the complexity of field-oriented control. It has been acknowledged that the Direct Torque Control (DTC) technique is the most straightforward and practical way to meet these needs. DTC is among the best and most effective induction motor control techniques. The goal of this technique, which is based on decoupled control of torque and stator flux, is to effectively regulate the torque and flux. It is one of the control techniques that is now the subject of the most active research. The DTC has no separate voltage or frequency defined pulse width modulators. [24][29]

The report presented by ABB shows the advantages in DTC and how it is proving to be so [30]. The basic functions described according to them is that a motor model that uses measurements of the two motor phase currents, the intermediate circuit dc voltage, and knowledge of the status of the power switches to estimate the real torque, stator flux, and shaft speed. Every 25 microseconds, calculations are made, including ones that account for saturation and temperature effects. An identification run, performed during commissioning, establishes the parameters of the motor model. a two-level hysteresis controller in which the motor model's computed real values are put compared to the torque and flux references. The stator flux is typically maintained at a constant value, and the motor torque is managed by the angle y between the stator and rotor flux. Finally, A controller's outputs are converted into the proper directives for power switching devices using optimal switching logic. The two-level voltage source inverter has six voltage vectors and two different types of zero-voltage vectors available, and the optimal switching logic chooses the appropriate one every 25 microseconds. Further additional options as described by them could also be flux reference, speed control, switching frequency reference and torque reference chain.

Advantageously DTC makes it possible to turn on an inverter for a spinning motor regardless of the direction of rotation or the motor flux levels; this is helpful for straightforward applications like a fan drive. The noise levels of DTC-controlled drives are better than those of standard PWM; they tend to be "white noise" without the potentially disruptive noise from pulse width modulation and fundamental frequencies. [30]

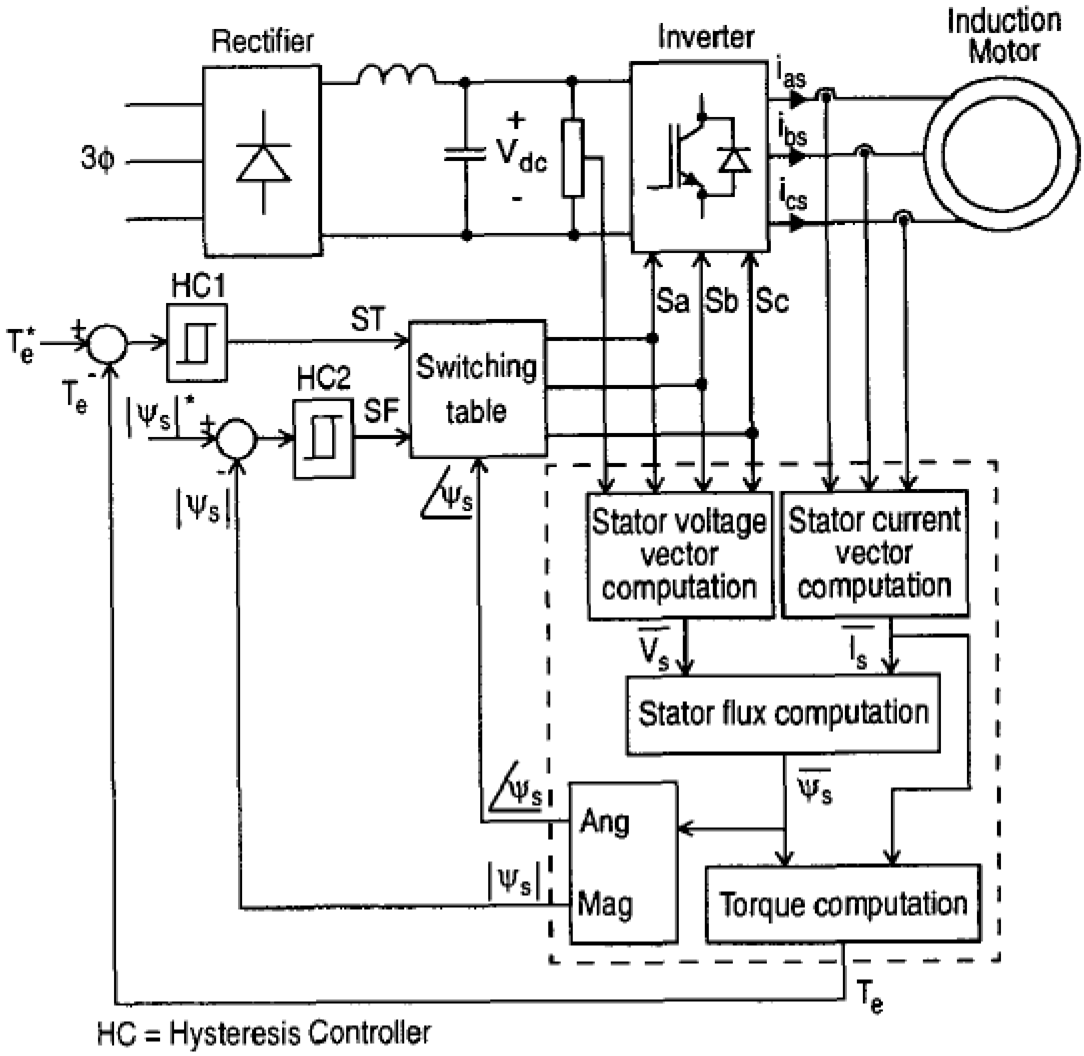


Figure 58 Conventional DTC Scheme with Hysteresis controller

4.6 Performance Evaluation of Motor Controls.

We need to evaluate the performance of the control techniques we used in our electric drives. Firstly, we need to minimize the supply current usage and deplete other losses such as copper loss, iron loss, hysteresis and eddy current losses which also partially depend on the copper quality or principal material enhancement. The rated velocity and the maximum velocity region must be evaluated to attain maximum performance and energy efficiency as depicted in Figure 59. The Performance could be evaluated for the speed range at which the drive can maintain constant power within limited values of voltage and current.

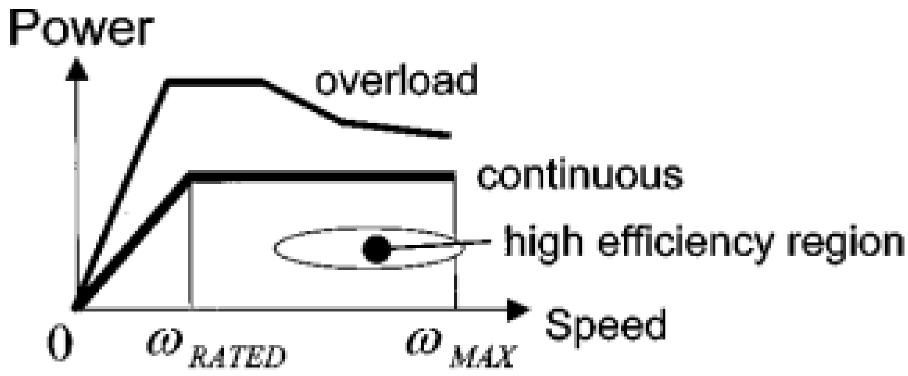


Figure 59: EV Drive Efficient Area.

The rated values for maximum voltage and current must be used. so that the motor can be protected from short-term, greater currents. Through the vector control method, torque and field are easily regulated. Speed can be increased by decreasing flux. Efficiency is lower compared to brushless permanent magnet motors because of rotor winding losses. Induction motors have a low power factor as a result. Using two inverters will enhance the constant power region. By minimizing rotor losses at low speeds, double fed induction motors can give superior performance. However, with a vector control, the torque constant is equal to the back emf constant, so a small inductance indicates a tiny pull-out torque. Reducing the stator coil's number while raising the coil current density is one way to reconcile these contradicting criteria.[10]

High Gains and Long Phase Shifts don't go well together. Example of a shower system could be used which has long delays for water to pour out from the heating system through the outlets. Transfer function for feed forward compensator should be considered as the reciprocal for plant transfer function. Real Feed Forward example could be PWM Modulation, using modulation to create desired duty cycle. The probable solutions to solve ripples at low frequency riding on the PWM Envelope and then phase voltage gets effected is by running them through integrator or RC filters. A much better solution hence would be feed forward without any phase delays and eventual stability issues. Hence feed forward compensation could be useful to get the exact waveform without ripples.

Chapter 5 Experimental Procedures

The data collection for different operation regimes were carried out in VTP Roztoky under viable experimental conditions.

The Motor Parameters given were.

- Maximum Power: 28kW
- Nominal Frequency: 100Hz
- Nominal Voltage: 180V, Star Connected Y
- Stator Resistance: 0.016 Ω
- Stator Leakage Reactance: 0.091 Ω
- Stator Leakage Inductance: 0.14mH
- Rotor Resistance re-calculated to stator: 0.018 Ω
- Rotor Leakage Reactance: 0.126 Ω
- Rotor Leakage Inductance: 0.20mH
- Magnetizing Inductance: 2.9mH
- Phase to Phase voltage: 180 V
- Nominal Current: 125A
- Poles: 4
- Nominal revolutions: 2850 rpm
- 1200 rpm is resonance, which is critical resolution of test bench.

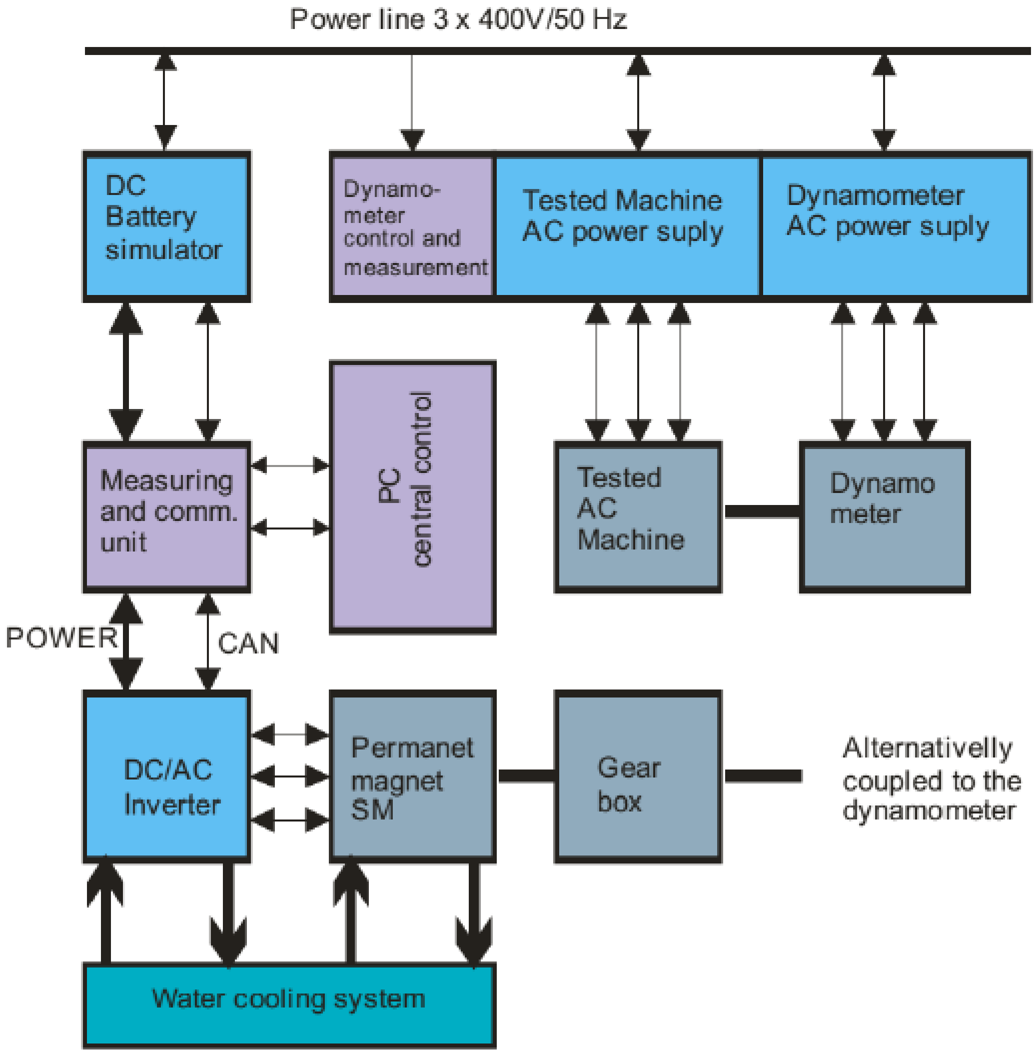


Figure 60 : Block Diagram for the test bench

5.1 Data Collection explained.

There was static as well as transient modes of data collection. Performing closed loop on test not possible but the validation in software turns out to be closed loop FOC.

During the static mode the v/f open loop control was used where the voltage and frequency were changed keeping the value of v/f stagnant at nominal 1.8.

To determine optimal working regime, we also considered values other than 1.8 to check efficiency.

During the transient operating regimes, there were certain operating conditions in which skips were arranged keeping certain values constant and changing the others. We first used the manual control to step up the voltage followed by the frequency to some value and later reset them to their initial values respectively.

While stepping down as well first the frequency was reduced followed by the voltage, this ensures there is no harm to the test setup.

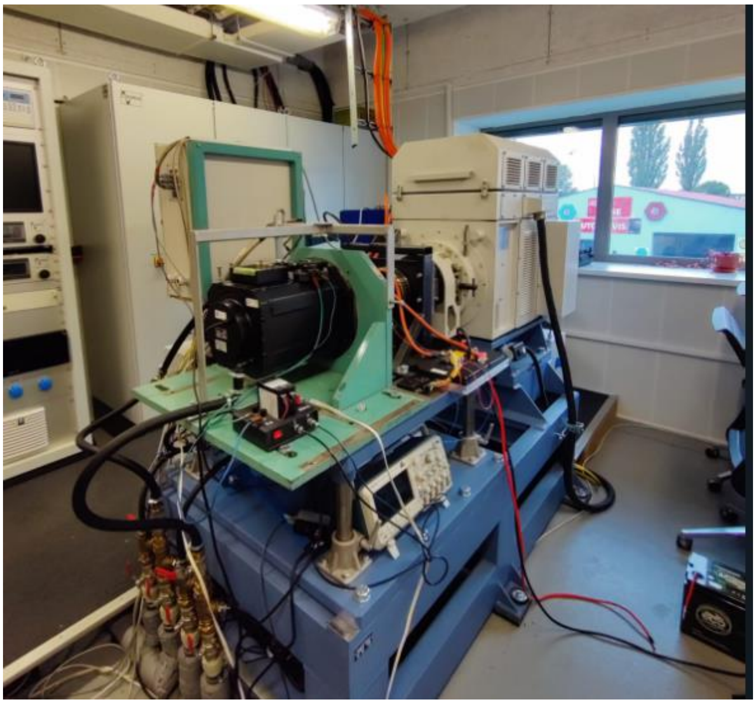


Figure 61 : Motor Test Bed

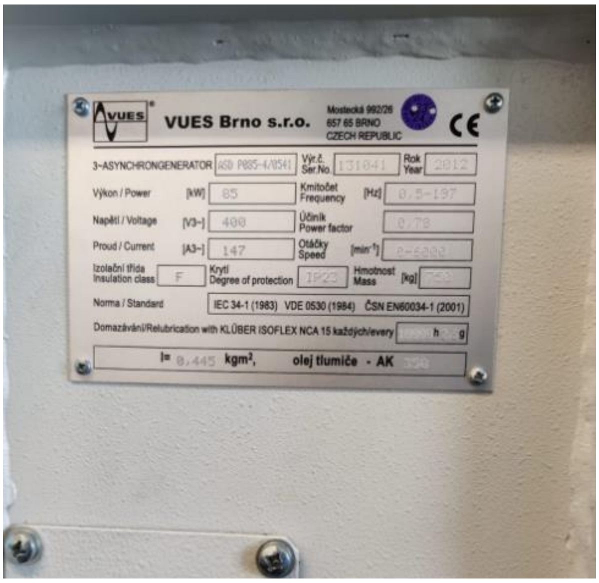


Figure 62 Dynamometer data

Figure 63 Emerson Control Unit

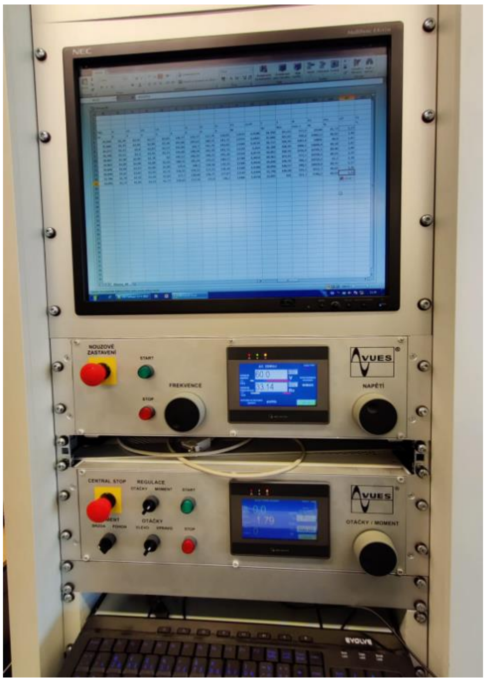


Figure 64ASMOT M4 control system

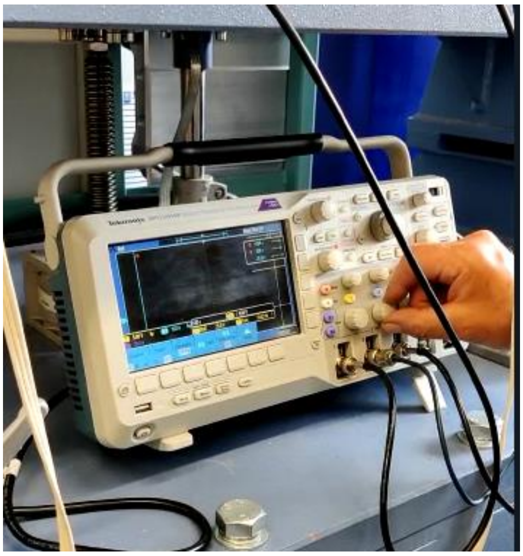


Figure 65 Oscilloscope Tektronix DPO 2004

Chapter 6 Model of Analysed Drive and Analysis

This Chapter deals with the Data Processing and Simulation in Simulink. To gather up understanding I referred to most of the whitepapers developed by MathWorks to be more accustomed to the environment. The Drive yet again could also be used for variable operating conditions and calibrated in terms of parameters and other load conditions. The controllers used are PI as the need for them is elaborated in the previous chapter. The observers are also used in the model as it is an essential part of the FOC algorithm. We have pursued the IFOC due to its robustness and attainable accuracy and provide good control.

6.1 Simulink Explanation

The Model is also framed using the Motor Control Block set for which their whitepapers and video lectures were useful.[28, 31–35]

The primary idea in accordance with FOC is to determine the rotor flux angle and here in the model position generator is being used along with space vector generator which generates the PWM corrected waveforms.

The mechanical slip speed of an induction motor—the difference between its synchronous and rotor speeds—is calculated using the ACIM Slip Speed Estimator block. The block outputs the induction motor's computed slip speed and accepts reference values for the d- and q-axis currents.

$$\omega_{sl} = \left(\frac{L_m \, i_{sq}^{ref}}{\tau_r \lambda_{rd}}\right) \quad \textit{Equation 28}$$

$$\Theta_e = \int \omega_e . dt = \Theta_r + \Theta_{slip} \quad \textit{Equation 29}$$

The equation for slip speed.[10]

The position generator in MathWorks generates a position ramp signal identical to the voltage waveform as reference. It is recommended to use fixed discrete solver to enable code generation and ensure accuracy. The model can be calibrated and changed for different speed measurement techniques and other PWM techniques. The voltage source inverter is the most beneficial to be used. The constructed diagram for modelling is shown in Figure 66 Reference model

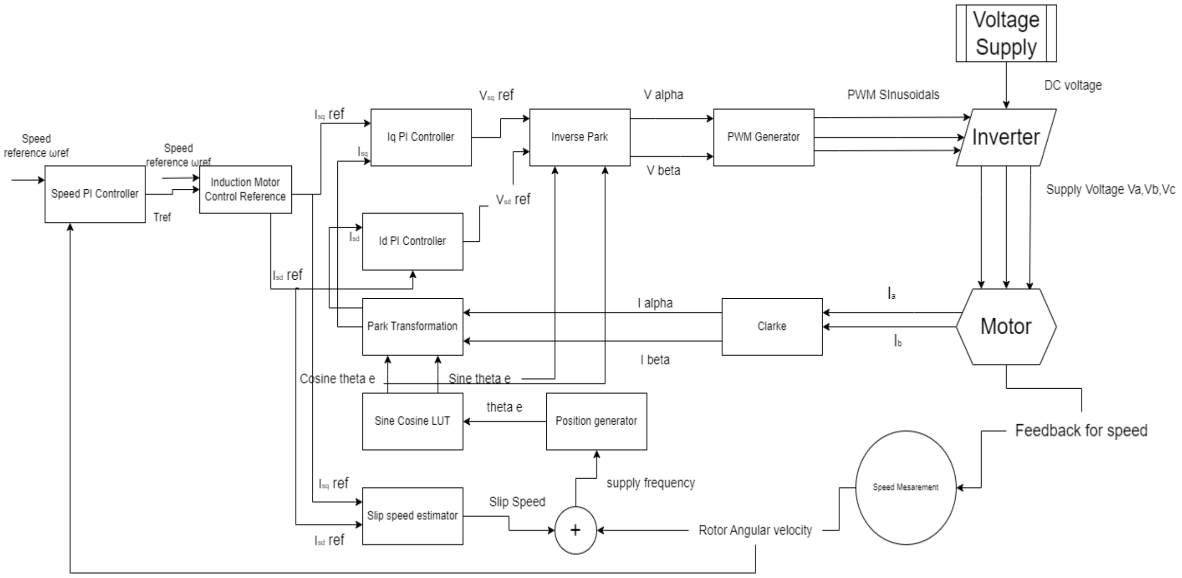


Figure 66 Reference model architecture

6.2 Challenges

While designing algorithms or implementing them numerous challenges were to occur, prominent ones are:

1. High Fidelity Motor Model
2. Motor Controller Design and Inverter Switching Frequencies
3. Loop Tuning and Bandwidth issues
4. Current Control.

[10] Source: https://www.mathworks.com/help/mcb/ref/acimslipspeedestimator.html?searchHighlight=Slip%20speed%20estimators&s_tid=srchtitle_Slip%20speed%20estimators_1

5. Measuring rotor flux angle errors due to minimal calibration.
6. Rapid Control Prototyping which is here out of scope.

6.3 Datasets

For Optimal Working regime targets:

1. Working area where I/T should be minimum.
2. Role of supply voltage U_1 and its frequency f_1 .
3. The rotor frequency $f_2\, optimum$ determines achievable torque and stator current.
4. Electromagnetic torque and given current I_1

$$T = \frac{1}{2} p m_1 |I|^2 L_1 (1 - \sigma) \quad \textit{Equation 30}$$

$$f_{2opt} = \frac{R_2}{L_2} \quad \textit{Equation 31}$$

$$f_2 = f_1 - \frac{N}{30} \quad \textit{Equation 32}$$

$f_2\, is\ the\ rotor\ current\ frequency\ Hz, f_1\, is\ the\ stator\ voltage\ frequency, N\ is$

All the datasets that have been used and studied have been attached as Annexure:

For understanding optimal regime in V/f control we had kept the constant value of 1.8. For example, 180V/100 Hz; 144V/80Hz; 97V/54Hz running at 1000rpm. Next for 2000rpm 120V/66.6Hz. Next up the optimum was analysed for different value of V/f.

For Transient, the skips have been arranged in incremental order to defined revolutions and then again skipped back to observe the transience in Oscilloscope and collected records.

After calculating the I/T values for each revolution from 1000-3500rpm at constant torque of 100Nm. I selected the minimal I/t value points for the optimum operating range on the drives.

U (V)	I (A)	P1 (W)	cos phi	f1 (Hz)	T (constant)	N(min-1)	P2 (W)	Eff (%)	I/T (A/Nm)	U/f
61,72	136,63	12060	0,8258	33,095	101	921,7	9748,5	80,83	1,35	1,864934
97,47	135,84	18410	0,8028	52,178	101,01	1500,8	15875,1	86,23	1,34	1,868029

120,16	134,09	22040	0,7769	63,441	101,06	1845,8	19534,1	90,1	1,326836	1,894043
150,13	136,56	28360	0,7981	81,485	101,01	2385,6	25234,3	89,04	1,35	1,842425
179,7	136,1	34230	0,802	98,981	101,28	2901,8	30776,5	90,6	1,34	1,8155
180,96	143,2	36970	0,8304	108,9	101,55	3476,2	33829,8	90,77	1,41	1,661708

- I/T vs f2 (rotor frequency for the different revolutions)

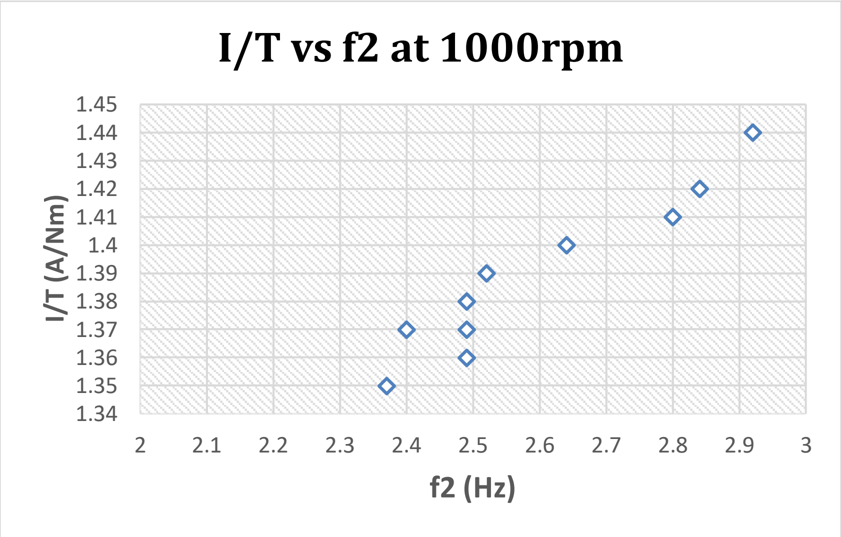


Figure 67: I/T vs f2 at 1000rpm

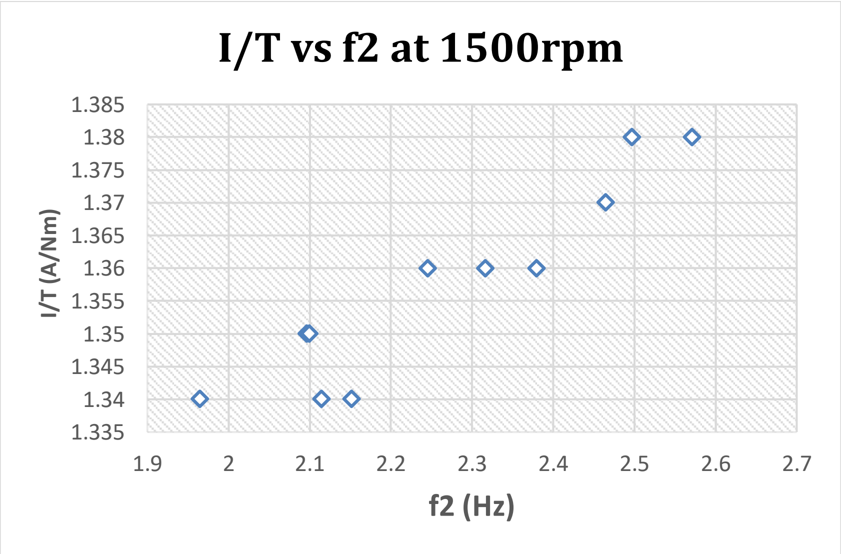


Figure 68 : I/T vs f2 at 1500rpm

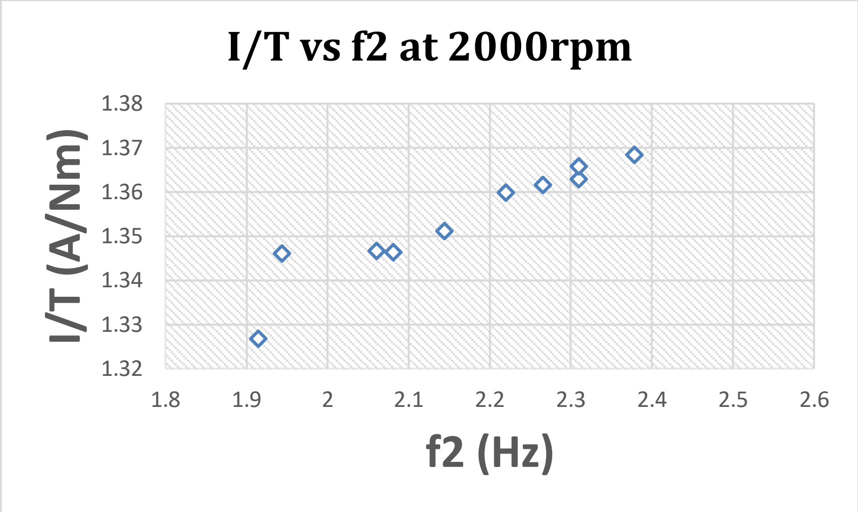


Figure 69: I/T vs f2 at 2000rpm

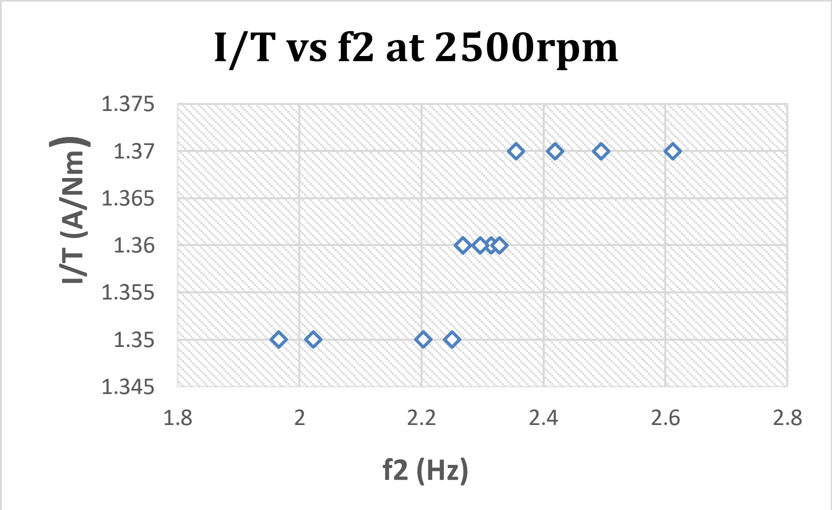


Figure 70 : I/T vs f2 at 2500rpm

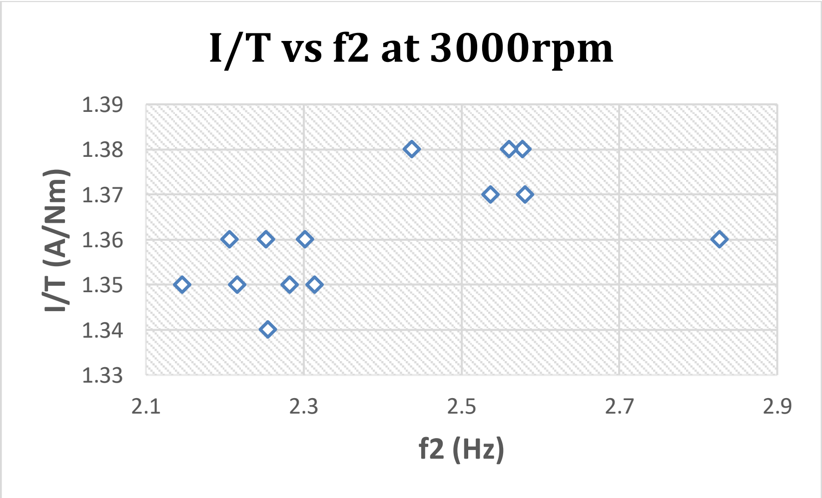


Figure 71: I/T vs f2 at 3000rpm

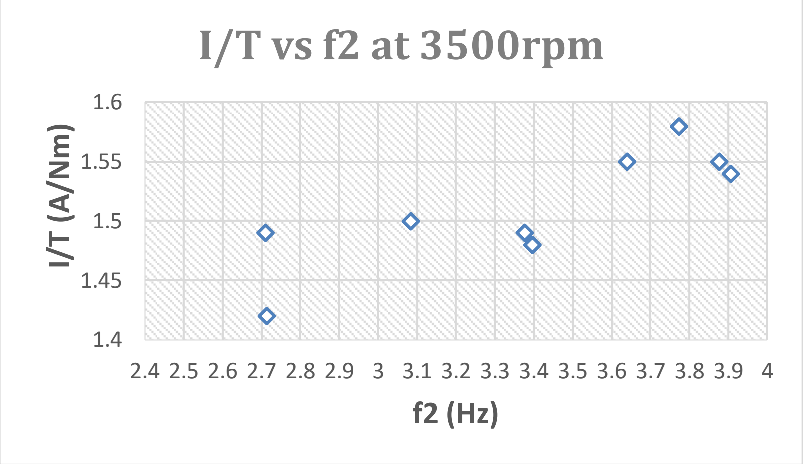


Figure 72: I/T vs f2 at 3500rpm

From Comparing the I/T with f2 which is the rotor frequency in the range of revolutions from 1000 to 3500rpm it is observed that for the minimum value of Supply current I, f2 is observed to be around 1.9 to 2.7 Hz.

- Max P1/T vs f2 for 1000rpm,2500rpm and 3500rpm

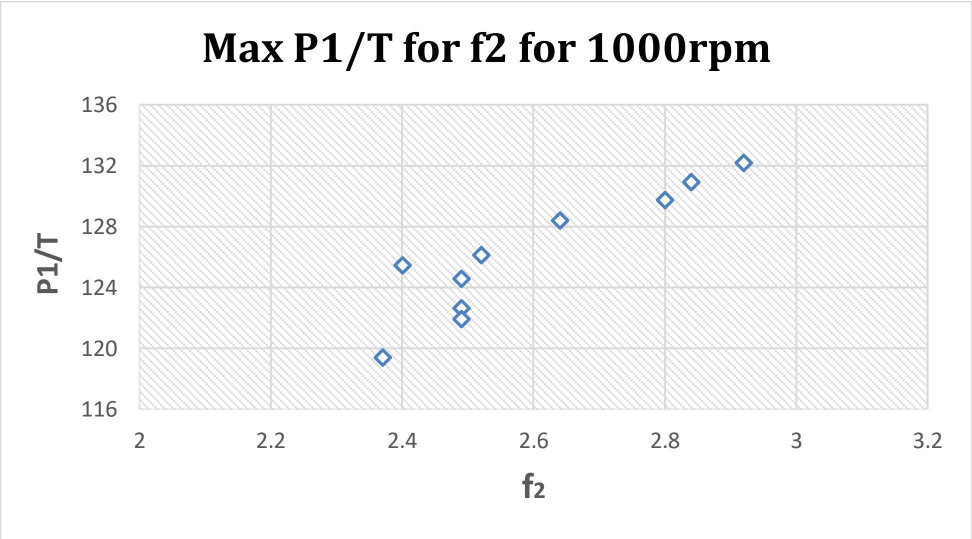


Figure 73: Max P1/T for f2 for 1000rpm

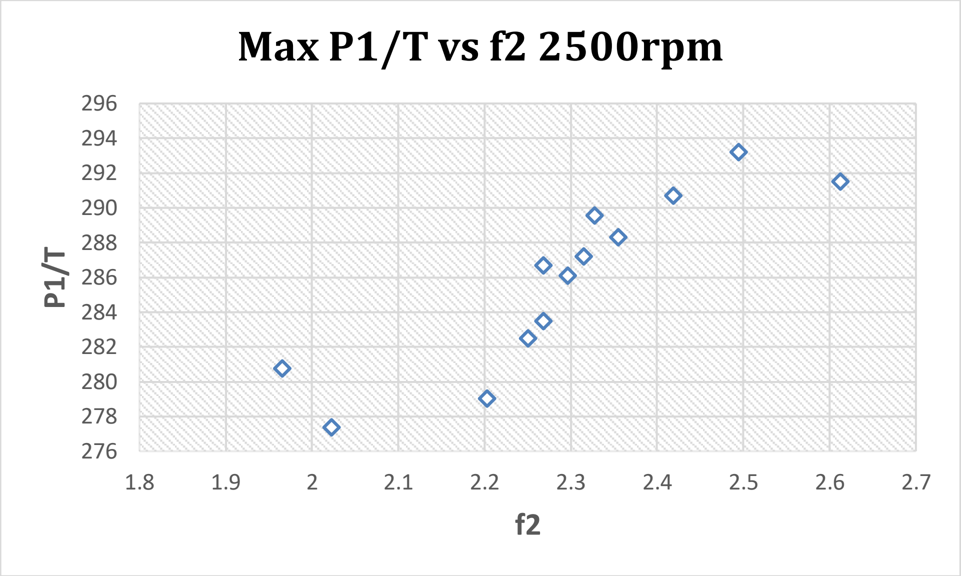


Figure 74Max P1/T for f2for 2500rpm

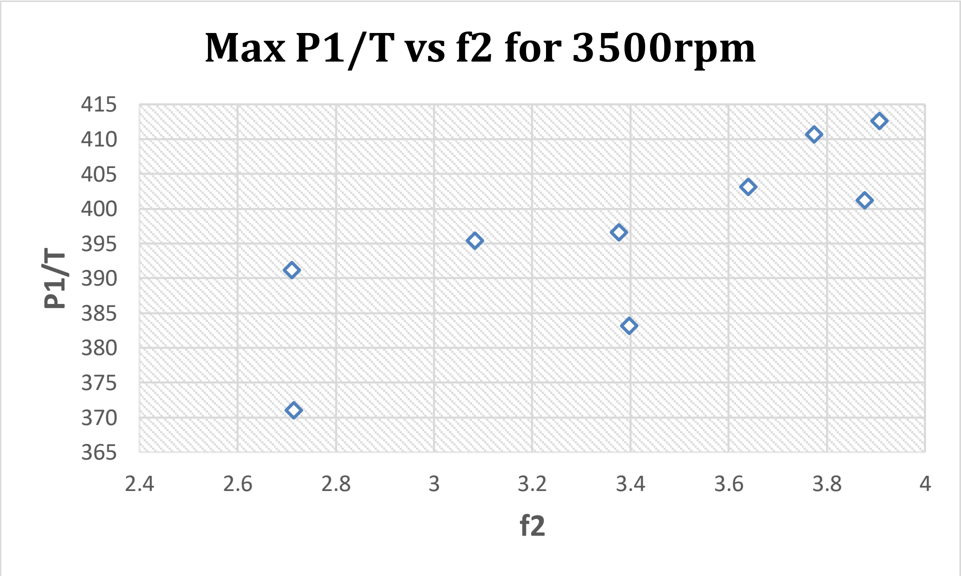


Figure 75Max P1/T for f2 for 3500rpm

- Optimal values comparisons with Mechanical Revolutions:

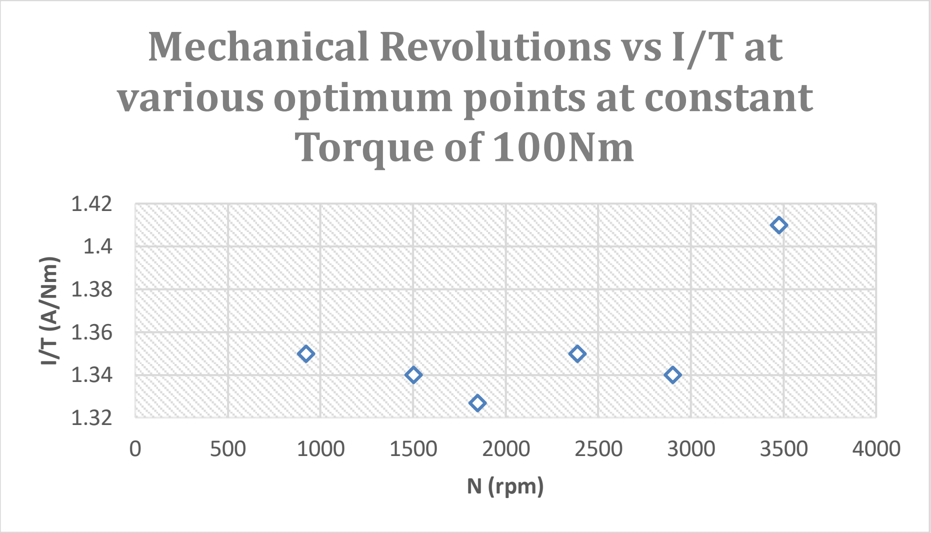


Figure 76: Dependence of current on Motor Revolutions

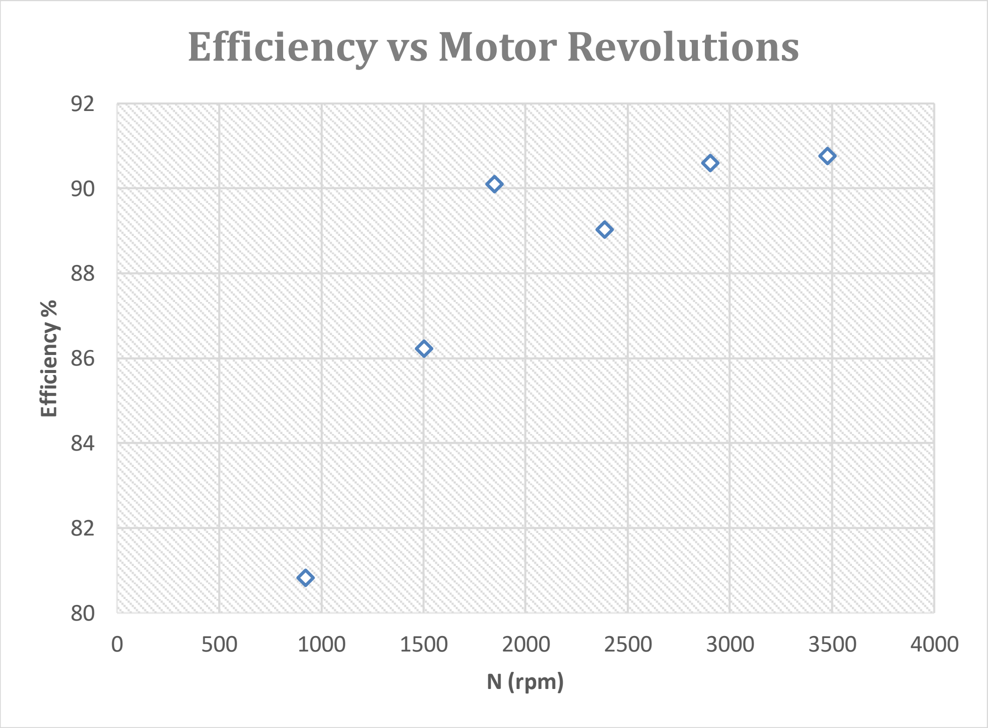


Figure 77: Efficiency vs N

The motors are generally more efficient when working on the higher ends of the rpm range. The 1500-3000 rpm is the Optimized Range or Operating area for the complete utilization of the provided power to the system. There is also a point on chargeable frequency.

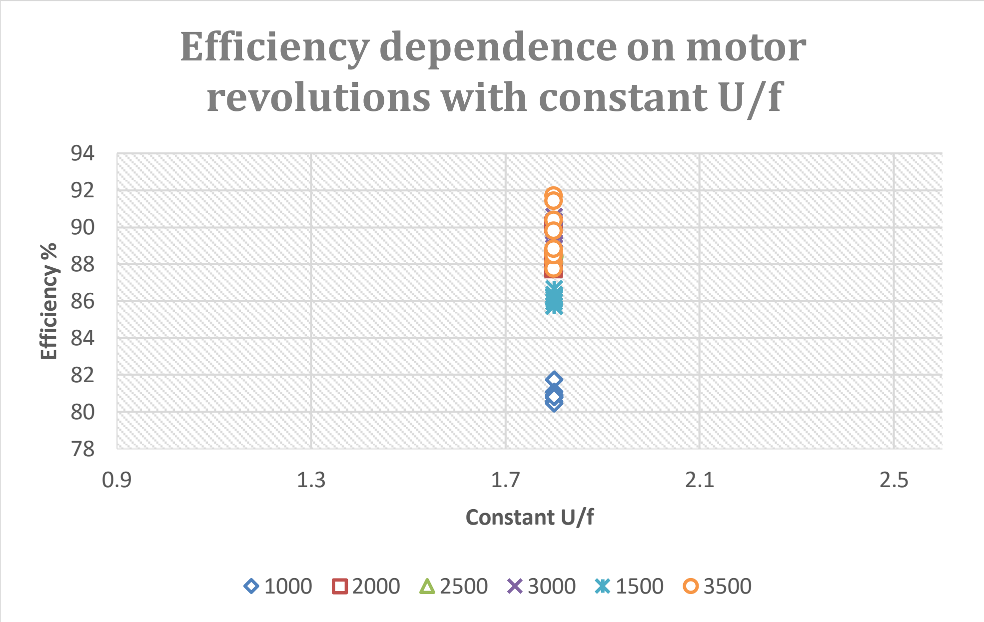


Figure 78 : Change of efficiency with motor revolutions seeking to constant U/f

As seen here for the constant U/f control the efficiency is low when the motor revolutions are low.

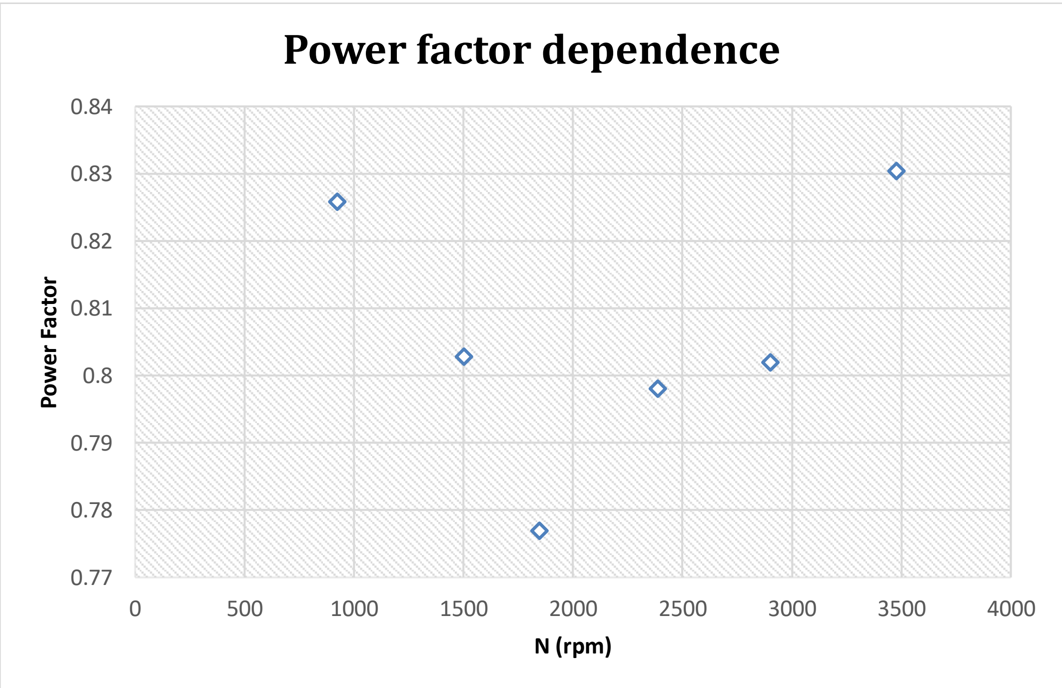


Figure 79 : Power factor as function of Motor Revolutions

The power factor is a crucial entity in the energy management of modern-day electric vehicles. It presents the efficiency or conversion of power when recuperating or energy transfer. POWER FACTOR is the ratio between the useful (true) power (kW) to the total (apparent) power (kVA) consumed by an item. A power factor around 1 means it is also well defined to cater to the needs and fully prepared about the upcoming.

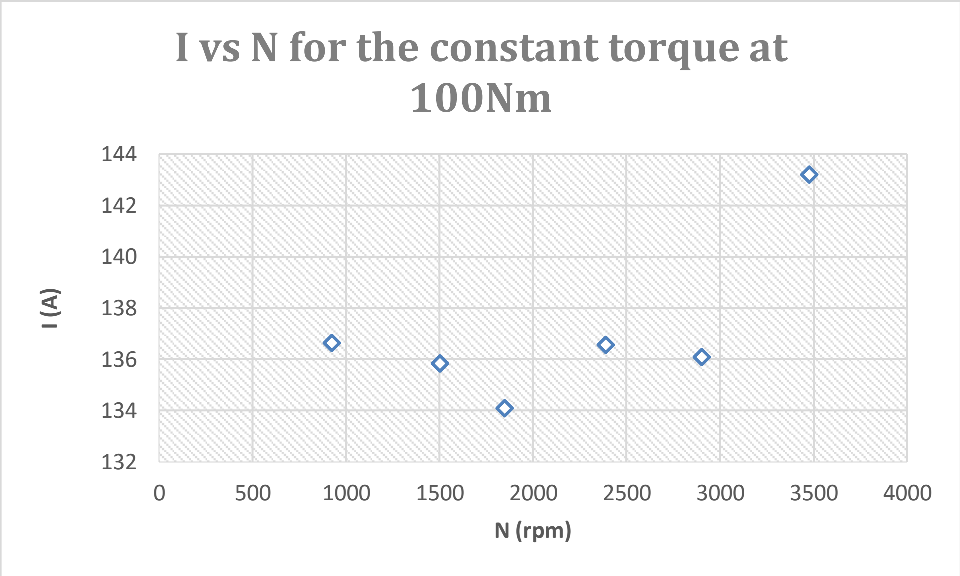


Figure 80 : I vs N

Each experimental finding provides evidence or constrained the validity of the underlying theory.

In our scenario, we made the mistake of assuming that some machine parameters (such as winding resistivity, inductances, and mutual inductances) were constant parameters whereas in reality, this is not quite accurate. Magnetic saturation effects may be important for the application of theoretical conclusions, particularly in electric vehicle and electric propulsion applications. According to the findings of the experiments, it is possible to establish operating conditions where the stator current required for the torque unit achieves its minimum for every machine speed and load. This region depends on the frequency of the rotor current frequency. The I/M criteria seems to be the most viable energy consumption talk perspective and is simply reliable for modern day EVs which suffer lot of issues like magnetic saturations and other shortcomings. The Stator voltage U1 and Magnetizing voltage corresponds to the flux in the circuit. According to the above-mentioned analysis and operating regimes. It could be concluded that the motor runs well on the region 1500-3000rpm as per its parameters valutations.

- Torque Characteristics Measurement.
  In case, when supply frequency is decreasing, supply voltage must be decreased to, to achieve relation U/f = constant. In our case constant = 180 / 100 = 1,8
  U for 100 Hz = 180 V
  U for 80 Hz = 1,8 * 80 = 144 V
  U for 60 Hz = 1,8 * 60 = 108 V
  U for 40 Hz = 1,8 * 40 = 72 V.
  2 times the nominal current should be the target set.
  Output power (from electrical to mechanical)

$$Pmech = Pin - Pstator - Protor \quad \text{Equation 33}$$

$$Effeciency = \frac{Pshaft}{Pin} = \frac{Prot}{Pin} \quad \text{Equation 34}$$

Prot are losses due to eddy currents and squirrel cage.

- Motor Regime

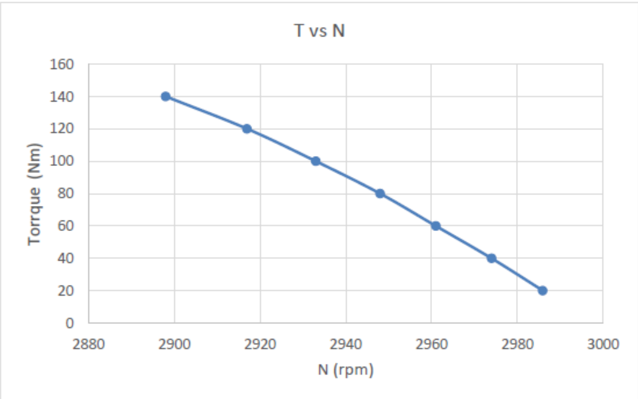


Figure 81: T vs N at 100Hz

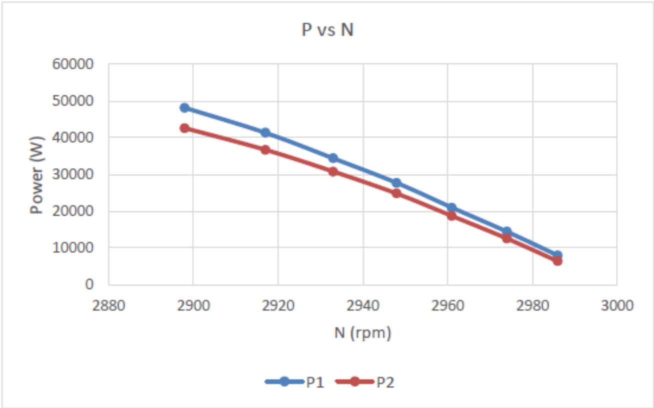


Figure 82 : P vs N at 100Hz

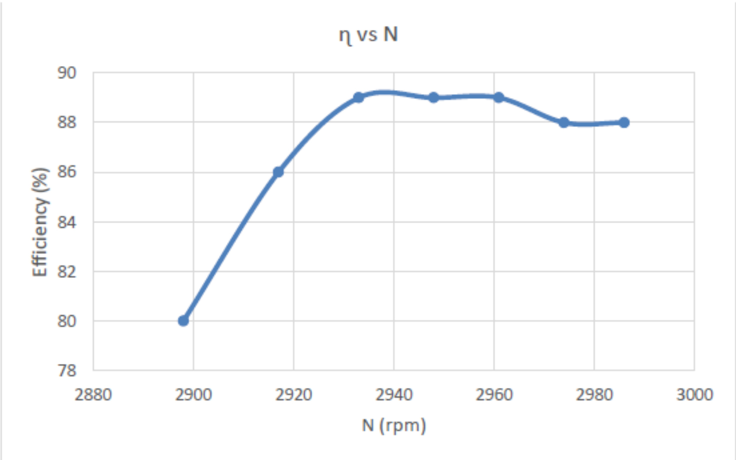
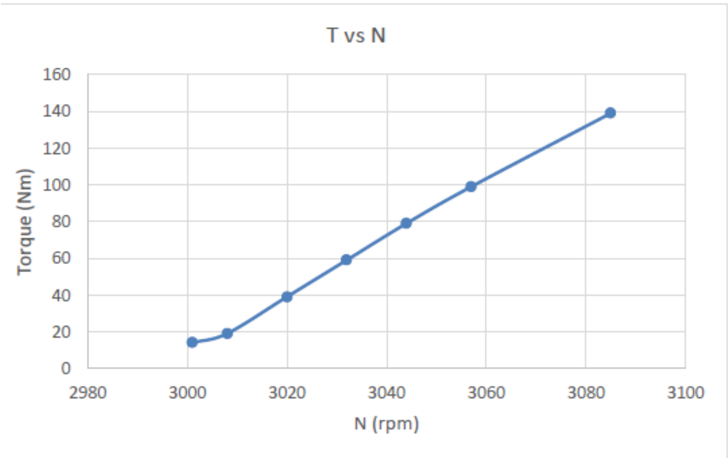
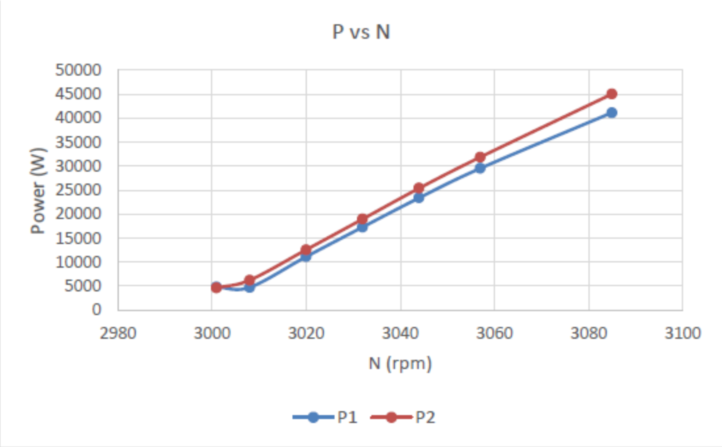


Figure 83: effeciency vs revolutions at 100Hz

- Generator Regime





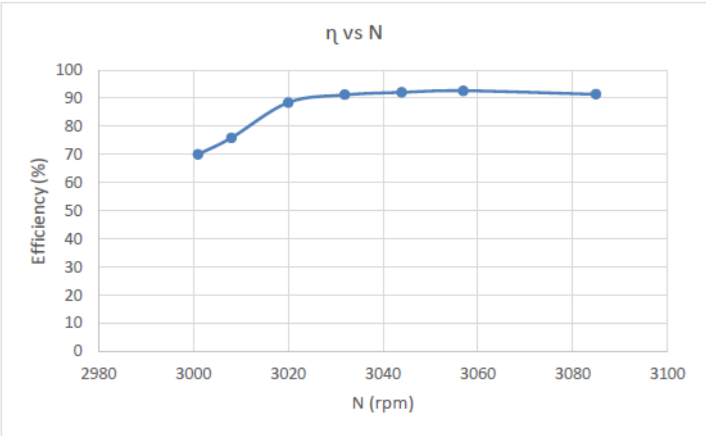


Figure 84 : T, P, efficiency vs N at 100Hz in Generator Regime

The motor operation is best near the linear range before torque starts decreasing to nominal values at the synchronous speed. Motor Torque is inversely proportional to speed. Similarly, power is also decreased when torque is lowered. Torque increases with increase in speed. Power also increases with increases in speed. Absolute values are taken for plotting the graphs. External source required for motor running as generator. The efficiency drops in less drastic and mostly stable in the generator regime

6.4 Arranged Skips and recorded Oscilloscope Plots

For the Transient analysis we have arranged skips of frequencies from a certain supplying voltage and its frequency level which has been control using the control system. For Transience the skip time from the initial and final point of stagnant movement is crucial as this is analogous to the acceleration demand of a moving electric vehicle. It has been recorded in the form of oscilloscope graphs to denote the transience.

Oscilloscope Legend:

Blue - Current

Yellow - Voltage

Purple - Frequency

Case 1: 1000 to 1500 rpm with voltages 70 to 105V, 35 to 52,5Hz

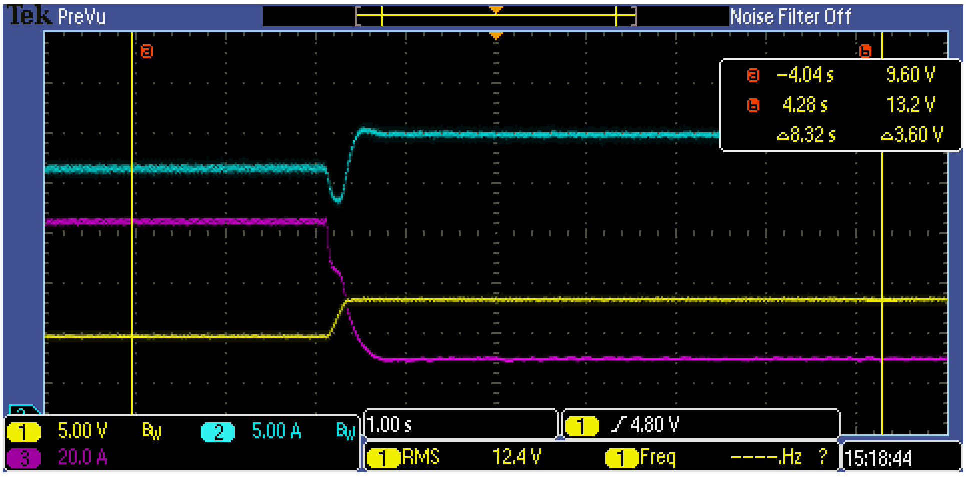


Figure 85: Skip of 1000 to 1500rpm

The marked area is the portion of concern and discussion for us. The transient time pertaining to the speeding up of the motor is subjected to some time delay. This delay would cause a uncanny lag to the electric vehicle and hence is a prime objective to study upon and to have conclusive ideas to remove such issues. Here as seen the transient time could be around 0.5secs. The graphs could also be prone to error due to scaling issues.

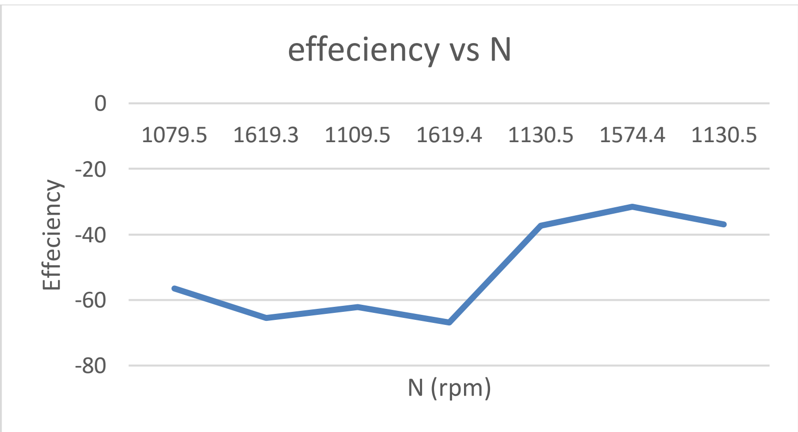
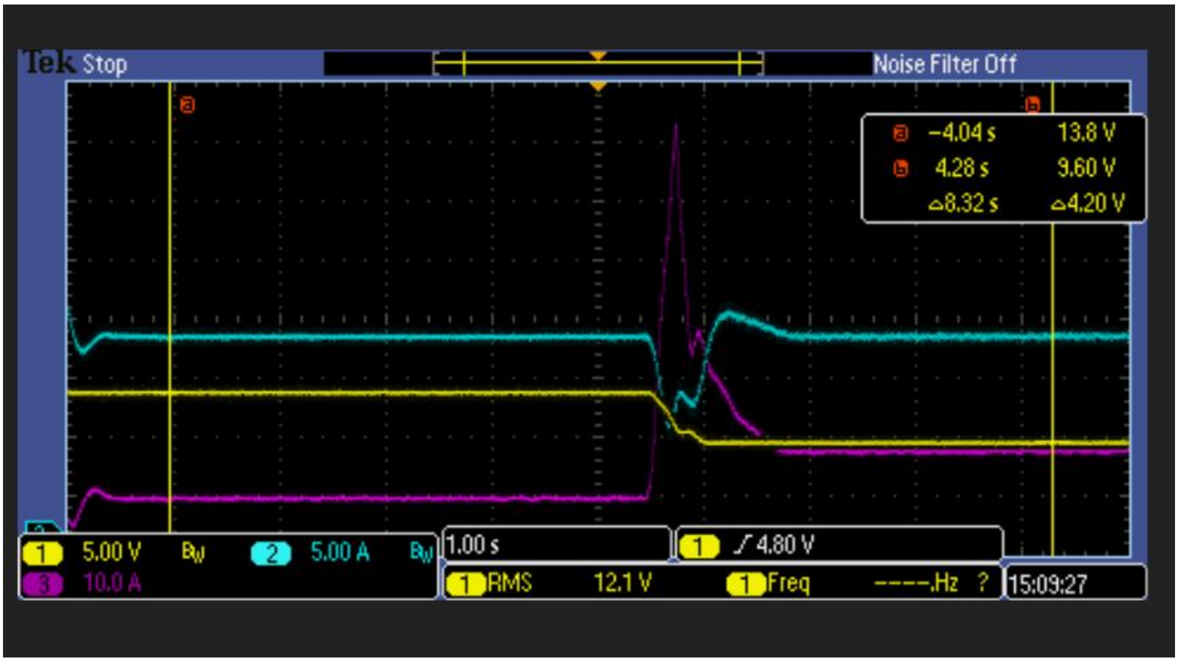


Figure 86 Efficiency with speed during the transience

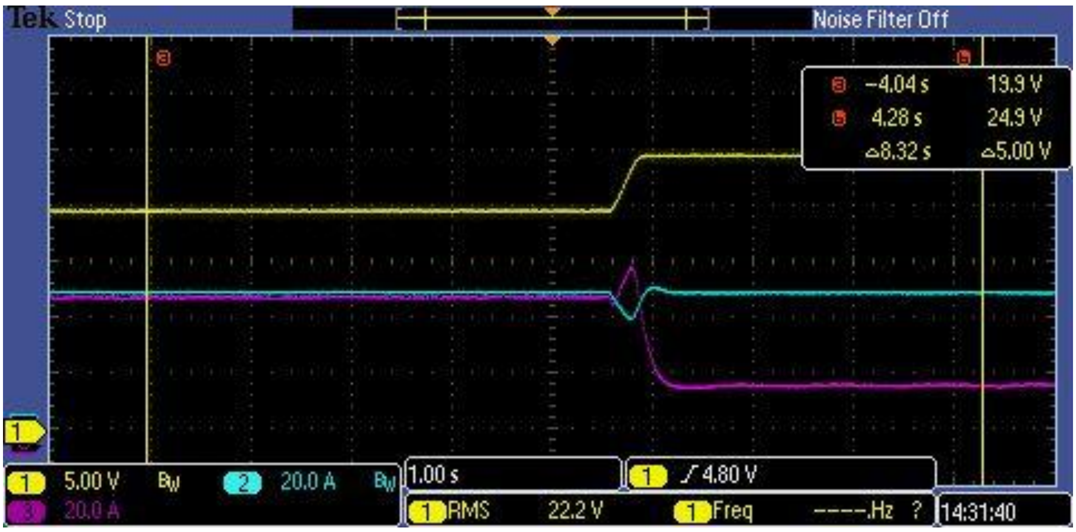
Case 2: On reversal from 1500 to 1000rpm



This shows variable timings for the voltage, current and frequency and arent aligned with their usual trend. The frequency spikes up due to probable anomaly and the current takes longer time to settle down in comparison to the step up in revolution.

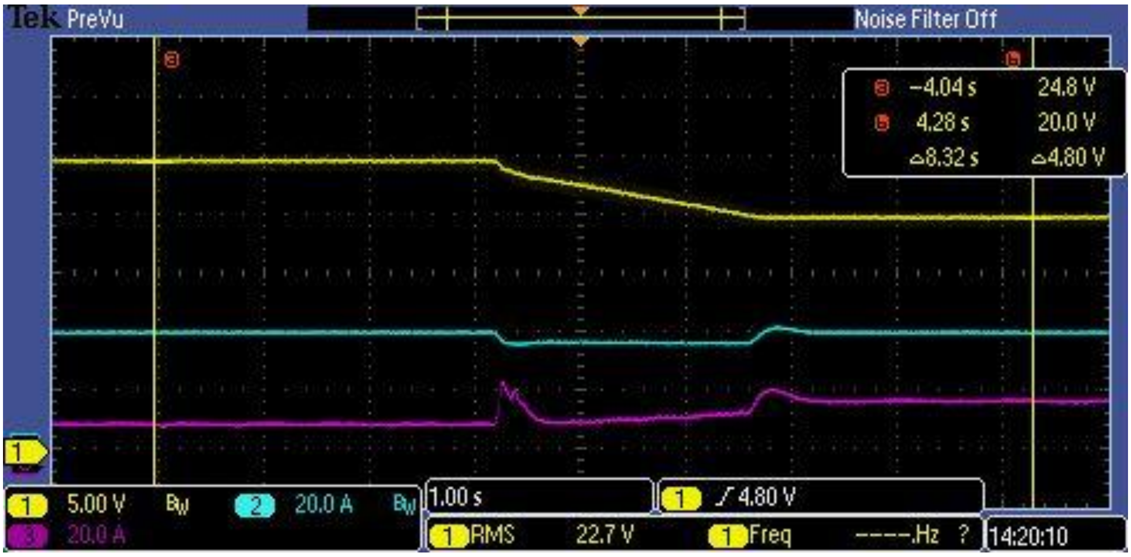
Another point to be noted is that the current surges are larger in comparison to ones during the static stage evaluation of I/T values.

Case 3: 2400-3000rpm 80-100Hz 145V



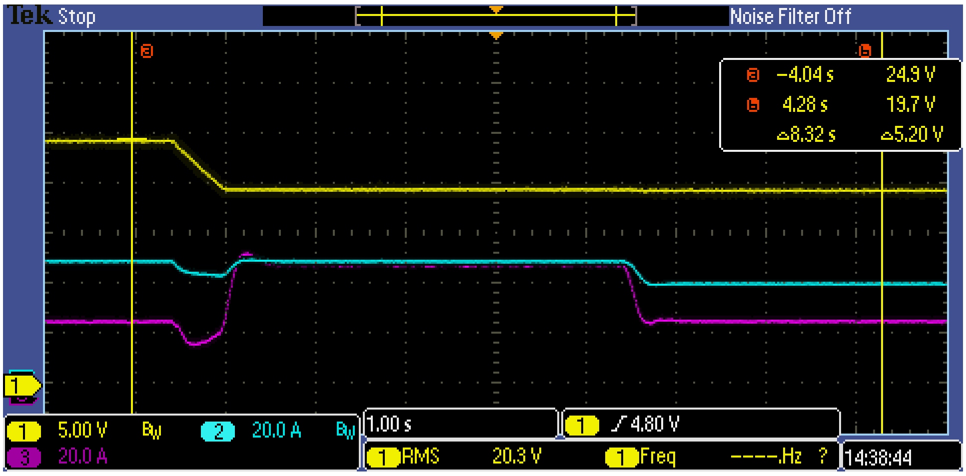
This is a stable skip and the transient time taken to evaluate the skip is also around 0.3s courtesy of the fact that there are no loads acting on the motor.

Case 4: 3000-2400rpm 100-80Hz 180V



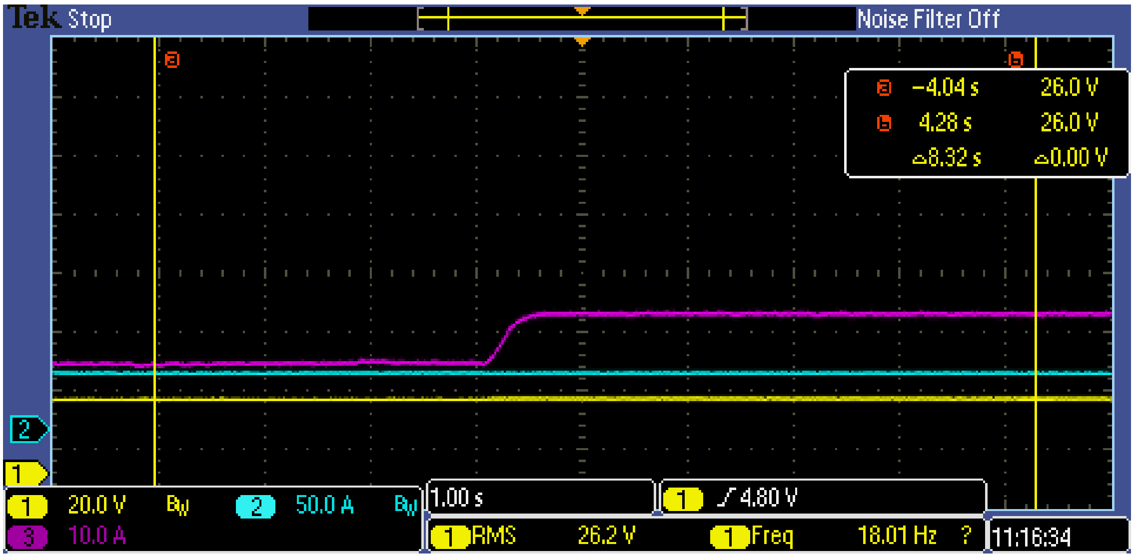
This is a long transition time taken for the step down. The probable errors could be human driven or the environmental issues like the windings heating up much and magnetic saturations. The Transient time here could be around 3secs.

Case 4: 3000-2400 rpm 100-80Hz with 50Nm Load



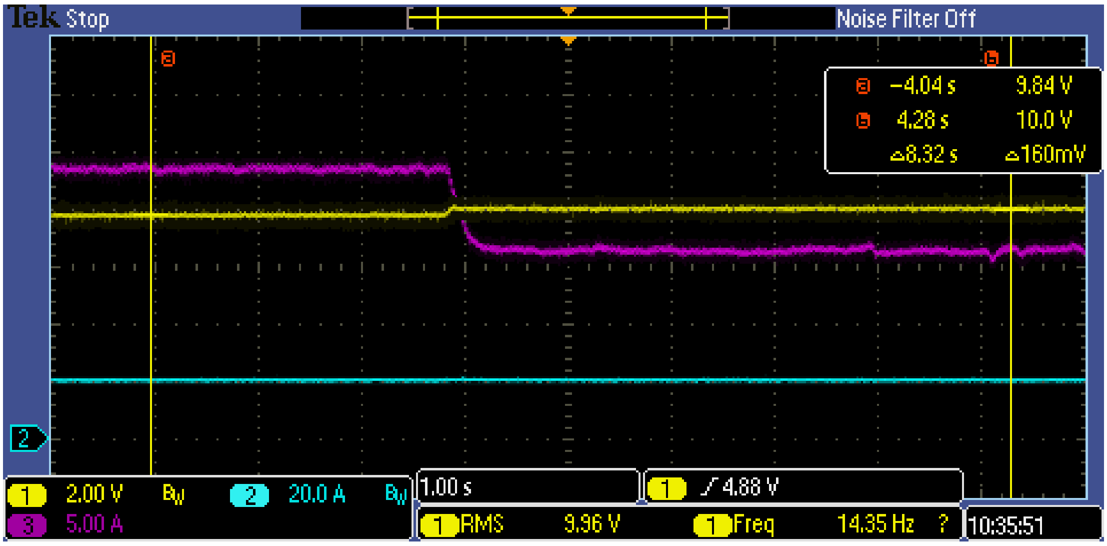
This is a pure case of motor inertial loading which leads to such long transition time of more than 2-3secs and it may cause a lot of troubles to the driver input and even lead to stall.

Case5: Generator Regime 3000 to 3030 rpm with -4 to -54 volt.



This showed an uncanny behaviour due to maybe the instability in the generator profile or a improper scaled results for the other two signals which are showing stagnant profiles.

Case 6: Skip recovery from 1200rpm with loading 50Nm to O Nm. As we step up through the unloaded side, there is rapid change in



The drawbacks of motor could be alleviated in the following ways.

1. the losses could be minimised.
2. there would be better behaviour prediction.
3. time response would be known from dynamic testing

6.5 Simulink model

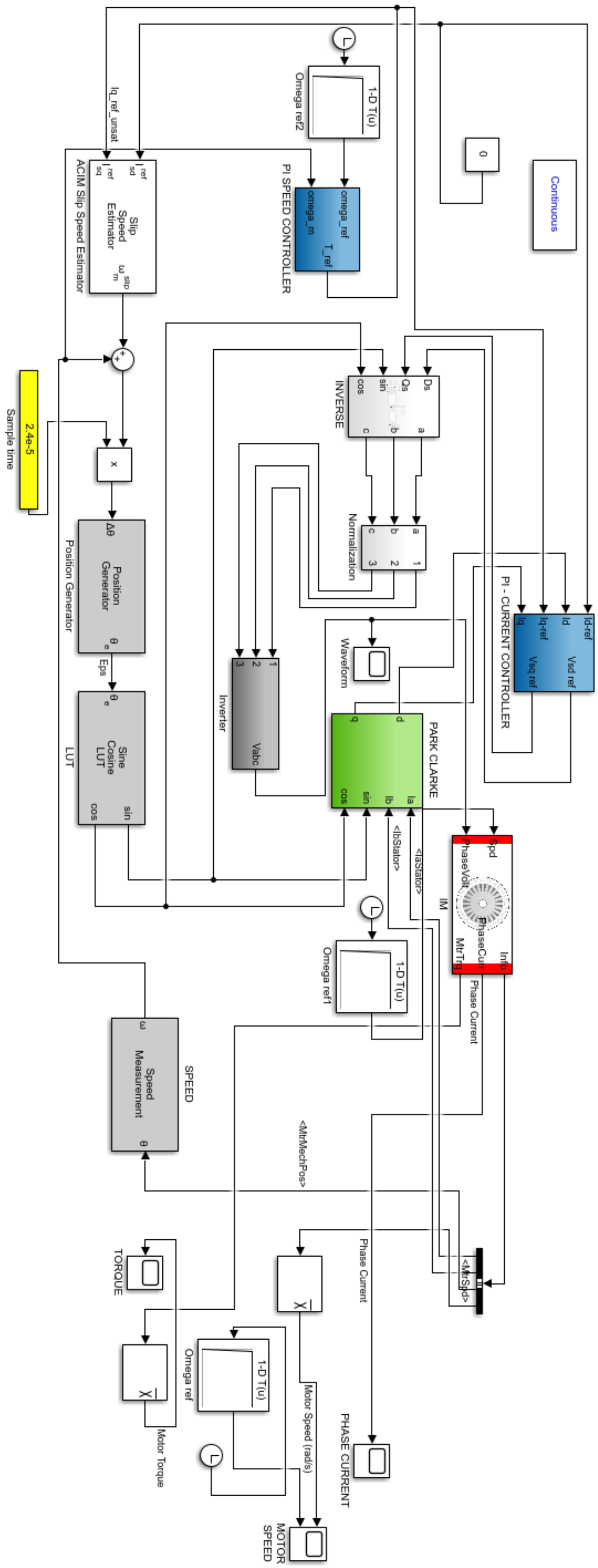


Figure 87Simulink Model

6.6 Analysis

For the Simulink Model. I managed to emulate a case selected from the optimal regime from the minimum I/T values processed.

As rule of thumb and simplicity.

- The current controller bandwidth is taken as 1/20th of switching frequency and the bandwidth of speed controller is taken as 1/20th of current controller.
- The bandwidth of the speed control loop should be around 5 times less than the current control loop and within the limit of 1/10th -1/20th of the current control bandwidth.
- Also, the sample time is taken as inverse of inverter switching frequency which is around 5-7KHz.
- Transfer function based tuning chosen

$$Proportional\ gain\ Kp = \sigma Ls\omega_c = 0.6704 \quad \text{Equation 35}$$

$$Integral\ Gain\ KI = \left[Rs + R_R \left(\frac{Lm}{Lr}\right)^2\right]\omega_c = 64.838 \quad \text{Equation 36}$$

$\sigma = (1 - \frac{L_m^2}{LsLR})$ = 0.108; total leakage factor.

These are intended for inner current loop.

L_m is the magnetizing inductance (2.9mH), LS is the stator inductance (3.04mH), L_R is the rotor inductance (3.10mH), R_S is the stator resistance (0.016Ω), and R_R is the rotor resistance (0.018 Ω)

$\omega_c = current\ control\ bandwidth$ = 2042rad/s (assuming switching frequency as 6500 Hz)

Outer Speed Loop

$$Kp = \frac{J\omega_{sc}}{K_T} = 5.67 \quad \text{Equation 37}$$

$$K_I = \frac{J\omega_{SC}^2}{5K_T} = 115.6 \quad \text{Equation 38}$$

J is Inertia (0.04kgm2) and K_T $is\ torque\ cnstant$ 0.72

$$\omega_{SC} = \left(\frac{1}{20}\right) * 2042 = \frac{102.1\ rad}{s}; speed\ control\ bandwidth$$

Sample time = $2.4e^{-5}$s

Voltage U	Current I	P1 Electrical Power	Cos phi	f1	Torque	Speed N	Mechanical Power W
97,47	135,84	18410	0,8028	52,178	101,01	1500,8	15875,1

Reference output speed = 145 rad/s

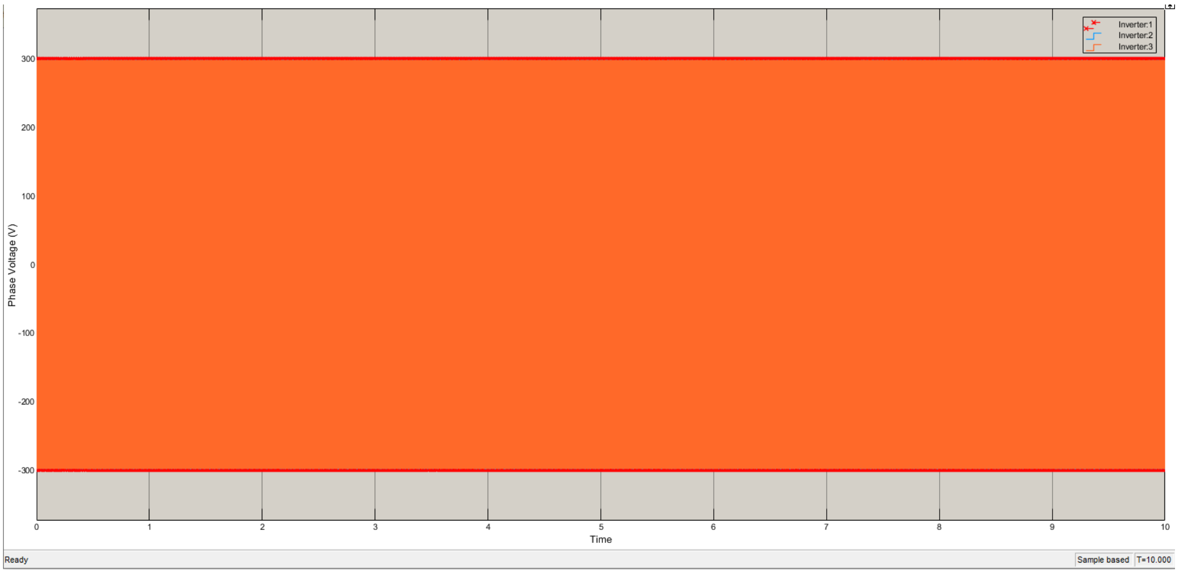


Figure 88Phase Voltage

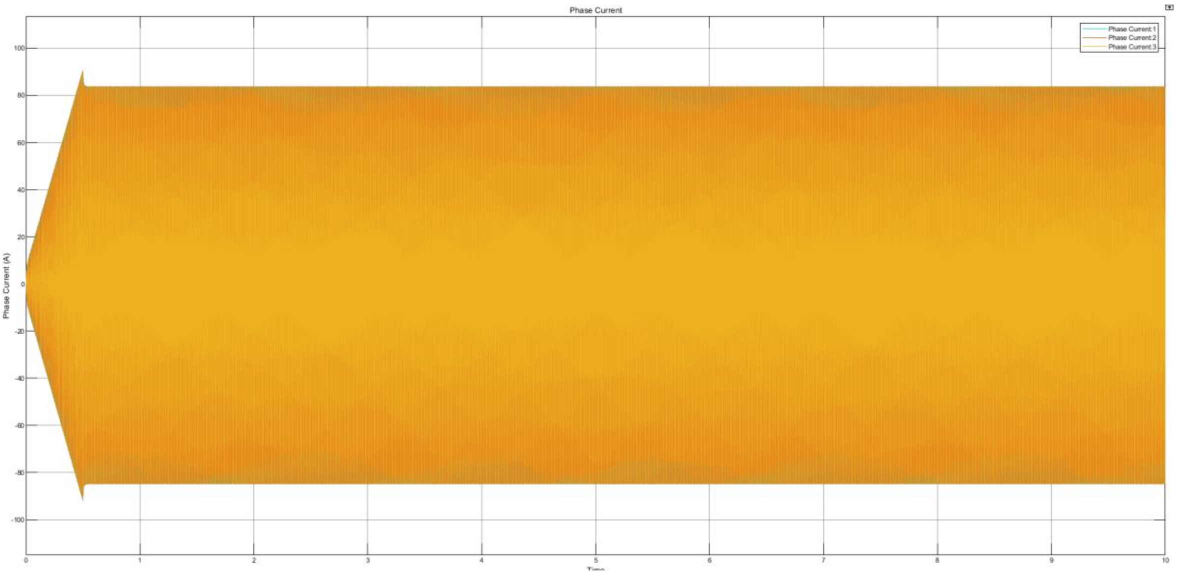


Figure 89Phase Currents

The phase currents do not comply exactly with the values due to error in tuning of the loops but the steady state achieved at 0.5secs.

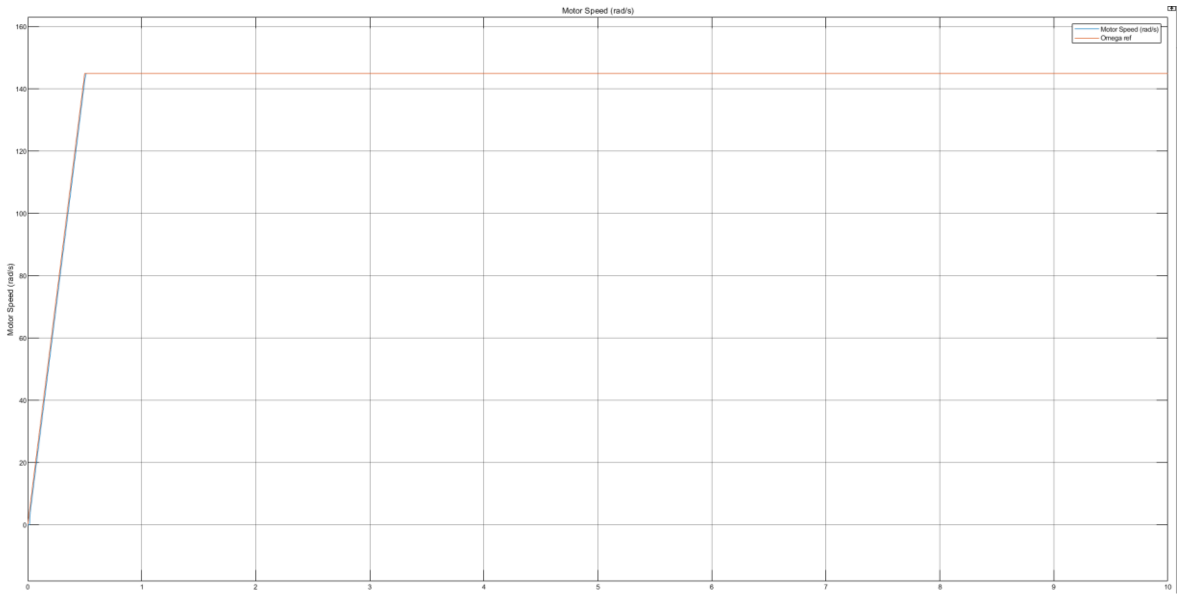


Figure 90 : Motor Speed Referencing

There is no visible and disturbing lag between reference and motor speed. Hence the control is acceptable.

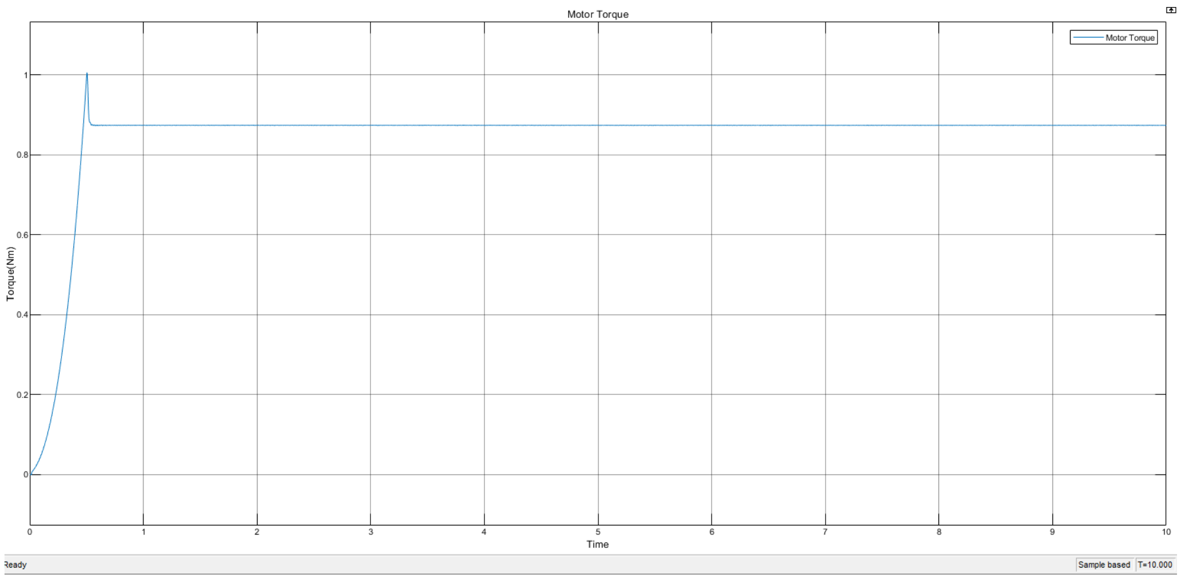


Figure 91Torque

The Torque starts settling to 1Nm from around 0.4secs prior to which there is peak torque seen.

- Transient Dynamics from 1000rpm to 1500rpm and back again

U	U1	U2	U3	I	I1	I2	I3	P1	cosfi	f	T	N	P2	eta
V	V	V	V	A	A	A	A	W		Hz	Nm	min-1	W	%
62,15	62,31	62,02	62,1	53,17	54,42	52,33	52,77	310	0,0552	36,017	-1,6	1079,5	-180,9	-56,52
91,47	91,62	91,4	91,39	50,64	51,19	49,96	50,77	396	0,0493	54,003	-1,53	1619,3	-259,4	-65,52
62,87	63,01	62,82	62,79	50,67	51,58	49,61	50,83	283	0,053	37	-1,56	1109,5	-181,3	-62,07

Switching Frequency considered 6000Hz: Sample time = $2.65e^{-5}$s

Omega c = 1884rad/s

Current - Kp = 0.6185 , Kt = 60.28

Omega sc = 94.2 ; Speed - Kp = 5.23 KI = 98.59

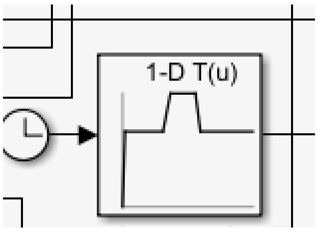


Figure 92 : The Skip in the LUT format

- Plots to enumerate the skips and transient time.

The voltages did not show much deviations. The reason might be inaccurate gain tuning and other common simulation errors.

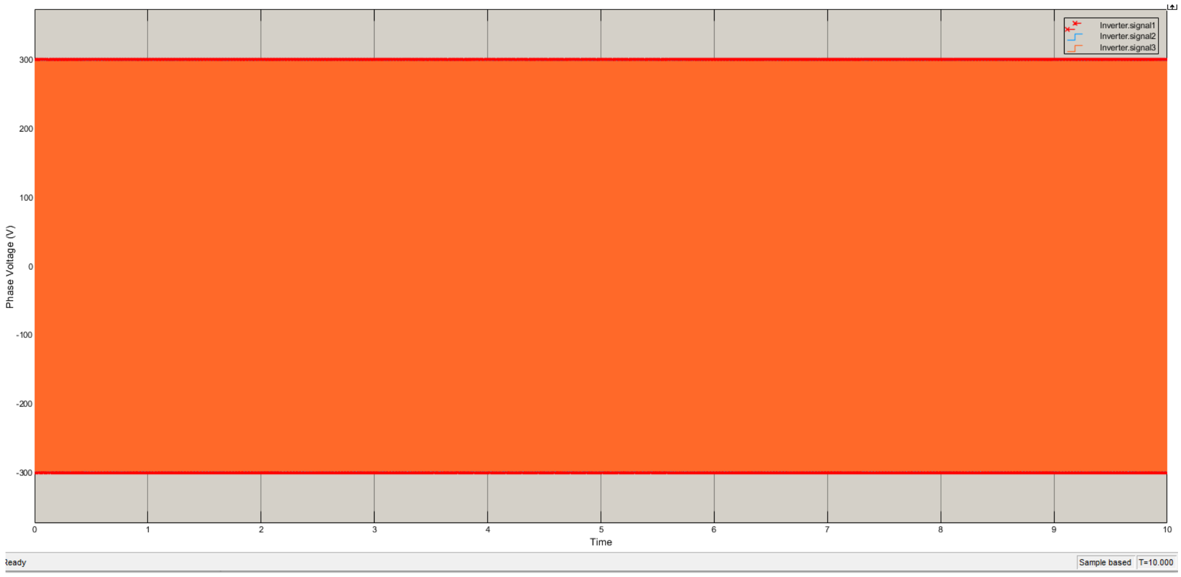


Figure 93: Phase Voltages

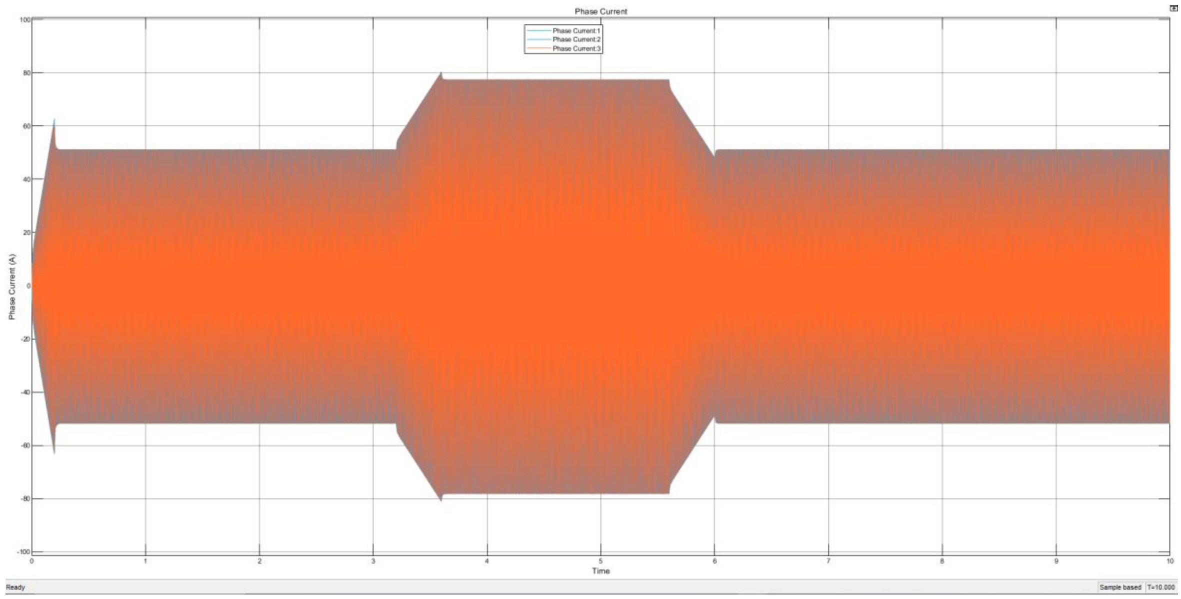


Figure 94: Phase currents.

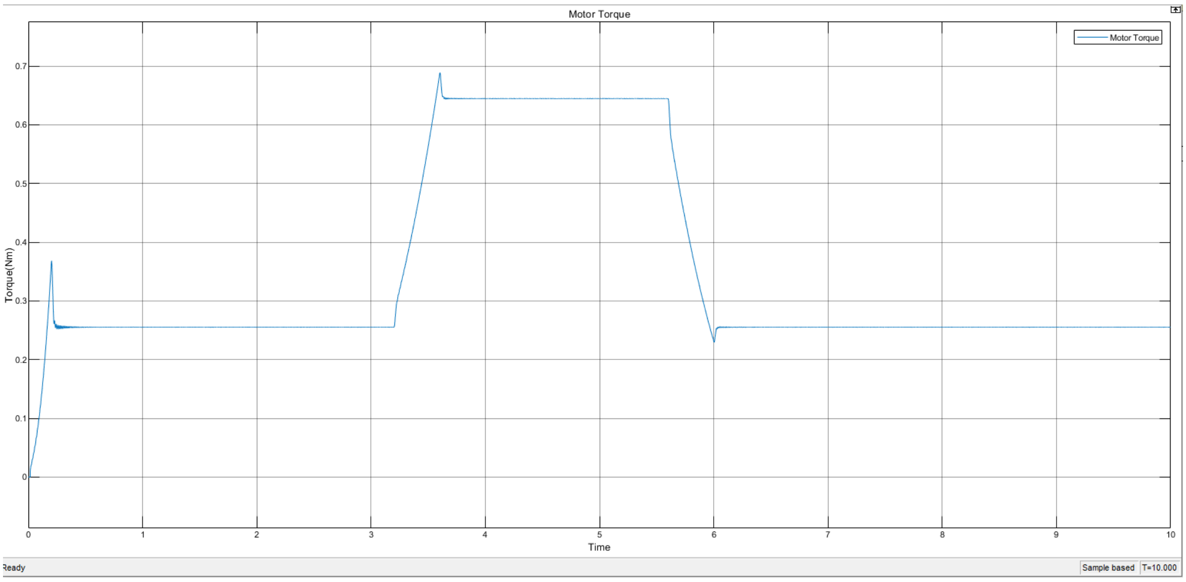


Figure 95Torque profile

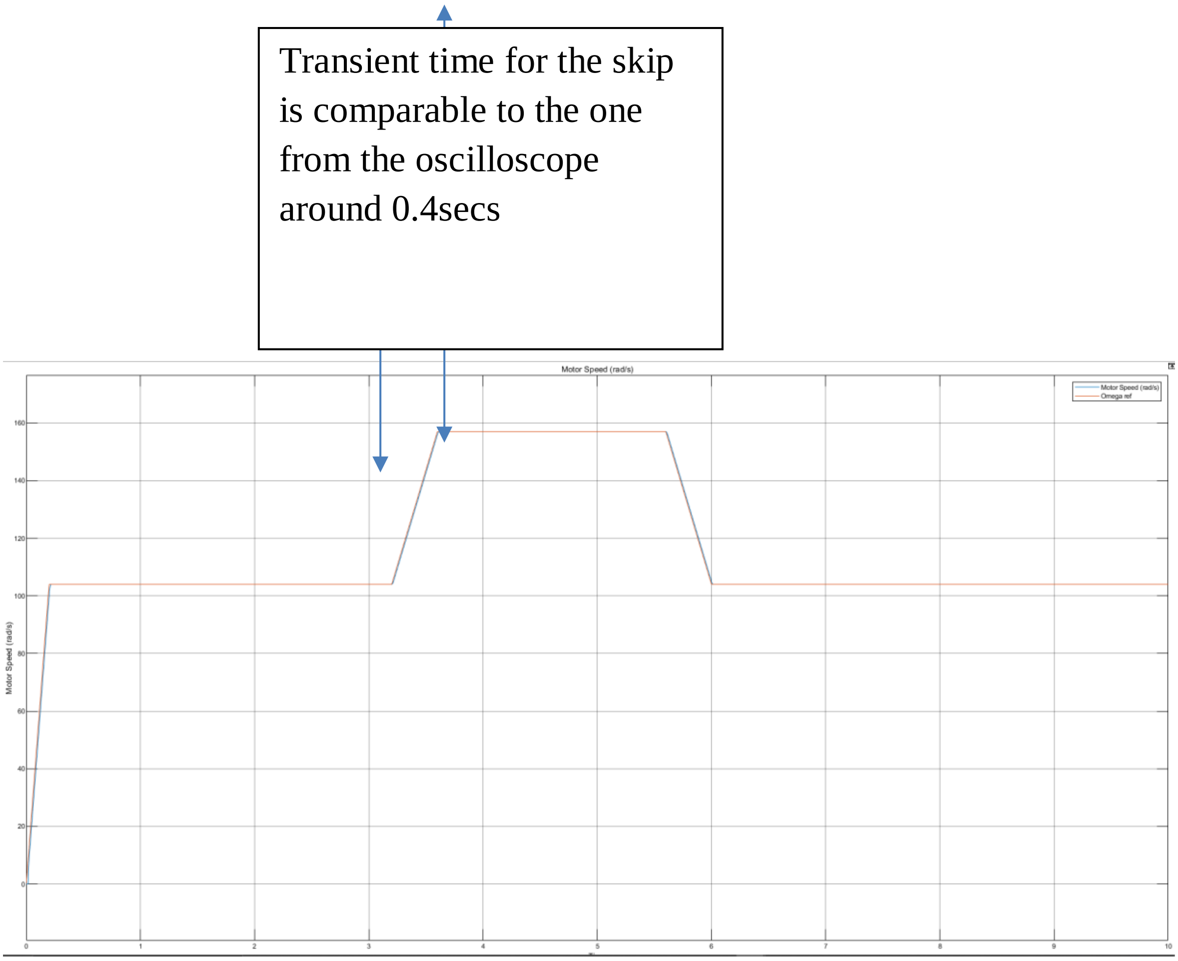


Figure 96 Motor Speed during Transience

The observations are similar to the ones from static data, but the transient skips tend to present some form of torque ripples or instability during the skip start and the end. These spikes could be curbed by filters or some other techniques. The time of transience corresponds to the oscilloscope data and hence the simulation gives us further opportunities to calibrate and generate results.

Chapter 7 Conclusion and Future Scope

7.1 Conclusion.

The thesis deviated more towards the theoretical study and with analysis of physical data. This leaves a gap for harnessing the work with computer simulations further on without the physical parameters at significance and at the transient phases more vigorously.

1. The Induction motor, its control, optimal range of operation, circuits and utilisation in a drive have been studied in the thesis. We have witnessed

that higher the torque surge higher is the current demand. To reduce such issues, the transient time can be studied when the skips take place from a certain frequency to the other. In electric vehicles on pushing the acc. pedal harder we command torque and the potentiometer driven acc. pedal enhances the I_q commanded. Studying this transient time from one revolution to another would lead to better performance.
The tolerances are very low, and the scaling should be done in adequate terms to save the amount of current from supply and allow the optimal functioning of the motor drive. The work could be used for multiple purposes even in the industrial world and not only confined to the electric vehicle platforms.
Also Field Weakening regimes could be tested when needed for higher speed in reduction of the back emf. Field Weakening leads to reduction of back emf to allow the bus voltage to drive the motor. Sometimes too much of transience can cause back feeding voltage into the bus.

There was an array of data collected for the experiments for different operating conditions and it was difficult to simulate it in the model with several parameter variations. Hence it was a thing to be continued later.

2. Carrying on the same methods and model. The transience skip time could be evaluated as a future work for analysing the optimum operating ranges.
3. An induction machine's speed must be controlled, as must the stator frequency and voltage. However, with voltage and current, the magnetic flux linkage will change. Together with the voltage drop on the stator resistance and frequency ratio. The machines' characteristics are altered by the stator resistance.
4. Main requirements of operating range for drives
   - Maximum Torque – Machine Design with an increase in linear current density
   - Maximum Speed – Rotor Design, high speed leads to high efficiency, rotor strength influences speed.
   - Maximum Power – Inverter Size and Cost and power factor dependent. Voltage is kept constant above base speed instead of being increased linearly with speed.

7.2 Future Scope

The study takes a practical approach to the subject, therefore the information used in various. Instead of using an idealized model, simulation was derived from real-world examples and experiments. The approach of this testing and optimal range determination can be extensively used with different motor control techniques like DTC as well. The investigated approach can be employed precisely in any powertrain train redesign, whereas preliminary modelling, for instance, can be done using the MATLAB motor control toolbox.

7.2.1 How to utilise data and manipulate the example.

The data for the better operating range can be utilised to test other parameter variations like inertia of motor, temperatures, peak currents etc.

When assessing the efficiency of the EV/HEV powertrain, there are two different operating modes that could be used:[11]

Mode A: The grid receives power from the vehicle. To charge the DC link, the back-end converter functions as a PWM rectifier, and the front-end converter is now acting as a grid-connected inverter. In this mode, the 28kW motor delivers load torque while simulating real-world road conditions, like friction. By adjusting the torque dynamically and appropriately, the road running test profile may be easily attained.

Mode B: The car receives energy from the grid. The front-end converter serves as a PWM rectifier for the DC connection, and the back-end converter powers the 28kW motor located under the chassis. The system simulates an automobile moving downward in this mode.

With this I put an end to the work and look forward to more experiences and learnings.

[11] Generally power ratings for EV motors are different and this is subject of debate.

Chapter 8 Bibliography

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Chapter 9 Appendix

1. Excel sheets for measured data
2. Simulink model