TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

JUUSO KUKKARO
STRADDLE CARRIER ELECTRIC POWERTRAIN OPTIMIZATION

Master of Science thesis

Examiner: Dr. Jenni Rekola
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ABSTRACT

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This thesis concentrates on improving the energy efficiency of a straddle carrier by optimizing the electrical powertrain. Mobile working machines have significantly varying power demands in operation. Average demand is considerably lower than the maximum power requirements. This results in the machine operating far from its optimum efficiency range significant amount of its operating hours. This work cycle power level variation is vastly different from road vehicle power demands and optimization scenarios. Diesel powered working machine efficiency can be significantly improved with electric hybridization.

The study is beneficial to both direct electric driven and hybrid systems. Main focus is the optimizing the motor and generator with the analysed load cycles. Comprehensive measurement data sets of vehicle use in real port operations are used as a base for the load analysis. In conjunction with the load models several mechanical and electrical simulation models were created. These component models were used to estimate changes that different motor and generator combinations would have on the overall efficiency. For this the efficiency maps for electrical machines are determined analytically in the whole torque–rotational speed plane based on the electrical machine parameters.

Electrical machine losses and torque generation were studied in depth to find appropriate future development paths for the electrical powertrain of a straddle carrier. Additionally the payback time for the most feasible improvements were estimated. The thesis provides a case example of dimensioning and improving electrical powertrain of a working machine.

TIIVISTELMÄ

JUUSO KUKKARO: Konttilukin sähköisen voimalinjan optimointi
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Tässä diplomityössä tutkittiin konttilukin energiatehokkuuden parantamista kehittämällä sähköisen voimalinjan hyötysuhdetta. Liikkuvien työkoneiden tehonkäyttö operaatiossa on hyvin vaihtelevaa. Keskiteho on merkittävästi pienempi kuin huipputehovaatimus. Tämän johdosta kone toimii tehokkuuden kannalta epäedullisella käyttöalueella valtaosan toiminta-ajasta. Työkoneen tehonvaihtelu eroaa merkittävästi tieliikenneajoneuvojen kuormitus ja optimointitilanteista. Dieselmoottorisen työkoneen energiatehokkuutta voidaan merkittävästi parantaa hybridisaatiolla.

Pääpaino työssä oli ajomoottoreiden optimoinnissa nykyiseen voimalinjaan. Erilaisilla moottorikombinaatioilla voimalinjan kokonaistehokkuutta tarkasteltiin todellisista kuormituksista luotua mallia apuna käyttäen. Työn tuloksena syntyi useita simulaatiomalleja koneen mekaanisista ja sähköisistä järjestelmistä. Moottoreiden hyötysuhteet kartoitettiin analyyttisesti moottoriparametrien avulla. Näiden mallien avulla arvioitiin erilaisten sähkömoottorien ja generaattorien vaikutusta voimansiirtoketjun kokonaishyötysuhteeseen.

Pääpaino työssä oli sähkövoimakoneiden häviöiden ja hyötysuhteiden tutkimisessa ja vaihtoehtoisten komponenttien kartoittamisessa olemassaolevaan rakenteeseen. Lisäksi erilaisten hyötysuhdetta parantavien ratkaisuiden takaisinmaksuaikaa arvioitiin. Tämä opinnäytetyö toimii esimerkkinä pitkälle erikoistuneen liikkuvan työkoneen sähköisen voimansiirron optimoinnista.

PREFACE

Getting a second degree was no easier feat compared to the first one. Was all this really necessary? Who knows? I don't, though there is no regret either. Maybe this was a path I needed to take for something that will present itself when the time is right.

First of all I would like acknowledge my thesis supervisor Dr. Jenni Rekola and colleague Juho Leskinen for the expertise during this process and pushing me through.

For my loved one, family and friends I would like to apologize for my absent-mindedness during the past years. I would also like to express my deepest gratitude for the support and kindness I have received. I would not be where I am today without all the people around me.

As I am no poet nor an artist I am unable to finalize this work with beautiful words of my own. Instead I will leave you with a sentiment expressed long ago in a far away land by someone else.

瀬を早み
岩にせかるる
滝川の

Tampere, 19.11.2017

Juuso Kukkaro

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LIST OF ABBREVIATIONS AND SYMBOLS

AC	Alternating Current
AGV	Automated Guided Vehicle
AVR	Automated Voltage Regulator
ATEX	Atmosphères Explosibles, explosive atmosphere
CPSR	Constant Power Speed Ratio
DC	Direct Current
EMF	Electromotive Force
EMI	Electromagnetic Interference
GaN	Gallium Nitride
HSC	Hybrid Straddle Carrier
ICE	Internal Combustion Engine
IGBT	Insulated-gate Bipolar Transistor
IM	Induction Motor
IPM	Interior Permanent Magnet
NEDC	New European Drive Cycle
PMG	Permanent Magnet Generator
PMSM	Permanent Magnet Synchronous Motor
QC	Quay Crane
RPM	Revolutions Per Minute
RMG	Rail Mounted Gantry
RTG	Rubber Tired Gantry
SiC	Silicon Carbide
SPM	Surface Permanent Magnet
STS	Ship-to-shore crane
TEU	Twenty Foot Equivalent Unit
TT	Terminal Tractor

a	acceleration
F	force
I	current
m	mass
P	power
R	resistance
t	time

1. INTRODUCTION

Globalization has made the world a one huge marketplace where commodities are traded between nations and commercial partners. Majority of worlds goods travel through the seas between ports. With regard to general cargo (goods, merchandise, commodities), almost 90 % of the total cargo volume today is containerized [1]. These two combined make container handling a vital part in port operations or rather container terminals. From 2000 to 2014 the world container traffic tripled to nearly 680 million TEU in a year [2]. The rest is bulk goods like oil or coal and special items like large machines or their parts. The massive quantity of cargo moved and manipulated requires equally significant amount of machinery and energy.

There is increasing pressure on container terminals to use sustainable and environmentally friendly technologies. The environmental aspects support minimizing diesel consumption when there is more efficient power sources available. There is financial incentive in minimizing the infrastructure costs like fuel storage besides the hourly running cost. Horizontal activities are all those activities realized by rubber tired gantries (RTG), reach stackers, rail mounted gantries (RMG) etc. These activities consume the greatest share of energy in terminal (ca. 45 percent) [3].

Majority of the free running container handling equipment are still based on diesel engine power source. Changing from direct driven to diesel-electric drive trains and later hybridization have improved the efficiency and reliability of the machines. Larger cranes and gantries are now being developed and modified for direct electric drive. Public electrical grid is connected to these via bus-bars or cable reel systems. Pure electrical drive systems are the simplest and most energy efficient solution. For the near future however the straddle carrier will still be mostly diesel driven. Improved efficiency will have direct impact on the fuel consumption of the machine and secondary effect for the logistics needed. Improvements in the powertrain energy efficiency will be beneficial for hybrid and later fully electric systems also.

Long term goal of completely replacing the diesel engine with other power sources has the potential in improving working conditions in the container terminal besides ecological impact. Less local pollution from burning fossil fuels has positive impact on air quality. Having smaller or no engine will lower the noise levels produced by the operation. These effects can already be seen in the hybrid straddle carriers.

1.1 Container terminal operations

Container terminals are designated for the handling, storage, and possibly loading or unloading of cargo into or out of containers. There containers are be picked up, dropped off, possibly maintained, stored, loaded and unloaded from one mode of transport to another.

Container terminal operations can be divided to quay, transport, yard and loading areas. In the quay area the ships are moored and ship-to-shore cranes handle the loading and unloading of the vessel. Cargo is moved to the yard area to storage via the transport areas. Trucks and trains are loaded in the loading are. Area utilization and equipment selection varies largely based on terminal size, geographical limitations, main cargo handled and selected operating strategy. Figure 1.1 shows an example of the port area division.

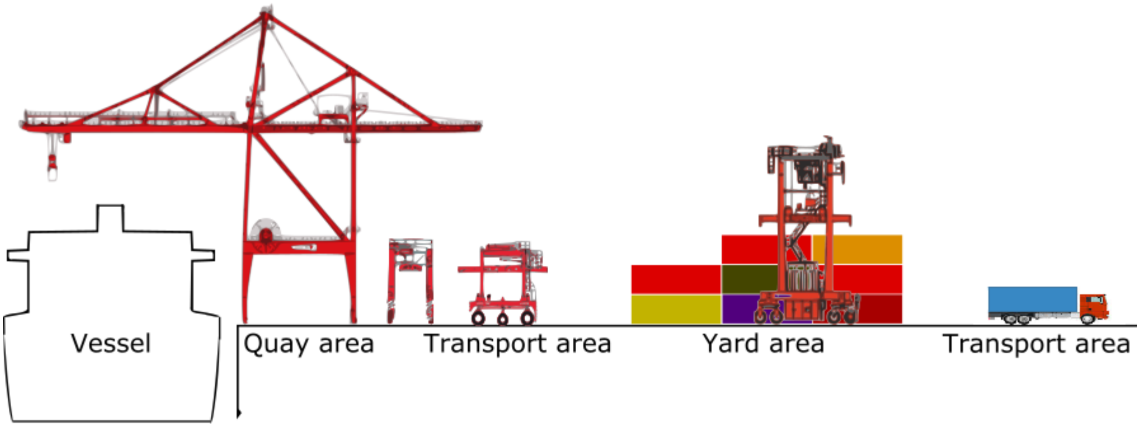


***Figure* 1.1** *Container terminal operational areas.*

On the quay area or seaside where the ocean going vessels and barges moor ship-to-shore (STS) cranes or in other sources quay cranes (QC) do the loading and unloading. There are also some vessels equipped with their own cranes. In such case STS is not needed. There are also Ro-Ro vessels mainly meant for wheeled cargo which can also be carrying containers but those are not included in this thesis.

Depending on the chosen strategy and available equipment the STS can either leave the containers on the tarmac to be picked up or directly load them to machine waiting.

There can be either human driven terminal tractors (TT) with trailer waiting for the container to be moved or an automated guided vehicle (AGV). Neither of these can self load the cargo. To maximize the operational throughput of the crane, several AGV's or TT's are required to wait in line as a buffer. Other option is shuttle or straddle carrier. Both of these can self load the container from the tarmac and move it to the next phase of the operation. Straddle carriers can also stack the containers up to 3 units high stacks and still carry one over. For small ports straddle carriers 1.2 can be the only moving machines necessary to complete the operation.

Figure 1.2 *Automatic straddle carriers and manual straddle loading cargo. (Kalmar)*

The horizontal moving machines move the container to a loading area where either the gantry cranes organize the yard area and possibly loading in next phase. In small ports straddle carriers can also take on the yard tasks. When using gantry cranes higher container stacks can be made and space allocation for the straddle carrier side frames between the stacks is not necessary. This improves the yard utilization rate.

The commissioner for this thesis, Kalmar, manufactures container handling equipment and provides port automation solutions and equipment services. Kalmar is part of Cargotec.

1.2 Contents of the thesis

This thesis concentrates on improving the energy efficiency of a straddle carrier by optimizing the electrical powertrain. The main part is the optimizing the motor and generator with the analysed load cycles. Comprehensive data sets of vehicle use data in real port operations are used as a base for the analysis.

Chapter 2 covers the electrical powertrain and its components. First the outline of the straddle carrier powertrain is introduced. The structure is the same as in any diesel-generator set powered electrically driven vehicle. The possibility of hybridization is always present although it is not covered in detail. The following sections will cover each component in more detail. The information is later used in chapter 4 to create practical models.

In chapter 3 the dynamic loading of the working machinery is analysed. The analysis is based on machine measurement data recorded by the engine control unit and on board logic system sensors. Comparisons are made to road vehicles and some of the differences are highlighted. The analysis works as a base for a load model later in chapter 4. Practical information of the loading and power requirements are vital for accurate analysis of the powertrain efficiency.

Modelling is covered in chapter 4. Based on the theoretical background and analysed date presented in chapters 2 and 3, models are created to estimate practicality of the powertrain improvements. Theory will include more variables than is necessary for the system level models derived. This is to remind the reader of the complex nature of optimizing electrical machines and to introduce some of the practical problems that designers have to overcome. It is always important to estimate the scale and impact each problem poses for reaching the final objective.

Chapter 5 discusses the results and practicality of implementation. Chapter 6 concludes the thesis. Further study is encouraged to make more advances in this field and to spread the knowledge of the gap between marketing banner specifications and practical implemented results in dynamical loading conditions.

2. ELECTRICAL POWERTRAIN

The straddle carrier powertrain consists of the engine, generator, rectifier, energy storage in hybrid versions, inverters and the motors. Each of these contribute to the overall efficiency but their optimization differ significantly. However this construction enables the most efficient use of the elements with highest losses and have the most impact to the total energy efficiency. Figure 2.1 describes the chain of conversion stages in electrical powertrain with power consumption marked in red and regeneration in green. In certain configurations power can also flow to the generator when it is used as a starter motor. Rest of this chapter will briefly introduce all the stages. As this thesis concentrates mostly on electromechanical power conversion efficiency the following chapters will describe different motor and generator technologies in more detail and also briefly touch the subject of electrical power conversion. For hybrid systems and energy storages readers are advised to seek publications like [4] [5] [6] [7].

Internal combustion engine (ICE) is the prime mover of the straddle carrier. The engine converts the chemical energy of the fuel which in this case is diesel to mechanical rotation. ICE is a heat engine where the fuel is oxidized with air in combustion chamber and the expansion of the burning gases is used to move a piston confining the chamber. The piston is attached to a crankshaft which rotates due to the force applied. Releasing the pressure in the chamber via a exhaust valve vents the gasses out while the piston reciprocates back to to minimize the chamber volume. Exhaust valve is closed and intake valve opened while the piston continues to move. This causes the chamber to fill with air and fuel mixture. Fuel can either be directly injected to the chamber or to the inflowing air. Intake valve is closed and the piston compresses the fuel air mixture. The mixture ignites due to the heat and compression thus completing the cycle. Most of the losses in the engine are due to heat and friction.

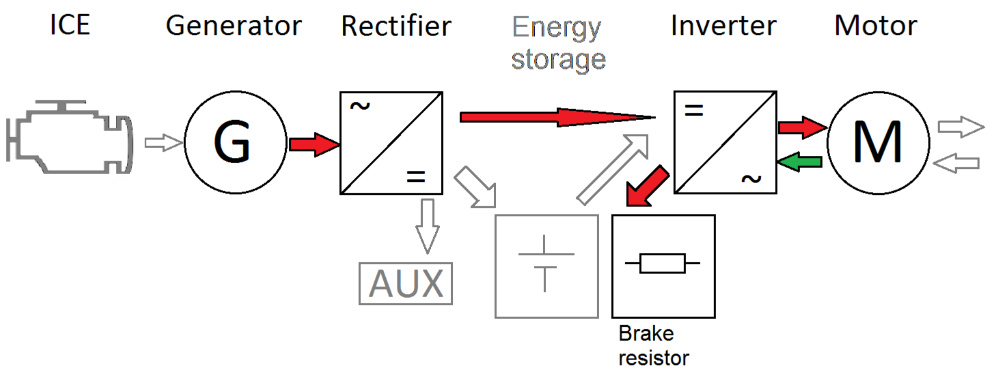


Figure 2.1 *Full powertrain block diagram.*

The mechanical rotation of the engine is converted to electrical power in the generator. In a straddle carrier the generator can be either permanent magnet or separately excited synchronous three phase generator. The rotor has a magnetic field due to the permanent magnets or the energized field winding. The rotation of the rotor or axis of the generator causes a rotating magnetic field. The flux of moving magnetic field induces current to the windings in the stator of the generator. Coupled together the generator and engine are commonly know as the genset.

Rectifier rectifies the alternating current from the generator to direct current. Six pulse diode rectifier is used for simplicity and due to the limitations of a mobile energy system. Feeding energy back to the network is not possible and trying to rotate the engine with the generator has negligible effect regarding energy efficiency. Also the power that could be fed backwards to the engine is very limited. Higher pulse order bridges offer little or no benefits in the confines of the mobile system and the transformers necessary for phasing in such rectifiers only add weight. Controlled rectifiers are not used as the engine is run according to demand and thus maximum energy transfer is preferable. Automatic voltage regulator (AVR) manages the output voltage regulation.

The rectified power is used to charge the energy storage necessary for a hybrid system or to directly run the motor inverters in direct electrical drive system. In the case of a hybrid system this kind of arrangement is called a series hybrid. The auxiliary loads can also be fed from the dc circuit. Motor inverters convert the direct current to alternating current of varying frequency according to control demand and the state of the motor rotation. The frequency of the inverter or motor drive is closely tied to the motors rotational speed. The phase of electrical current in respect to rotor position affects the torque of the motor and is used for control. Motor converts the electrical energy stored in the system to mechanical for traction or manipulation of loads.

Filters are not included in the system evaluated in this thesis. However there are cases where filtering has to be incorporated in to the electrical transfer chain and it is important to understand why and how they affect the system. The generator and the drives can produce high frequency harmonics. These will cause heating in the motors and lower their efficiency. In extreme cases the heating can be localized and cause component failure even with increased cooling. The filters are not lossless either and the benefits must be evaluated separately. Besides electrical parameters the heat dissipation caused by the loss must be taken into account when designing the filter.

2.1 Generator

The electrical power for the machine is produced with a three phase synchronous generator. A genset consist of an internal combustion engine and a generator. These are paired to match the load requirements and ICE capabilities. The pairing has major effect on the system efficiency. For static back up generation systems a narrow operating window can be optimized. Mobile system need wider margin for the dynamic loads. Depending on the application and requirements the generator can be either permanent magnet type or separately magnetized synchronous generator. Even an induction motor can be used as a generator though it has severe limitations.

When using induction motor (IM) as a generator magnetisation current must be provided with separate source like external power or capacitors as induction machine can only consume reactive power. This external source also controls the terminal voltage of the generator [8]. The one great advantage of an induction generator is its simplicity. An induction generator does not need a separate field circuit and does not have to be driven continuously at a fixed speed [8]. Despite all these properties induction machines as a generator are not further studied in detail. The focus will be on synchronous generator structures.

Straddle carriers synchronous generator is excited by a separate permanent magnet generator (PMG). The PMG provides power for excitation of the exciter field.

Voltage is controlled by feeding it through an automatic voltage regulator (AVR). The AVR senses the voltage from the generators stator winding directly, through a measurement transformer or from separate sensing tap. The AVR regulates the output voltage by controlling the current to the exciter field. By controlling the low power of the exciter field, control of the high power requirement of the main field is achieved through the rectified output of the exciter armature. The PMG system provides a constant source of excitation power irrespective of main stator loading and provides high motor starting capability as well as immunity to waveform distortion on the main stator output created by non-linear loads.

The AVR senses rms voltage on three phases ensuring close regulation. In addition it detects engine speed and provides an adjustable voltage fall off with speed, below a pre-selected speed (Hz) setting, preventing over-excitation at low engine speeds and softening the effect of load switching to relieve the burden on the engine. It also provides over-excitation protection, which acts following a time delay, to de-excite the generator in the event of excessive exciter field voltage. The AVR also incorporates over-voltage protection.The AVR also has input for emergency excitation cut off signal coming from machine control logic. Figure 2.2 shows the basic structure of the AVR governed separately excited synchronous generator.

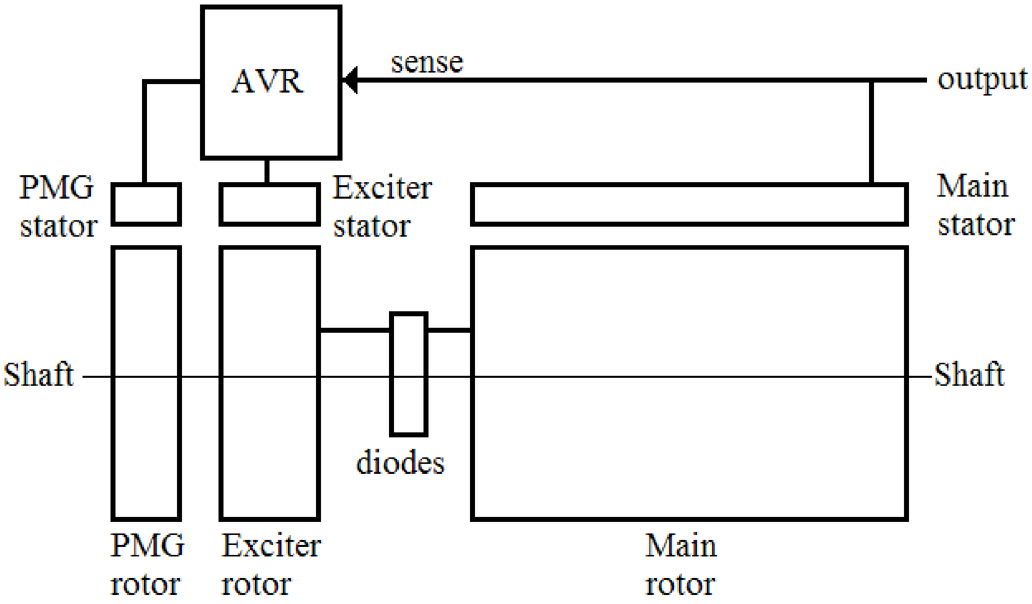


***Figure* 2.2** *Basic construction for separately excited synchronous generator.*

In the hybrid (HSC) system a different smaller permanent magnet generator is used. Permanent magnet generator is a device where the excitation field is provided by a permanent magnet instead of a coil. This however makes the voltage regulation more complex compared to wound rotor synchronous generator. While idling the main generators iron losses can be minimized by removing the excitation. However due to the nature of the permanent magnets the magnetic flux in the excitation generator can not be shut down and will cause iron losses and heat up the pmg. To lessen the effect of idle heating and unnecessary fuel consumption the genset is mostly run either close to its nominal load point or shut down.

PMSM generator has better power factor than induction generator as the permanent magnets provide the magnetization flux [9]. The difference between permanent magnet or separately excited and induction generation can be derived from manufacturer datasheets. When the magnetizing flux is provided by other means than induction the efficiency charts are nearly identical for motoring and generation. In the case of induction motor generation the charts have notable difference due to reactive part of the current needed for magnetization.

2.2 Electrical converters

Mobile systems introduce a whole new set of limitations for the rectification and power electronics. There is a lot more to take into account than just the obvious need for shielding the circuits against moisture and vibrations. The feasibility of many common solutions has to be separately evaluated. System optimization needs to have totally different approach when compared to stationary systems. These evaluations and research regarding the subject have been and will most probably continue to serve as field vast enough for several books and thesis works.

In the straddle carrier powertrain, electrical energy goes through several conversion stages most important being rectifier and inverter. In direct electrical drive system both the rectifier and inverters must be powerful enough to be able to deliver the maximum dynamic load. Hybrid machines need to manage the conversion of electrical energy to chemical and back. Hybrid systems however are not discussed in depth in this thesis.

Readers interested hybrid system energy storage and its optimization would perhaps like delve themselves into [6] [10] or [11]. Besides the main conversion stages in the system there are also several low power stages mainly for auxiliary loads. These will cause a constant load during idling or waiting periods and thus lower apparent efficiency. Their effect is minor during normal working cycles. The next two chapters will briefly describe the mentioned main conversions before continuing to electromechanical power conversion for traction.

2.2.1 Rectifier

Rectifier changes the 3-phase alternating current of the generator to direct current for the inverters, auxiliary loads and the energy storage of the vehicle. There are several common topologies and semiconductor devices used depending on the needs. Chosen technology will affect the creation of accurate loss model. Several interesting articles and books are written on the subject of rectifier and diode losses. Readers interested about the topic are encouraged to study power electronics in depth from sources like [12] [13] or [14].

Industrial installations have more flexibility in choosing the rectifier and differing set of requirements. In vehicle use the only power source is the genset which is not capable of sinking the regenerated power from the system. Active bridge with the ability to feed the excess power back to the network is not strictly necessary and simple diode rectifier bridge can be used. Active bridge is however more energy efficient choice as it gets rid of diode forward voltage losses and resistance in conducting state of modern semiconductors switches can be lower.

Common solution in industrial sites is to use two separate transformers or a single transformer with two secondary windings with 30 degree phase difference. This makes it possible to use 12 pulse rectifiers. These are preferred due to lower harmonic distortion content they produce. Technically distribution network harmonic current levels are not required as the system is self-sustaining. Thus there is no practical benefit of carrying a high power transformer in a vehicle as this would just increases the weight and electrical losses. However standards for electromagnetic emissions still apply and the system susceptibility to interference set the practical limitations for harmonics.

The rectifier consist of diodes. In its simplest form the dynamical model of diode consist of voltage drop V_fw and resistance R_d as shown in equation 2.1 and depicted in figure 2.3. The six pulse rectifier has two forward biased diodes conducting at

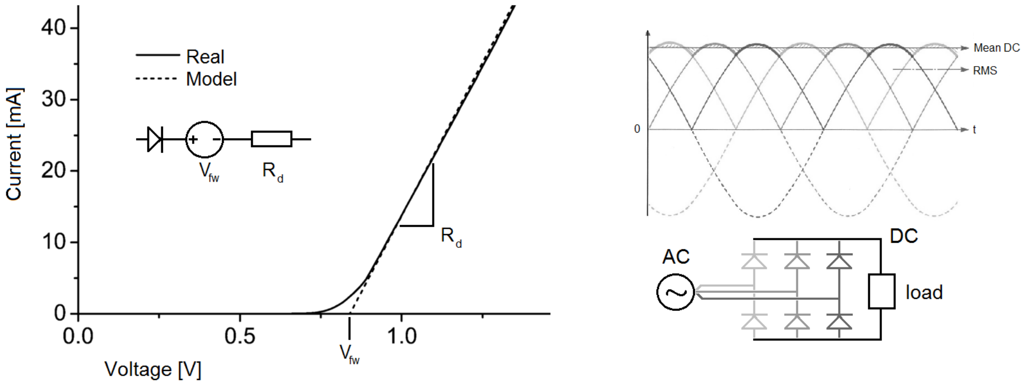


Figure 2.3 *Six pulse rectifier and diode model.*

all times. Figure 2.3 shows how the mathematical model can graphically derived from the operational curve of a real diode. The parameters are given in datasheets.

$$P_{diode} = V_{fw} I_{average} + R_d I_{rms}^2 \tag{2.1}$$

When changing from forward to reverse biased the diode has a limited reverse recovery time during which the diode conducts current. Reverse recovery conduction causes significant losses in high speed switching. They increase linearly with frequency and exponentially with temperature. Reverse recovery losses of each cycle depend on the average current and diode characteristics. [15] Reverse recovery characteristics also affect the circuit electromagnetic interference (EMI) generation.

2.2.2 Inverter

The motor inverters, later drives, are fed from the DC source via the main DC bus bars. In smaller systems the rectifier, DC link and inverter stage are self contained in one unit but in straddle carrier the modules are discrete. As described above the electrical powertrain consists of generator, rectifier, possible energy storage, inverter and motor. There can be filtering after the generator and before the motor. There are also several variations possible in the DC link construction within the inverter which can affect how the motor is driven. The DC link topology in drive can have capacitor, inductor or both depending on the application and power class.

For effective vehicle operation the drives must be able to operate in all four quadrants ie. motoring and generating to both directions. In hybrid systems the generated power can fed to the energy storage and reused. In direct electrical drive the power has to be consumed in brake resistors to prevent the system voltage from rising too high. A basic topology for a three phase inverter is shown in figure 2.4.

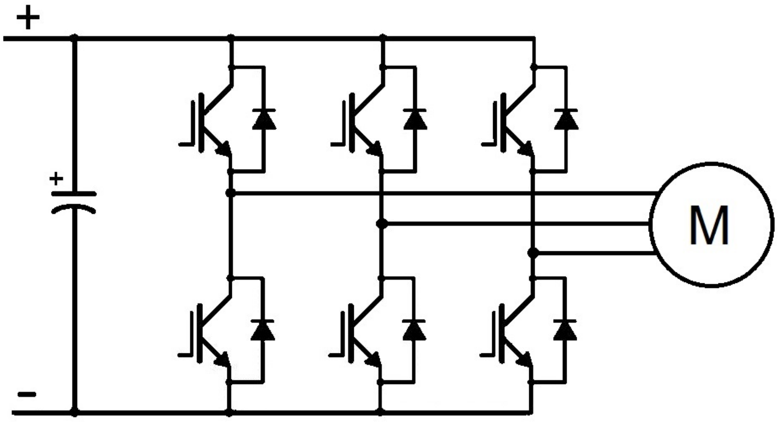


Figure 2.4 *Inverter .*

Drives create alternating current from DC with solid state switching. The carrier signal that controls the switches is modulated according to the needed AC frequency, voltage and current waveform. This creates a quasi sine wave that is filtered and fed to the motors. Due to the motor back EMF the drive maximum operating voltage also limits the maximum rpm for the motors. Back EMF increases with speed and surpassing the operating limits will cause an electrical breakdown in the switches.

Drive main losses are caused by the switch on-state resistance, the switching loss during opening and closing periods and the conduction loss through the diode. On state resistance is a component parameter and varies slightly over temperature. Losses during the switching period are caused by increased resistance in the switch when it is neither in completely open nor completely closed state. Switching losses are dependent on the switching frequency, voltage and current. Frequency affects how many high loss transitions there are per time unit. Voltage and current affect the loss during the transition. Current also affect the conduction loss during the on period.

Commonly used insulated-gate bipolar transistor (IGBT) switch packages include an anti-parallel diode. The diodes are necessary to free wheel the inverter system current over the single directional IGBT. The diode power loss during conduction is the same as was explained in the rectifier section.

Similarity between three phase inverter and rectifier diode set up is apparent. The diode conduction time depend on how the drive is controlled and the switch blanking time. Blanking time refers to the period when neither the upper nor the lower switch in a row is controlled on. Blanking is done to prevent short circuit across the DC source also called shoot through or cross conduction.

Main ways to minimize the inverter losses are using switches with low conduction as well as switching losses, different topologies and improved control algorithms. Control includes how the switches are controlled and how the load ie. motor is controlled according to its speed, position and input. Multilevel topologies could be used and commonly result in improved harmonics levels which in turn also reduce losses in the electric motor.

Semiconductor technology which affects the speed and losses of the system are a great interest in pursuing better efficiency. For example the speed of SiC switches which would enable lower losses and more possibilities for control would be good topic to look into. There are also some novel solutions with GaN based devices to reduce the reverse conduction losses. [16] Semiconductor properties also change the dielectric strength and thus the susceptibility to breakdown caused by motor back EMF.

2.3 Motors

Main moving and lifting force in the system is generated with electric motors. There are several ways of classifying motors one of which is shown in figure 2.5. The first classification used in this thesis is the driving current.

All motors compared and simulated in this work are principally AC motors as they are preferred in vehicle use for their more uniform torque generation and simple construction. The focus is on polyphase and in this case 3-phase motors. Other type in this classification being DC motors which are excluded from further study in this case.

The basic idea of AC motor is that the alternating current in the stator windings create a rotating magnetic field. Rotor tries to follow this rotation due to torque

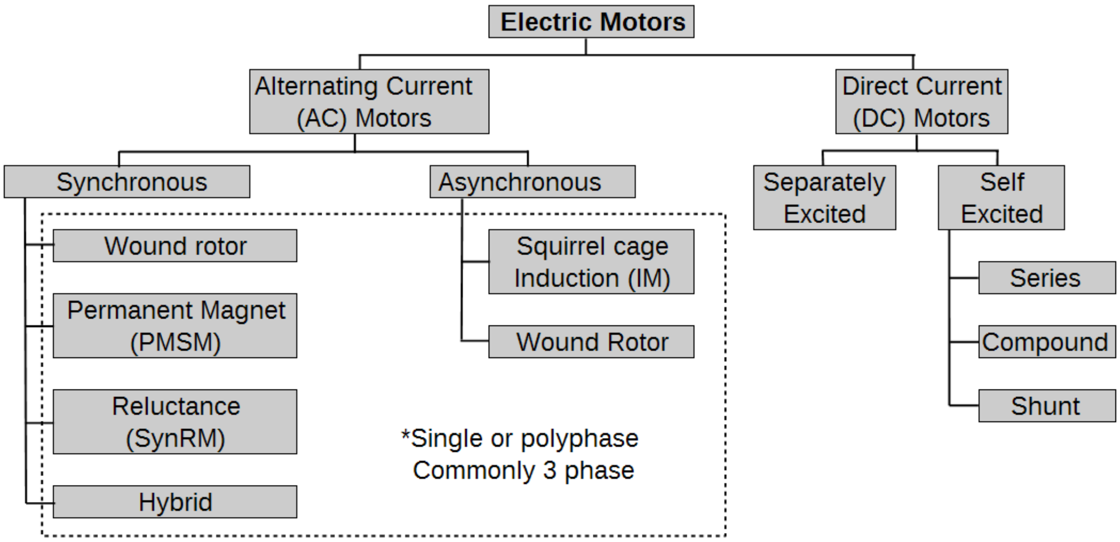


***Figure* 2.5** *Electric motor type classification.*

created between the field and rotor. The rotational speed depends on the input frequency and pole count of the stator winding. This is called the synchronous speed and can be calculated as:

$$n = \frac{120f}{p}[rpm] \tag{2.2}$$

Where f denotes the input frequency in Hertz and p the pole count. For a directly line fed motor the set frequency limits the speeds achievable for an AC motor. Frequency converter or inverter can overcome this limitation and vastly increase the control possibilities of the motor. Inverters can also be used to lower the required starting current that is usually very high. Up to the nominal speed joule heating in the windings are the main contributor to stator losses. These copper losses are directly related to the current needed to produce torque.

Besides the resistive losses there are stray and mechanical losses. Mechanical losses are common for all motors. They are caused by friction in the bearings and the aerodynamic drag of the rotor. Bearing friction increases linearly with speed and motors intended for higher load and more severe side loading will have higher bearing friction coefficient. The drag caused by the rotor core is usually comparatively low. In industrial motors the main part of the drag comes from the cooling fan mounted on the same axis. This fan load increases exponentially with speed. Self cooling is also the reason why standard induction motors can not be run below nominal speed with high load for prolonged periods. With low rpm the self cooling is significantly reduced and overheating the windings is a real risk.

The next chapter will explain the construction of the stator in more detail. Basic construction of the stators in all of the motor types studied basically the same if not identical. Air gap and field optimization will vary but that is again beyond the scope of this thesis. The following chapters will first cover the basic stator structure and continue to explain the rotor construction of different types of motors in more detail, how force is generated in each case and the major loss sources.

2.3.1 Stator

In AC machines the goal is to establish a continuously rotating set of rotating set of poles on the stator, which interact with an equal number of poles on the rotor, to produce uniform torque[9]. The stator core includes the stator slots in between the stator teeth. The slots are filled with slot conductor which, along with the end turns, form complete coils. The windings of the machine are termed distributed because they are not wound as simple coils, but are rather wound in spatially distributed fashion [9] The windings have major impact on torque generation and losses.

Figure 2.6 shows the basic construction of the stator core for the more common axial flux motor. Radial flux motor can be used in application where high torque and good power density is needed. There are many interesting designs emerging from smaller manufacturers but there is still no widely used industry standard solution like there is for the ubiquitous induction motor and the standard frames associated with those. In very small motors the stator can be a single steel casting. The stator shown in figure 2.6 is made by laminating thin steel plates together. The plates are cold rolled silicon steel also known as electrical steel which is similar to the material used in transformers.

For smaller motors the stator plates can be stamped or electrical discharge machining (EDM) cut as a single piece. For larger machines the plates have to be made in sectors and assembled. The stator plates that form the stator core are round in shape and have slots to accommodate the windings. The plate packet can also have axial channels for cooling either with liquid or air. Alternatively the plates can be

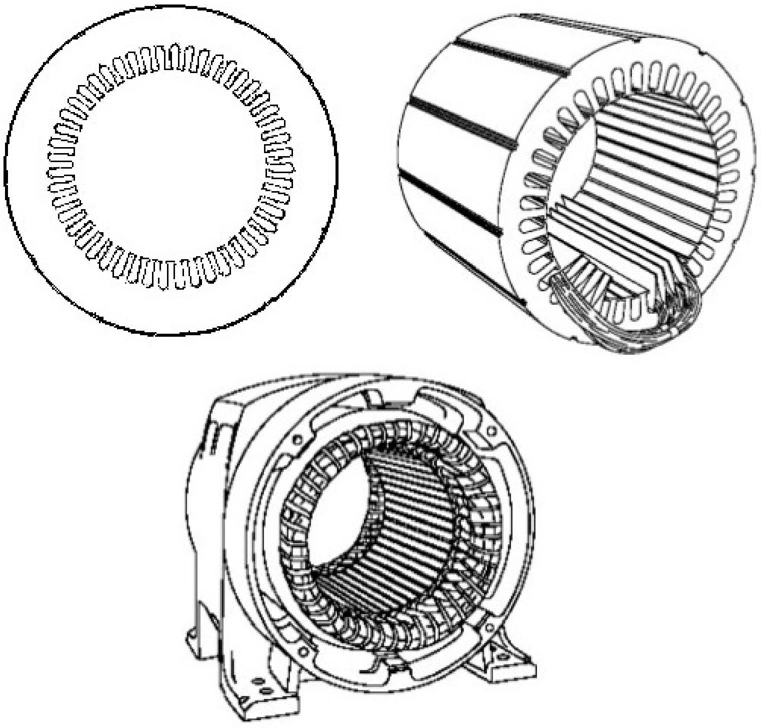


Figure 2.6 *Stator core. (Alibaba)*

bundled and these segments then be separated from the next with a small gap to allow air flow between them for cooler operation.

Most common industrial motors encase the stator core with cast or a machined metal chassis, that has ribbed surface for improved cooling directly to ambient. Aluminium is often used for good heat dissipation. However there are still many industrial applications where steel frame needs to be used for either strength or due to the operational environment constraints.

The main loss components of the stator can be seen in the power flow diagram 2.7. The loss division percentages represent typical values. Variation is high in the loss division and depend a lot from the motor size and design. Noteworthy observation is that permanent magnet or reluctance machine have practically no rotor magnetization losses.

Stator copper losses are dependant on the winding current. Magnetization needed by induction motor will increase the current and thus also stator losses. Even without any load there will be some core loss causing a small current to flow. This current

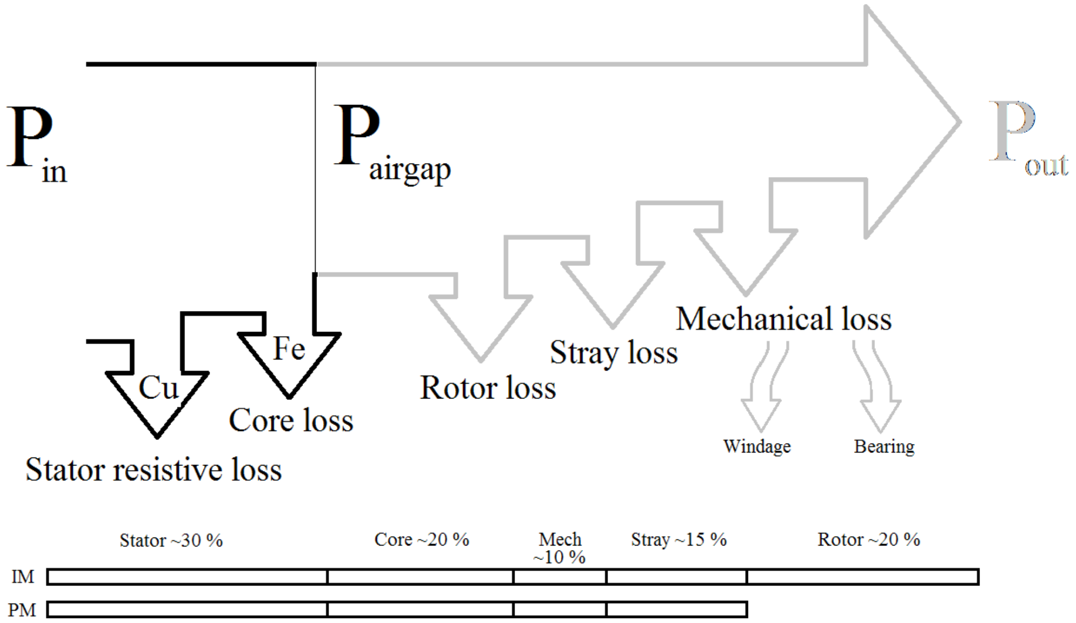


***Figure* 2.7** *Diagram for electric motor power loss division. [17]*

will cause small resistive losses in the windings but the main loss in this is the eddy current and hysteresis losses in the iron. These are depend on the input frequency, voltage and stator winding impedance. In short, higher input voltage and frequency will directly increase the losses in the stator. Magnetization energy needed for the stator is a constant set by the motor design [17]. Usually expressed in W/kg wherein the losses increase linearly with motor size. Most of the winding losses are due to resistive heating caused by the current consumed in producing the load torque and increase exponentially with load.

Iron losses are especially important in inverter driven motor due to the need for higher frequency drive for the motor. Inverters current switching also causes high frequency content to be fed in to the motor in the form of harmonics. Due to the non linear nature of the motor magnetic circuit the motor itself creates harmonic currents even in normal operation. These harmonics create heat due to eddy current losses in the stator iron and skin effect in windings reducing effective cross section of conductors. If the motor is not originally intended for inverter use, special care must be taken to limit high frequency content in the driving current for example with filters. Filter losses have to be taken into account in efficiency optimization when used.

The stators self induced harmonics are due to the non-ideal distribution of the windings. Slotting the windings cause the field to have stepped response instead of ideal sinusoidal distribution. The steps can be thought to be constructed from an infinite summation of sinusoidal waves similarly to a square wave. The harmonic currents are also one of the causes for torque ripple as some of them cause fields that rotate to same direction as the main field and some to the opposite direction. The resulting torque is the sum of all the fields.

Motor steel is not directional like transformer steel is. Alloying silicon to the steel is used to increase its resistivity to minimize eddy current losses. The silicon also changes steels magnetic properties and alloying needs to be controlled to minimize losses caused by hysteresis. [11] Traditionally the plates have been insulated from each other with paper. Nowadays lacquer is used. The purpose of the transformer like structure is to maximise the magnetic coupling from stator winding to rotor. Summary of the loss minimization methods is shown in figure 2.8. Hysteresis loss is minimal when the area covered by the hysteresis curve is minimized.

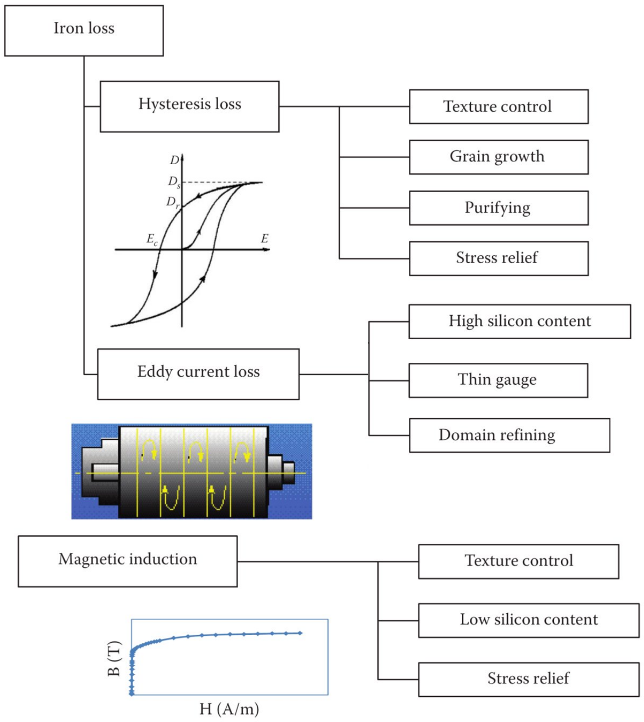


Figure 2.8 *Methods to reduce the eddy current loss, hysteresis loss, and improve magnetic induction during electrical steel manufacturing [11]*

Thin sheets of insulated high resistivity steel are used to minimize eddy current losses by confining them in smaller cross section. The thickness of the plates is always a compromise. Thinner sheets give better high frequency behaviour, but due to the need for insulating them, reduce the effective steel cross section in the magnetic circuit. Using thinner sheets also increase manufacturing costs. This reduction is known as fill or stacking factor and is used similarly in transformer calculation. Reducing the steel inversely increases the flux in it and limits the maximum level before the core saturates. Welding the sheet together is used to improve the structures mechanical rigidity but it will also increase losses. As the welding points increase so do the core losses [11].

In the flux weakening region the motor is operating faster than the nominal speed. In this region the magnetizing current is reduced and this reduces also the copper losses. Increasing speed increases the driving frequency which in turn increase the eddy current losses in the iron. The relationship of copper and iron losses is shown in figure 2.9. In short, current affects copper losses and iron losses are dependent on voltage and frequency. Optimizing the copper winding and cross section is a compromise between required electrical and magnetic properties and material costs.

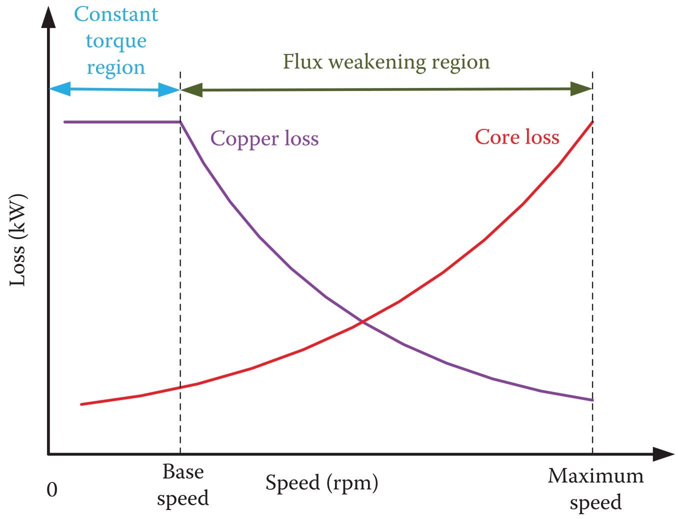


***Figure* 2.9** *Copper and core losses at different operating speeds [11]*

2.3.2 Induction motor

The practicality of induction motor especially in vehicular use like train was recognized early on. [18] Nowadays induction motors (IM's) are widely used in industry. Their simple and robust construction have made them popular in multitude of applications. They are readily available in standard sizes from several manufacturers. The competition and mature manufacturing technology makes induction motors a safe and relatively cheap option. The closed structure also enables the use of IM's in many industrial sites that require ATEX (risk of explosive atmosphere) compliant devices to be used. There are no moving contacts and the motor structure can be made fully enclosed.

Induction motor consist of the body, end plates, stator, rotor and axle. Usually the stator lamination are integrated to the main body and the rotor is rigidly fixed to the axle. The end plates and the bearings in them hold the axle and rotor concentrically inside the stator. Figure 2.10 shows the basic construction on induction motor. The rotor is a laminated steel cylinder which is manufactured similarly as the stator.

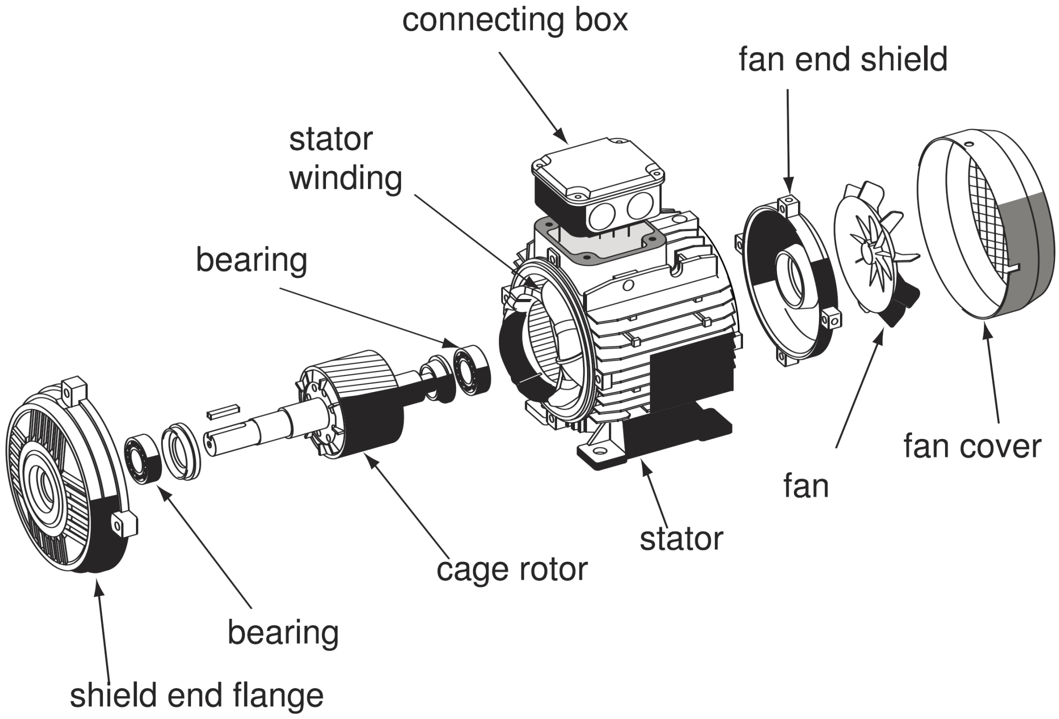


Figure 2.10 *Induction motor parts. (Schneider Electric)*

The squirrel cage rotor has slots for electrically conducting aluminium or copper bar windings and shorting rings in the ends. The bars and the end rings can be made by casting molten copper or aluminium over the laminations in a mould. In enclosed motor types where there is no external cooling flow to the motor, the shorting rings have small vanes to move the air inside motor body to circulate the air.

The squirrel cage is essentially a short circuited winding. The rotating magnetic field generated by the stator is seen as a changing field by the static rotor. This induces current to the rotor winding which in turn creates a magnetic field. This field opposes the stator field effectively creating torque force to the rotor shaft. As the rotor starts turning the frequency of the changing magnetic field seen by the rotor decreases as shown in equation 2.4.

Induction motor will never reach synchronous speed under load due to this phenomenon. The closer the rotor speed matches the synchronous speed, the less change in the magnetic field it sees. Changing field being the requirement for induction, at synchronous speed the field change is zero and thus generated torque is zero. This lagging of synchronous speed is called slip and is expressed as a percentage or ratio of the nominal speed and can be calculated with equation 2.3. Typical values range from 1 to 5 %. The slip s can be calculated from the synchronous or nominal speed n_s with the rotor speed n_r as follows:

$$s = \frac{n_s - n_r}{n_s} \tag{2.3}$$

The frequency in the rotor circuit f_r is dependent on the stator frequency f_s

$$f_r = s f_s \tag{2.4}$$

The slip affects efficiency of induction motor and is very important factor especially on dynamic loads. As the rotor is not locked to the synchronous speed of the stator the position must either be measured or estimated for accurate control. The position of the rotor compared to the field is especially important in torque control and vehicle use. Changing slip also affects circuit parameters and is represented in figure 2.11 as a variable impedance on the rotor side. The rotor bar material and shape affect the resistance and impedance accordingly. Aluminium has higher losses then copper but due to the lower inertia caused by lighter material more rapid speed changes are possible. The rotor impedance and how it changes can be optimized to have desired properties. Slot and bar shaping affect the reactive part of the rotor impedance.

Figure 2.11 shows a Steinmetz equivalent circuit of an induction motor with added iron loss resistance R_{fe}. The circuit shows that even without load the stator consumes magnetization current mainly set by the winding reactance X_s and magnetization reactance X_m. This small current causes losses in the winding resistance R_s and the hysteresis losses in the core is realized with the iron resistance R_{fe}.

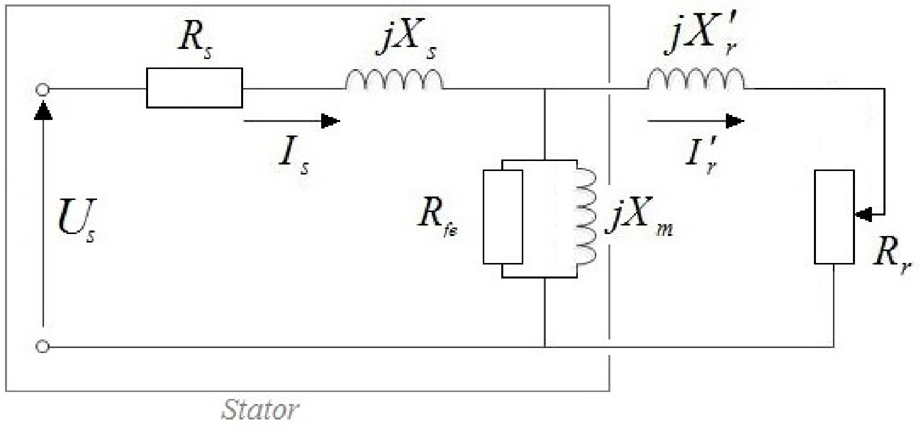


Figure 2.11 *Steinmetz equivalent circuit for IM.*

Figure 2.12 shows the basic construction of the squirrel-cage induction motor. "The low-resistance cage also has high inductive-reactance because it is surrounded by a great deal of rotor core material. Conversely, the high resistance cage has relatively low reactance. During starting, the rotor frequency is high so the preponderance of torque-producing current flows in the high-resistance squirrel-cage. At higher speeds, rotor frequency decreases and induced current gradually diverts to the low-resistance cage. This favours desirable running characteristics for the motor" [19]. Induction motor is inherently self starting and can be directly connected to the network, however the start-up current is very high.

Slotting of stator windings and rotor bar cause a stepped field distribution which in turn causes harmonics and torque ripple. These harmful effects can be slightly reduced by skewing the rotor bars. Skewing will also reduce the chance of rotor locking to harmonic field component also known as cogging. The main disturbance

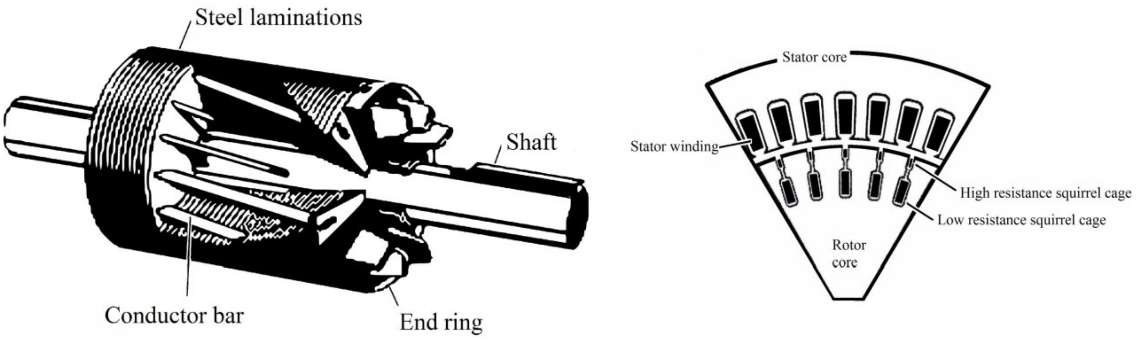


Figure 2.12 *IM rotor and lamination cut out. (Electrical Science)*

component can be cancelled by dimensioning the skew so that there is 180 electrical degrees phase difference between the shorting rings on that frequency [8].

Dynamic model of the induction motor can be created by using space vector theory. The induction motor is typically modelled in rotor flux reference frame. Detailed equations for modelling the induction motor can be found in [10] or [9]. There are several methods for estimating the model components and dynamic changes in motor parameters. [20] [21] [22] [23].

Majority of the power losses in induction motor rotor are caused by the squirrel cage resistance by the magnetization current. Stator losses are described in previous chapter. Namely stator copper and iron losses and rotor windage and bearing ie. friction losses as shown in figure 2.13. All of the magnetic flux created by the current flowing in the stator windings does not couple to the rotor ie. due to winding end effect and causes stray losses. Mechanical losses are caused by aerodynamic drag of the rotor and bearing friction. Windage losses also depend heavily on the how the motor is cooled. Self cooled units (IC 411) incorporate a large impeller on the rotor axis which also increase the drag and thus losses. The mechanism for stray losses are still not comprehensively understood and their estimation methods are often based on measurements.

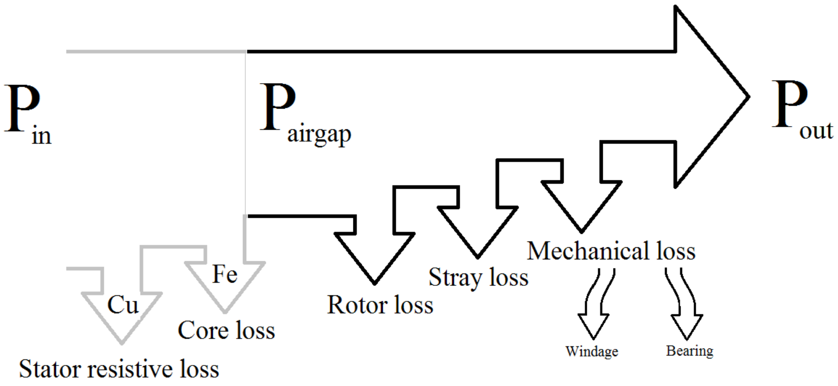


Figure 2.13 *Induction motor power loss.*

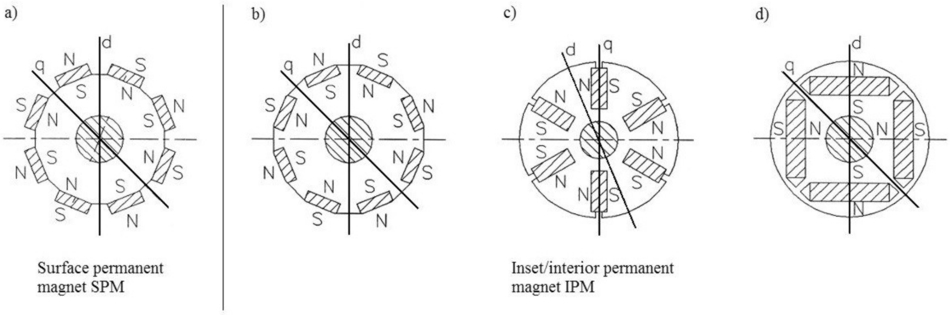
Despite its drawbacks induction motor technology is popular due to simple and rugged construction. Manufacturing methods have long history and high maturity. Completely closed constructions enable their usage in ATEX classified locations. Their high overload tolerance is attractive in certain applications. Good level of standardisation has made it almost a Lego brick like components in many industries. Modern drives with high processing power and advanced control algorithms have enabled more precise servo use of induction motor.

2.3.3 Permanent magnet synchronous motor

Permanent magnet synchronous motor (PMSM) is a synchronous motor, meaning that its rotor rotates at the same speed as the motor's internal rotating magnetic field. PMSM is similar to winded synchronous motor but the excitation flux is produced by permanent magnets instead of the magnetizing current. The magnets produce fixed excitation flux and this makes driving PMSM in field weakening region more difficult than separately excited machines. [24] [25]

The basic stator structure is the same for IM and PMSM. Parameter optimization can change the slotting, windings and air gap of the motor. The rotor for PMSM has magnets either on the surface (SPM) or embedded in the rotor (IPM). Some examples of the rotor magnet positioning are shown in figure 2.14. Surface permanent magnet motor(example a) has the magnets on the rotor surface. As the permeability of the magnets is nearly the same as air, the air gap of the SPM rotor is constant resulting in almost no magnetic saliency. Saliency is the difference in motor inductance at the motor terminals on different angles between stator and rotor. Attaching the magnets on the surface is difficult and the weaker mechanical structure often limits the safe maximum speed.

Interior permanent magnet rotor (example b) has the magnets set into the rotor which improves structural stability and introduces saliency to the system. Saliency of the rotor causes also a reluctance torque component. Radially magnetized rotor can be seen in 2.14 c. Example d shows and interior or buried permanent magnet rotor. This type of structure has the added benefit of having also reluctance torque due to the magnet material permeability and orientation.



Surface permanent magnet SPM

Inset/interior permanent magnet IPM

Figure 2.14 *Different PMSM rotor magnet configurations. (Posterus)*

Permanent magnet motor speed is limited by back EMF because the latter increases directly with motor speed. The motor is connected to the electronic drive and the dielectric strength of the electronic components limits the maximum voltage the drive can handle. In normal operation the motor and controls remain well below the absolute maximum limits. However, if motor speed exceeds the design speed range (either due to control or being driven by the load ie. towing) it is possible to exceed the maximum voltage of the drive components and cause them to fail. Drives are capable of limiting motor back EMF in nominal operation and slight overload conditions. If the drive faults and loses control during overspeed, it typically cannot protect itself unless crowbar circuit is installed.

Similarly to induction motor, dynamic model of the PMSM can be created using space vector theory. Detailed equations for modelling the PMSM can be found in [10] or [9].

Unlike induction motor the permanent magnet motor has no significant rotor losses as the magnetizing flux is provided by the magnets instead of induced current.

This also decreases stator current due to better power factor and thus losses in the windings are reduced. As the flux provided by the magnets cannot be controlled, operation in the field weakening region is more complex [25] [26]. The constant flux also causes more losses in stator iron in the high speed region as it induces eddy currents. The induced current cause counter torque and lowers the efficiency at high speeds.

Synchronous operation offers more precise speed control, higher efficiency and lower rotor/bearing temperature. PM motors eliminate rotor conductor losses. They have lower resistive or Joule losses in the stator mainly due to lower current and exhibit a flatter efficiency curve than induction motors. They also run cooler than IMs, resulting in longer insulation and bearing lifetimes. PM motors have better power density giving more torque for the same size of package or the same torque in a smaller package.

For the same frame sizes PM rotors typically have lower inertia thus having faster response than IM. The rotor has no windings or electrical connections to the stator. This requires more advanced drive and sensing. To operate the machine properly, the rotor position has to be known, either from the feedback given by a position sensor, or from a position estimation algorithm [11]. Position can be measured either with encoder or resolver.

Permanent magnets are expensive and their price is unpredictable. Currently majority of worlds rare earth magnet mineral are controlled by China and their economical aims can have drastic effects on magnet production. Permanent magnets are sensitive for overheating and overcurrent which can cause partial demagnetization. The rare earth magnets are ceramic like substance which causes limitations for the magnet geometry and installation. Losses and less rugged construction limit high speed use. In addition, the strong magnetic rotor field can make servicing, a key feature of a mainstream industrial motor, more difficult. The created electric power also has to be taken into account when servicing ie. during towing situations.

2.3.4 Synchronous reluctance motor

The synchronous reluctance motor stator structure is identical to IM and PMSM stator. The rotor manufactured similarly with magnetically soft steel laminations, but without any windings or squirrel cage. The shape shown in figure 2.15 is designed to have flux barriers that cause the smallest possible reluctance in one direction with the highest possible perpendicularly to that ie. the rotor has saliency. The practical difference between IM and SynRM is the salient rotor. Torque is produced as the rotor attempts to align and lock the magnetically least resistive direction to the rotating stator field.

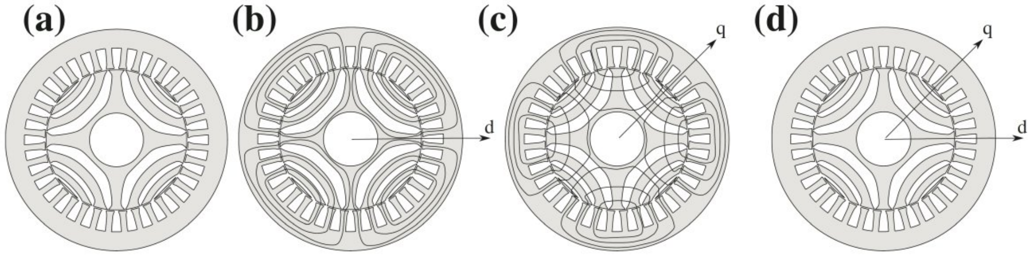


Figure 2.15 *Four pole synchronous reluctance motor with a geometry, b d-axis flux lines, c q-axis flux lines, and d reference frame [27].*

When the rotor is rotating on synchronous speed there is no current conduction and losses are minimized. As the rotor rotates on synchronous speed there is no current induced in the rotor and thus effectively no rotor losses. Reluctance motor is no new design idea, but the complicity of controlling them has so far been prohibitive for widespread use. Newer generation drives have the computing power for accurate and efficient control.

SynRM has no significant rotor loss but has comparatively poor power factor which potentially increases inverter current requirements [28] besides the control capability needs. Main loss components are stator copper and iron losses and mechanical losses. The loss division is similar to PMSM. The reluctance machine can be used in field weakening region without the problems caused by demagnetizing of permanent magnets or heating of the stator core, which are the problems with PMSM. Similarity of SynRM to IM can be seen in figure 2.16.

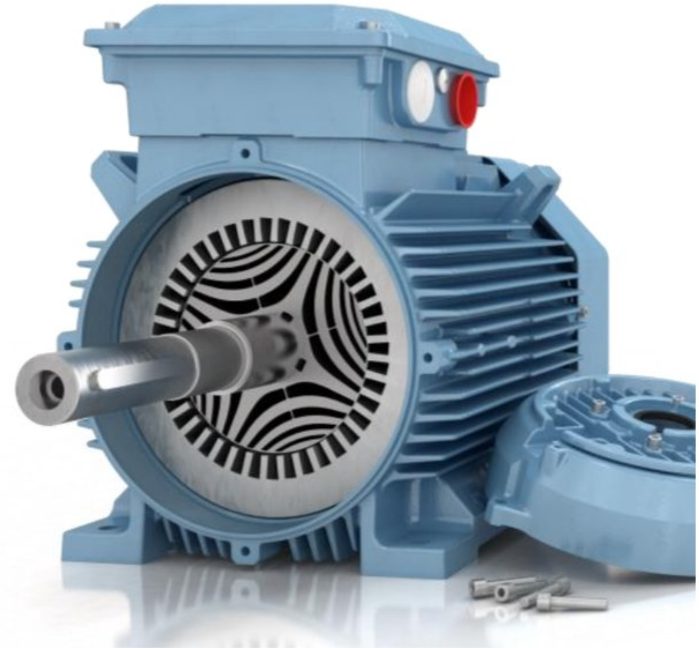


Figure 2.16 *Synchronous reluctance motor built in standard IM frame. (ABB)*

As a positive side SynRM have a cost advantage as they do not need expensive rare earth elements. SynRM tolerate overloading well, as there are no magnets to overheat and demagnetize. They generally have lower starting torque and poorer power to weight ratio compared to PMSM. The slotted rotor has low inertia which means faster torque dynamics. As a downside especially for vehicle use SynRM have more torque ripple than IM and PMSM [29]. Without magnets and without a cage, the rotor construction is simpler than either IMs or PM motors. Maintenance is identically simple as with induction motors.

The poor availability, low power factor and torque ripple do not encourage the use of SynRM's in vehicles just yet. Some reports also indicate noisy operation which causes problems for working machine design. Despite the robustness and good efficiency the usage of SynRM in straddle carrier is not studied further in this thesis. However permanent magnet assisted reluctance motors seem an attractive option for future developments. Especially with ferrite magnets instead of rare earth materials to reduce the potential continuity risks.

3. LOAD

The load demand and how power is used has a major impact on hybrid system optimisation. As the load patterns for road vehicles are comparatively simple there are standard load cycles available. One such example is the NEDC (New European Drive Cycle) for automotive industry. There are similar data sets available for US, Australia and Japan.

Working machine load depend largely on the type of work it is designed for. Hybrid system load optimisation depends more on the actual load cycle than the application the machine is designed for. The possibilities for power regeneration will also differ. Thus the tasks and pace of work will affect the outcome. Because of this complexity of the load patterns there is no standardized load cycle available for working machines. This chapter will compare automotive and working machine load cycles and look into straddle carrier specific load scenarios. The focus will be on different powertrains and improving the energy efficiency of the auxiliary loads like work lights or air conditioning is not considered.

While driving in level conditions a vehicle has only kinetic energy of the movement. Power is only used for acceleration, overcoming roll friction and aerodynamic drag. Ascending a slope will increase power consumption as potential energy is increased and this can be recovered during descend. In a road vehicle the drag is a major energy loss component but for a slow moving working machine the roll friction causes biggest losses.

In a hybrid road vehicle the energy can normally only be regenerated by slowing down ie. braking. There has also been research to regenerate power from vehicle suspension [30]. The drive motors capability to provide negative torque and the energy storage charge rate will limit the maximum instantaneous power regeneration. These will also affect the braking force the regenerating system can provide. Mechanical brakes has to be applied for very fast deceleration, i.e. emergency braking. Using mechanical brakes will lower the overall efficiency of the hybrid system.

The braking strategy will have a major impact on traction regeneration efficiency and should be optimised according to application needs and known drive patterns [31]. Tweaking the braking strategy is comparatively cheap and efficient way to improve the vehicle efficiency as it is a optimisation problem that can be made in control software and no mechanical changes need to be made. In non-hybrid system the recovered energy is wasted in brake resistors. The only added benefit is less wear on brake calipers. Working machines can recover energy also from other sources besides traction.

A working machine will have different load handling mechanisms for its needs and those can also be used for regeneration. The systems can be hydraulic or electrical. For example the swing of the base or the movements of the boom in an excavator. In the case of the straddle carrier the potential energy stored in the mass of the cargo when lifting a container can be regenerated during lowering besides recovery from traction. Straddle carrier uses more power for traction than load manipulation. In construction machinery the major part of regeneration is from actuators. The regenerated power can be significant and vary rapidly [10]. The load dynamics are also very different for a road vehicle and a working machine.

For a road vehicle the changes in used power are comparatively slow and predictable. Power is used for acceleration followed by comparatively long stable periods with minute variations in power. This is due to the simple load patterns the highway or even city traffic provides. Economical driving in mind, stopping completely are being avoided and control movements are gradual instead of instant stop/go sequences. This will also cause the peak demand level being closer to the average consumption. A working machine will have much faster rate of change and the load demand can have very high peak power levels [5] [32]. In some applications there can be periodic or cyclic high and low load alternation. The load will differ depending on the industry and application thus forming a comparable drive cycle model is difficult. From figure 3.1 we can see how the drive motor power demand is distributed during a working shift and sample of the instantaneous power as function of time. Negative values represent regeneration. Similar data for the hoist motor can be seen in figure 3.2

The data shows that most of the time the machine uses relatively low power levels and the average consumption is low compared to the peak level. This does not mean that the load torque would be low on the drive motors. High currents are needed to

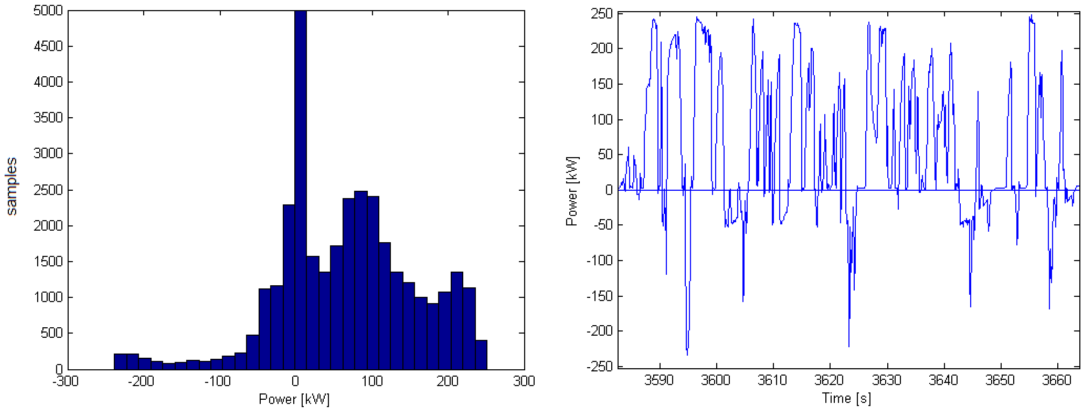


Figure 3.1 *Distribution of drive power levels during a shift.*

create significant torque but in the low rpm region the supplied voltage is low and thus the total power is also low. High current equals high copper losses. With typical induction motors used the low efficiency in start up region and reduced cooling cause performance constraints. This is also the reason why many of the traction motors in automotive industry are liquid cooled. Standard induction motors with the cooling fan on the same axis as the load work are simple and work well when used on nominal speed.

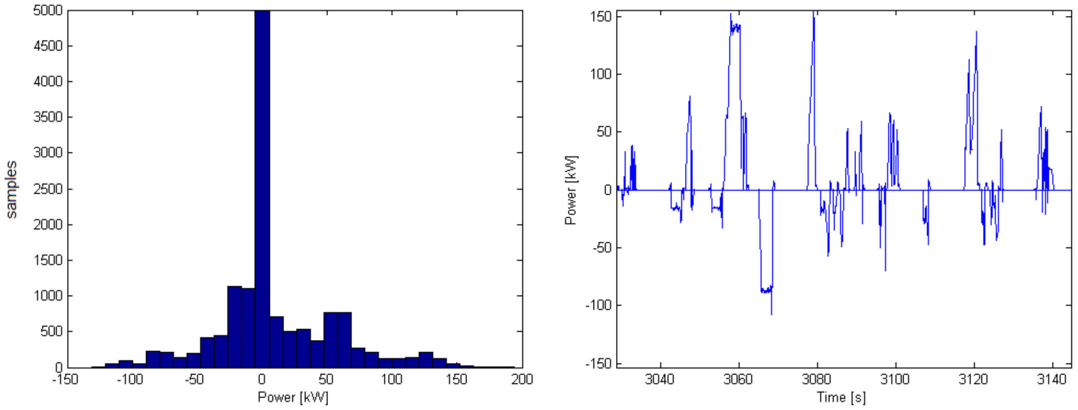


Figure 3.2 *Distribution of hoist power levels during a shift.*

Straddle carriers work cycle can be simplified to three actions moving with and without the load and manipulating the load. This can further be divided to hoisting and lowering the load and possible wait periods. A waiting machine is not productive and from the operators point of view the wait periods should be minimized and the utilisation rate of the machine maximized. To maximize the operational efficiency the problem can be given to the computer running the port operating system. There are an automated ports for example in Brisbane and Los Angeles where this kind of automation is in operational use.

As the machine does seaside work the wind certainly has an effect on the bulky and aerodynamically less than optimal shapes movements. There is no data available about the wind direction and thus it can not be calculated. The wind effect is estimated to average out to zero. This is not strictly correct as the drag increases by the square of the speed and thus the combined effect of the drag should be slightly higher than zero. Aerodynamic drag can be calculated as shown in equation 3.1. The machine main pillars are separated enough that both the front and rear can be considered to increase the aerodynamic drag area A. The machine is divided into simple parts and each uniform shape is given drag coefficient C_d. Combining the frontal areas with the different aerodynamic drag coefficients the total force F_d can be calculated with the air density ρ and speed V_m.

$$F_d = \tfrac{1}{2}\rho A C_d V_m^2 \tag{3.1}$$

Roll friction can be estimated from steady speed driving or deceleration data. Different speeds and few different container weights are used for calculations. Rolling resistance force F is calculated from normal force N the vehicle weight causes to the surface and the rolling resistance coefficient C_{rr} as shown in equation 3.2. Besides friction the tires affect the accuracy of speed estimation as the effective radius changes in respect to speed.

$$F = C_{rr} N \tag{3.2}$$

Along with the bulk inertia of the machine, rotating masses like the motor rotors, transmission gears, axles and the tyres affect the movement of the straddle carrier. Combined effect of these need to be taken into account when calculating the physical model. Especially the fast rotating motor rotor inertia has impact on vehicle dynamics. These work in a sense as a low pass filter for the machine movements.

4. MODELLING

Modelling is representing real world complex phenomena in a simplified mathematical form with the aim to estimate certain behaviour within limited operating conditions. Model limitations depend on the simplifications made and the required accuracy. Derivation of good analytical model can be difficult and time consuming even with very confined operating conditions. With complex phenomena or interlinked systems the level of difficulty quickly increases.

There are several ways to approach the problems presented depending on the modelling need and data available. The models can also be constructed for different needs like dynamical modelling of changes happening in the system or static models for the steady states of operation. These both have different limitations and requirements. This should be taken into account when defining the modelling approach and must be remembered when interpreting the results. Constructed models should be verified when possible with representative test cases or known input to output results. Besides the created model the underlying software platform can be a source for errors. Software is constantly being developed and improved as they offer many benefits.

By modelling and simulations the design and implementation process can be made easier and more economical. By discarding inefficient solutions or just plain bad ideas with the help of simulation models the costly implementation and unnecessary test can be reduced. This way only the potential solutions and their models need to be tested to confirm the accuracy of the model and to improve it. The following chapters describe the modelling process for different parts of the Straddle carrier needed to estimate the current efficiency of the whole powertrain and for finding the most critical parts for improvement.

4.1 Genset

In hybrid machine the generator runs at its nominal speed most of the time. There are occasions where it is either idling for short periods or overloaded for limited duration to fast charge the energy storage. In practice the hybrid machine generator is used as a constant power charger for the energy storage and thus a single efficiency figure can be used for the machine model although manufacturer efficiency chart as well as estimated chart from machine parameters are available.

The separately excited generators practical efficiency can be either found from datasheet figures provided by the manufacturer or calculated from the vehicle sensor data. The input mechanical power is calculated from the diesel engine rpm and torque data reported by the engine control unit (ECU). The generator electrical output is measured in the input side of the rectifier. Comparing these two figures an efficiency chart for the electromechanical conversion can be mapped by using Matlab or even a spreadsheet program. The dynamic range for the measured values is limited by the selected energy management algorithm which controls the engine and charging. With a basic second degree model of the generator and manufacturer data these maps can be extrapolated with reasonable accuracy. Figure 4.1 shows the comparison for manufacturer reported efficiency and the efficiency derived from the model.

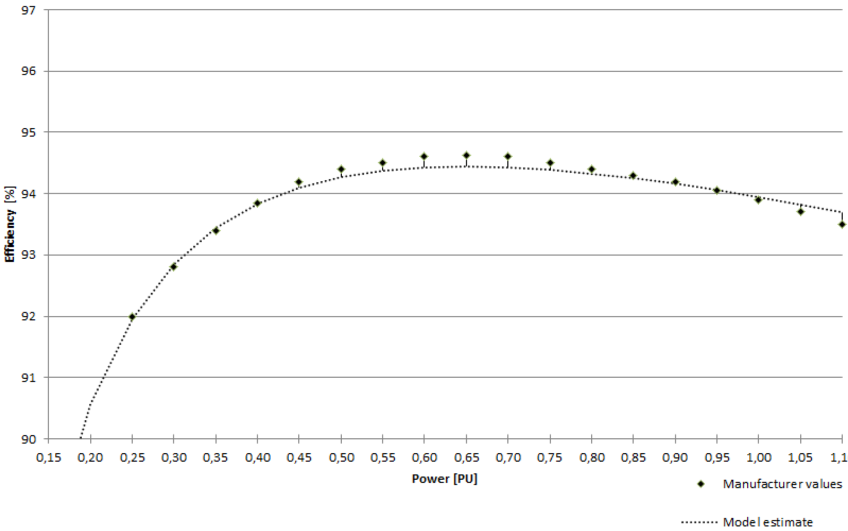


Figure 4.1 *Comparison of generator nominal efficiency and model estimate.*

Due to the AVR keeping the output voltage constant the iron magnetization losses can be estimated to be constant for the operating range. Machine control keeps the engine rpm on two main operating points with small variation due to load changes. Efficiency for both speeds can be estimated with the same equation as the total error is within 1 %. Method to calculate the generator efficiency is presented in 4.1. As the genset is operated on nearly constant speed the P_{wdg} or the winding loss can be estimated as a constant. This is also true for the core iron losses P_{fe} as the AVR keeps the stator voltage constant. The stator and magnetization copper losses are dependent on the output power or more specifically the output current. Stator loss is output phase current I_o squared times stator winding resistance R_s. Similarly for the magnetizing circuit I_m is the current and R_m the winding resistance.

$$P_{loss} = 3R_sI_o^2 + R_mI_m^2 + P_{fe} + P_{wdg} \tag{4.1}$$

Strictly speaking neither the coefficients for the linear part nor for the quadratic part can be completely separated with the existing data. Available data is input to the equation and remaining partly estimated coefficients are tweaked to final value with curve fitting. For the limited range where the model is used this method results in less than 0,5 % unit error. For faster calculation the efficiency curve of the generator is implemented as an array in the system simulation model.

4.2 Rectifier and drives

The rectifier is modelled as a diode. The dynamical model of diode consist of voltage drop V_fw and resistance R_d as shown in equation 2.1. The six pulse rectifier has two forward biased diodes conducting at all times. The electrical loss is calculated as two diodes in series with the circuit. For thermal calculations all six are considered separately.

The current for the diode is not the rms phase current. The diode is conducting only when the capacitive storage is charged ie. when the input voltage level is higher than in the capacitors. This causes very high current for a short time period resulting in higher losses. The current peak can be estimated from the maximum allowable voltage ripple. Average current is derived from the power and the main DC bus voltage. Generators power factor is controlled close to 1. This minimizes losses caused by diode reverse recovery and thus those can be excluded from the loss model resulting in average efficiency close to 99 % for the rectifier. This is unrealistically optimistic but is accepted due to the low impact rectifier has on the overall accuracy.

Due to the low impact on the overall accuracy of the complete powertrain loss model the rectifier efficiency could be treated as a constant. However joule heating losses in the current conducting parts of the system add up and are thus included. Motor drive efficiency is estimated to be 98 % according to manufacturer and measurement data. The efficiency is dependent on the drive current. As the drives are not the main focus of the work more detailed model is not implemented.

4.3 Motors

Most of the motor efficiency models are based on similar calculations. However the accuracy and methods in retrieving motor parameter vary significantly. For example there are methods for estimating the parameters from nameplate data [21] or other parameters [22] [23]. These variations and their effect on accuracy has to be taken into account when comparing the models. Some but not nearly all have been confirmed or compared with manufacturer models or detailed information about the motor in question. In cases where accurate and abundant enough information was given by the motor manufacturer, separate motor model has not been made. Some motor models used to extract the efficiency charts are manufacturer "black box" models where the workings and modelling approach is unknown. Due to the system level approach and intended application of these models they are deemed accurate enough for the purpose.

4.3.1 Induction motor

Induction motors are modelled in Simulink according to the equations in [9] and [10]. There are some additional loss components not covered in the equations like the iron saturation and cooler fan load. These are implemented as separate modules. The model inputs are the load torque and speed. Voltage is speed dependent. The inputs are swept linearly and the output is saved to a matrix representing the efficiency chart. Figure 4.2 shows the dynamic model for the induction motor. Majority of motor parameters are from manufacturer datasheets but some have been estimated according to principles presented in [21] [22] [23] literature.

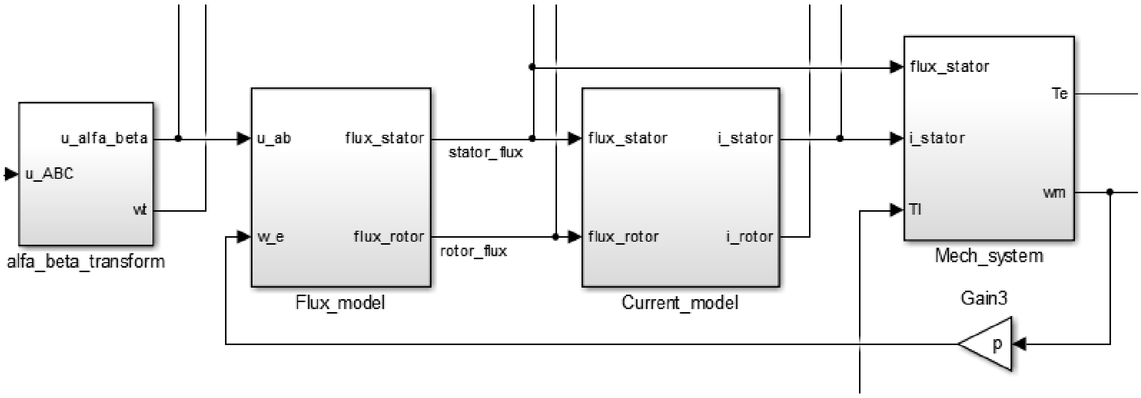


Figure 4.2 IM dynamic model main components.

4.3.2 Permanent magnet synchronous motor

PMSM's are modelled in Simulink the same way as the induction motors. Equations are represented in [9] and [10]. Figure 4.3 shows the basic structure of a dynamic model for the permanent magnet motor. Motor parameters are from manufacturer datasheets where model had to be made. Some suppliers have provided complete efficiency and torque charts and those are use instead of the charts derived from modelling.

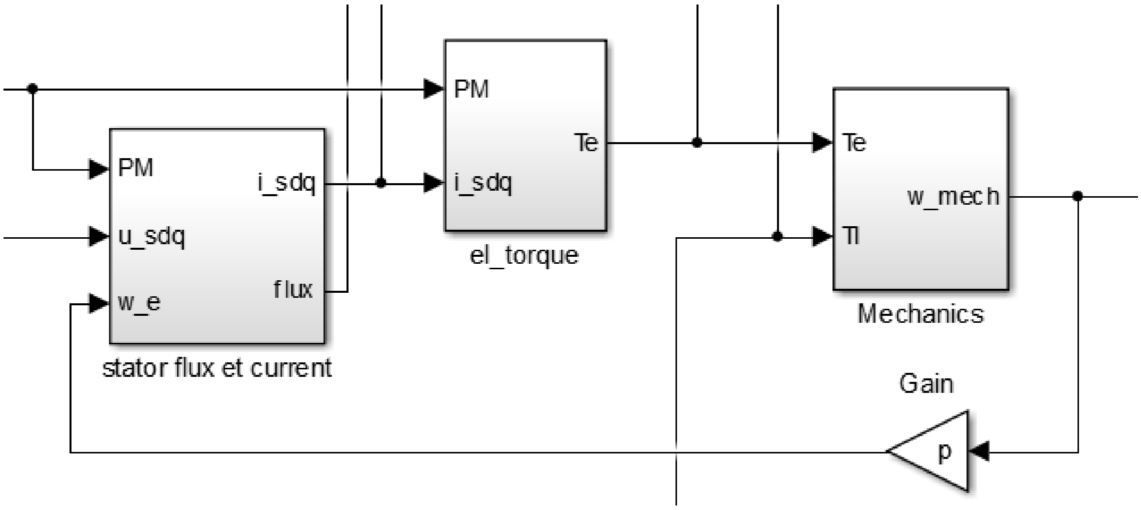


Figure 4.3 PMSM dynamic model main components.

4.4 Load

The simulated powertrain is loaded with work cycles constructed from measurement data. The model is made simple enough for calculation with full data sets. Load point clouds can be used to compare different powertrain models and how their efficiencies behave during different loading conditions. The data is filtered through the model of the machine physics to discard unrealistic values caused by ie. measurement jitter. Example of the plotted machine data is shown in figure 4.4. With simulated load ramps the full efficiency charts can be mapped even outside the normal loading conditions as long as the models are valid in those regions.

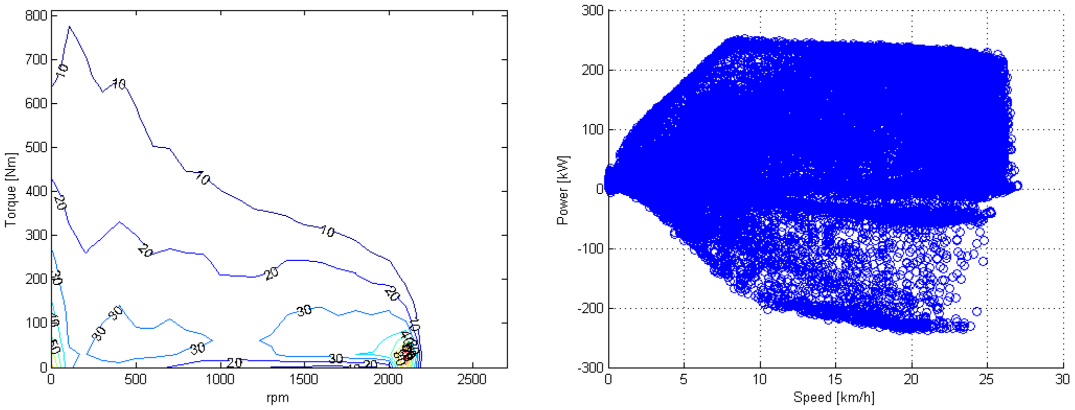


Figure 4.4 *Normalized load distribution and measurement point cloud.*

The full data set with different measurements are used for more accurate estimation of machine parameters and operating conditions. However even with the myriad of data certain assumption still have to be made. For instance from the speed and its changes acceleration can be calculated. From the cargo weight and acceleration with the machine datasheet the needed torque can be estimated. This however still does not take into account if the machine is changing its direction or climbing a slope. There is no measurements available for the gradient nor how the load is shared between the drive motors during non linear motion and it is assumed that the machine is on level surface and not turning.

Torque for the hoist motors is derived from the load cell data and machine documentation. From the hoist system there is no speed or cargo height information available from where the hoist motor rpm could be calculated. This limits the mapping of the hoist load. When the hoist power distribution 3.2 is compared to the drive motors 3.1 the more balanced nature between power use and regeneration can be seen.

This is also evident from the measured power as the function of time figures. The lower losses in the hoisting system contribute to the better level of power regeneration. The movements are also simpler to model and less environmental assumptions need to be made. The cargo can only move limited distance and the direction of movement is dictated by the guide rails the spreader is attached to.

During movement the rolling friction and aerodynamic drag must be taken into account. When accelerating or decelerating the combined masses of the machine and cargo must be included. Rotating masses like the motor rotors, transmission and tyres also affect dynamic load conditions. From system point of view the aerodynamic drag has very little effect on the overall forces in the system and could be excluded in low speeds. Up until 20 km/h speed the drag is less than 2 % of the total force. Roll friction is estimated from several steady speed driving sections power usage. Different speeds and few different container weights are used for calculations. The final value for the model is the average of these separate calculations.

From the recorded machine data the percentiles for different load modes of the straddle carrier can be calculated. As the majority of the data is from customers testing phase the average load levels are very high and can be considered as the upper limit or even beyond real world situation. The distribution however can be considered representative of real work cycles when normalized.

Movement takes up around 70 % of the time and manipulating the load 20 % the rest 10 % being uncategorised. From the the total time the machine is carrying cargo 40 % of the time. From this division a single ended moving operation can be concluded as half of the time the carrier is driving without a container. This data can be used for general level calculations. These numbers are however not enough for any kind of powertrain optimisation. Overall for electrical vehicle design the complete drive or load cycle is very important and it is not enough to consider only the nominal operating point of the electrical motor. [33]

Analysis of the hoist regeneration reveals around 50 % return ratio in majority of the cases. It can be concluded that the hoist regeneration is closing on to its optimal point when taking into account the losses in the system both in hoisting and lowering action. However the regeneration for the driving is less than 20 % which still has a lot of room from improvement. The drag and friction losses for traction are higher than in the hoist system. Due to the comparatively high regeneration percent and low total energy usage of the hoist system improving the efficiency of power generation and traction is seen more beneficial. For direct electric drive system only the forward conversion path impacts the system overall efficiency as the regenerated power can not be stored. When needed the brake resistor heat could be directed towards cabin heating [34] to gain some benefit from the regeneration.

5. RESULTS AND ANALYSIS

When reading this analysis, reader should keep in mind that the economical feasibility of implementing changes to production is also taken into account. The payback period of efficiency improvements are based purely on estimated diesel costs linked to machine hours spent on yearly basis. With high enough volumes the unit cost could reach low enough level to reach an acceptable payback period but in depth economic study is beyond the scope of this thesis. With additional incentives and more thorough cost study some discarded ideas could be revisited.

The overall powertrain efficiency was calculated as a product of the component efficiency maps. The resulting efficiency map combined with the load data can be used to calculate efficiency percent for the system in defined application. Figure 5.1 represents the mathematical operation graphically.

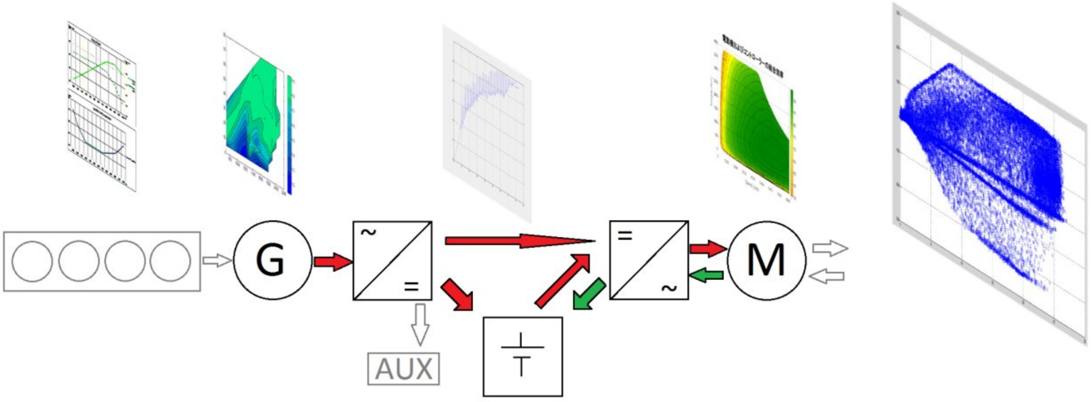


Figure 5.1 *Combining powertrain efficiency maps for application efficiency figure.*

Two types of permanent magnet motors were compared in generator use. One with higher nominal speed compared to the diesel engine would operate outside of its nominal efficiency window. At best it could reach 78 % efficiency when loading the model with the operational data. For more efficient operation the generator would need a gearbox. However this would increase the weight and size of the system unacceptably and lower the overall efficiency. From the system point of view, efficiency can be more easily improved with changes in application control of the complete genset instead of small increases in generator efficiency. In addition pairing the generator and diesel engine by using efficiency and load charts has the potential for significant improvements.

Keeping in mind that implementing changes to a industrial working machine is costly, improving the rectifier and inverter efficiency from the current set up gives diminishing returns compared to other options. Instead of just for efficiency improvements, these should be developed further with other operational parameters in mind also. Inverter control has impact on the motor efficiency. However the effect of control was not studied in such depth during this thesis that quantitative estimates could be formed. As SiC and GaN devices become more widely adopted, the technology could prove to be a good choice. Currently there are very few units available appropriate for the application.

With the current systems motor interfacing and limitations in both synchronous reluctance and permanent magnet motors overloading capabilities there is no direct replacement. The mechanical frame limits the options available. There are units that could meet the specification for short overload periods, but not for sustained use. They are also limited by the speed range they can tolerate. The comparison between performance requirements and limitations can be seen in figure 5.2.

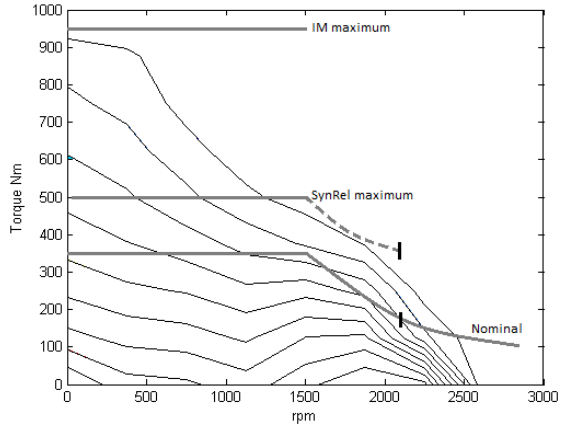


Figure 5.2 *Dynamic load requirements and motor limits for a 55 kW standard frame unit.*

With torque limitations units with better efficiency could be used. This however would not only limit the performance but also increase the cost which is a very difficult proposal to make to a customer. The inefficiency of induction motor in start up and low speed region is the most penalizing for overall efficiency in straddle carrier application. With one liquid cooled automotive permanent magnet motor the accumulated load efficiency is 92,6 % being considerably better that the standard solution.

Significant changes to the structure are needed for notable changes in system efficiency. At this point standard frame motors do not provide improvements worth the design time. Improvements are possible, but the cost of many existing solutions is prohibitive. Permanent magnet assisted reluctance motors seem an attractive option for further developments. They have decent operational parameters and the risk associated with the ferrite magnets is more manageable than with Neodymium or other rare earth magnets.

6. CONCLUSIONS

Majority of container handling equipment are still based on diesel engine power source. The environmental aspects support minimizing diesel consumption when there is more efficient power sources available. Improving energy efficiency is vital. Optimizing vehicle powertrains is one of the methods to achieve more sustainable working machines.

The thesis consisted a lot of data analysis not specifically shown in the literary work. Learning the machine and analysing the performance from data was how the focus for the thesis was finally defined. Both measurement data and physical calculations from datasheets were necessary for meaningful modelling. Finally, several statistical and dynamic models were created to estimate the changes the different motors would have on the overall efficiency. The process familiarized the author with Matlab and Simulink as well ass straddle carriers. Most effort was put towards learning and implementing electrical motors. It was soon apparent that measuring and modelling motor losses is a deep though very interesting rabbit hole.

In the end it was not possible to justify efficiency improvements based only on diesel purchase costs. There is no direct replacement available that could meet the dynamical performance requirements of the current design with this grossly simplified cost model. With more novel solutions the payback period became greater than the lifetime of the machinery. If the economical effects were studied more in depth the simulated solutions could prove to be beneficial but was beyond the scope of this thesis. All in all, better performance and efficiency is attainable but with significantly increased cost either from the components or major redesign of the system.

The subject matter was interesting although some stigma of writing a thesis did attach to it. Next the author would like to get back to work and implement something useful to the system. Visit to Japan would not be bad either.

REFERENCES

[1] J. Federley and M. Hippinen, "Fact-finding study on opportunities to enhance the energy efficiency and environmental impacts of ports in the baltic sea region," *Baltic Sea Region Energy Cooperation*, 2014.

[2] "Container port traffic," *Containerisation International Yearbook*, 2015.

[3] G. Wilmsmeier and T. Spengler, "Towards benchmarking energy consumption in container terminals," *Maritime and Logistics Bulletin*, pp. 1–9, Jul. 2015.

[4] J. Leskinen, "Electrochemical energy storages of mobile work machines," Master's thesis, 2015.

[5] T. Lin, Q. Wang, B. Hu, and W. Gong, "Development of hybrid powered hydraulic construction machinery," *Automation in Construction*, vol. 19, no. 1, pp. 11–19, 2010.

[6] D. Chrenko, S. Gan, Z. H. C. Daud, Z. Asus, E.-H. Aglzim, and L. Le Moyne, "Sizing of ice and lithium-ion battery for series hybrid vehicle over life cycle with battery aging," pp. 1–5, IEEE Transportation Electrification Conference and Expo (ITEC), 2013.

[7] P. Immonen, L. Laurila, M. Rilla, and J. Pyrhonen, "Modelling and simulation of a parallel hybrid drive system for mobile work machines," pp. 867–872, 2009.

[8] S. J. Chapman, *Electric machinery fundamentals.* 2005.

[9] P. C. Krause, O. Wasynczuk, S. D. Sudhoff, and S. Pekarek, *Analysis of Electric Machinery and Drive Systems.* IEEE Press, third ed., 2013.

[10] P. Immonen, *Energy Efficiency of a Diesel-Electric MobileWorking Machine.* PhD thesis, Lappeenranta University of Technology, 2011.

[11] A. Emadi, *Advanced electric drive vehicles.* CRC Press, 2015.

[12] B. M. Wikamowski and J. D. Irwin, *Power electronics and motor drives.* CRC Press, 2011.

[13] B. K. Bose, *Power electronics and motor drives: advances and trends.* Academic, 2006.

[14] B. K. Bose, *Power electronics and variable frequency drives: technology and applications*. IEEE Press, 1997.

[15] P. Haaf, “Understanding diode reverse recovery and its effect on switching losses,” *Fairchild Power Seminar*, 2007.

[16] T. Morita, S. Tamura, Y. Anda, M. Ishida, Y. Uemoto, T. Ueda, T. Tanaka, and D. Ueda, “99.3% efficiency of three-phase inverter for motor drive using gan-based gate injection transistors,” pp. 481–484, Applied Power Electronics Conference and Exposition (APEC), 2011.

[17] M. Paavola, *Insinöörin käsikirja III: Sähkötekniikka*. K.F.Puromiehen Kirjapaino Oy, 1955.

[18] C. P. Steinmetz, “The alternating-current railway motor,” *Transactions of the American Institute of Electrical Engineers*, vol. XXIII, pp. 9–25, 1904.

[19] I. M. Gottlieb, *Practical electric motor handbook*. Newnes, 1997.

[20] M. Ranta, M. Hinkkanen, and J. Luomi, “Inductance identification of an induction machine taking load-dependent saturation into account,” pp. 1–6, International Conference on Electrical Machines (ICEM), 2008.

[21] K. Lee, S. Frank, P. K. Sen, L. G. Polese, M. Alahmad, and C. Waters, “Estimation of induction motor equivalent circuit parameters from nameplate data,” pp. 1–6, North American Power Symposium (NAPS), 2012.

[22] J. Pedra, “Estimation of typical squirrel-cage induction motor parameters for dynamic performance simulation,” *IEEE Proceedings: Generation, Transmission and Distribution*, vol. 153, no. 2, pp. 137–146, 2006.

[23] H. R. Akbari and S. Sadeghi, “Calculation of inductances of induction machines under axial nonuniformity conditions,” pp. 1113–1118, IEEE International Symposium on Industrial Electronics (ISIE 2007), 2007.

[24] M. Li, *Flux-weakening control for permanent-magnet synchronous motors based on Z-source inverters*. PhD thesis, 2014.

[25] Y. Sheng, W. Zhou, Z. Hong, and S. Yu, “Field weakening operation control of permanent magnet synchronous motor for railway vehicles based on maximum electromagnetic torque at full speed,” pp. 1608–1613, Control Conference China(CCC), 2010.

[26] M. Eskola, *Speed and Position Sensorless Control of Permanent Magnet Synchronous Motor in Matrix Converter and Voltage Source Converter Applications.* PhD thesis, 2006.

[27] G. Pellegrino, T. M. Jahns, N. Bianchi, W. L. Soong, and F. Cupertino, *The Rediscovery of Synchronous Reluctance and Ferrite Permanent Magnet Motors, Tutorial Course Notes.* Cham: Springer, 2016.

[28] S. Cai, M.-J. Jin, H. Hao, and J.-X. Shen, "Comparative study on synchronous reluctance and pm machines," *COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, vol. 35, no. 2, pp. 607–623, 2016.

[29] M. Ferrari, N. Bianchi, and E. Fornasiero, "Analysis of rotor saturation in synchronous reluctance and pm-assisted reluctance motors," *IEEE Transactions on Industry Applications*, vol. 51, no. 1, pp. 169–177, 2015.

[30] M. Arizti, *Harvesting energy from vehicle suspension: Master of Science Thesis.* Tampere University of Technology, 2010.

[31] D. Perrotta, B. Ribeiro, R. J. F. Rossetti, and J. L. Afonso, "On the potential of regenerative braking of electric buses as a function of their itinerary," *Procedia - Social and Behavioral Sciences*, vol. 54, pp. 1156–1167, 2012.

[32] D.-Y. Jo, S. Kwak, and N. Kim, "Development of fuel-efficient construction equipment," pp. 31–37, IEEE 8th International Conference on Power Electronics and ECCE Asia (ICPE ECCE), 2011.

[33] Y. Wang, W. Zhu, and U. Schaefer, "Study on the real time driving cycles and its influence on design of the electrical motor of ev," pp. 1–6, Transportation Electrification Asia-Pacific (ITEC Asia-Pacific), 2014.

[34] J. Lieb, E. Sawazki, M. Brull, and B. Baker, "Potential of an electric brake resistor to increase the efficiency of electric vehicles," pp. 1–10, Electric Vehicle Symposium and Exhibition (EVS27), 2013.