CHALMERS

The most important characteristics for dimensioning electrical components

Thesis work in Bachelor of Science in electrical engineering

ELIN NORÉN

Department of signals and systems

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden, 2014

Examiner:

Manne Stenberg

Supervisor at Chalmers University of Technology:

Lennart Widén

Supervisor at Volvo Group trucks technology:

Hamid Yhr

Acknowledgement

This report is the result of a thesis work at the electrical engineer program, 180 hp, at Chalmers University of Technology and includes 15hp. The project was made at Volvo group truck technology (GTT) in Lundby, Gothenburg at the department of Vehicle functions and electronics, in January to April 2014.

First I would like to dedicate a big thanks to Niklas Seger. Niklas has not only been my mentor at Volvo GTT for the last two years, he has also been a very good role model for me. I would also like to thank the employees and consultants in the department of vehicle electronic and functions for all help and support, especially Hamid Yhr who has been my supervisor at Volvo GTT. Last I would like to thank my supervisor Lennart Widén, engineering lecturer, at Chalmers University of technology for all help during the project.

Abstract

Volvo GTT is one of the largest distributers of trucks today and they are known worldwide. For a company like Volvo GTT it is important to always be in the forefront, and develop new functions and components. In September 2012 released their new heavy duty truck, Volvo FH.

Despite the release of the new Volvo FH, it is important to further develop the electrical system in the new truck. To be able to do that, it is important to know the most important characteristics for different electrical components connected to the ECU in the truck. This report describes the function and construction of eight common electrical components in the truck. As a result, a table with the most important characteristics for each component is represented in the result. The characteristics are numbered 1 or 2, where 1 is the most important characteristics and 2 is just important characteristics for the components. The eight components contained in this report are: bulbs, LED lamps, linear solenoid actuators, relays, stepper motors, PMBLDC motors, NTC thermistors and PTC thermistors.

The conclusion of this report is that it would provide several advantages for the Volvo GTT, if they had this type of information gathered for all of the electrical components in for example a data base or connected to the technical report for the components. If the main characteristics for all components, connected to an ECU, were descried in a database, it would make it easier to compare different component to minimize the risk of oversizing and under sizing the electrical systems.

Table of Contents

Figures

Abbreviations

ABS: Absolute

AC: Alternating current

CPU: Central Processing Unit

DC: Direct current

ECU: Electronic control unit

EMF: Electromagnetic field

GaAs: Gallium arsenide

GaP: Gallium Phosphide

GaAsP: Gallium arsenide phosphide

GTT: Group trucks technology

HB: Hybrid

LED: Light emitted diode

N: North Pole

NTC: Negative temperature coefficient

PM: Permanent magnet

PMBLDC: Permanent magnet brushless direct current

PTC: Positive temperature coefficient

PWM: Pulse width modulation

S: South Pole

1 Introduction

1.1 Problem description

Volvo group truck technology (GTT) is a company known worldwide with customers in 140 countries and production in 16 countries, such as Sweden, USA, India and France. Today Volvo is one of the world´s most famous brands in the heavy duty truck industry and is at the forefront of technology and development. In September 2012 Volvo GTT lunched the new Volvo FH, their largest and most established truck model.

Within the electrical system in the truck, new functions and components are developed all the time. To facilitate the development of the electrical systems, the company needs to know the most important characteristics of the components in the electrical architecture. Developing new systems and designs are expensive and with information from this project, the company will maybe be able to reduce their costs because it makes it easier to dimension the component with the correct dimension from the beginning

1.2 Purpose

The purpose of this project is to create an overview of the most important characteristics of eight components in electrical architecture in the truck. Components considered in the project are relays, lamps, sensors, actuators and Direct current (DC) motors. If possible the different component should be divided into families where e.g. different types of DC motors are described.

The result of the project shall be compiled in tables, one for each component. The resulting tables shall contain the most essential characteristics for each component, such as rated voltage, inrush current etc.

The resulting characteristics can then facilitate the work on growth and development of the electrical systems in the truck. The result can also be a good support when further development of the Reports (TR), who describes the Electric control units (ECUs) and components in the truck, is done so that the most important characteristics of the component is not forgotten and to broader the knowledge about the components.

1.3 Scope

The purpose of the project is to facilitate the future development of the electrical system in the truck and not a compiling of the characteristics of the already existing electrical components in the truck.

The gathered characteristics in the result do not contain any numbers or data. The purpose is to establish the most important characteristics of the components so that Volvo Trucks and the subcontractors can use the result as a support for continued development of the electrical systems in the truck.

1.4 Specification of issues

- Which important characteristics Volvo GTT needs to know about the components to be able to make the right designs from start?
- Which characteristics are the most relevant for the components considered in this report? Most relevant numbered as 1the the remaining as 2.

1.5 Method

The project started with an overview of the components included in the project, such as where they are positioned in the truck, found out who is the component owner of the different components at Volvo GTT and how to gather information about the components.

The next steps of the project consisted of focusing on the different components, one at the time. Some component contained much research about their construction and characteristics in different databases and some parts where gathered by interviews with employees and consultants at Volvo GTT in Lundby, Gothenburg. Some information where also gathered by mail exchange with employees in other countries where Volvo trucks has productions.

A compilation about the components characteristic where then made with information from the interviews and information from the databases and a description about the components construction and functions were made so that the important characteristics could be established and gathered in tables, represented in the result.

2 Thesis

To be able to decide which characteristics of a component that is the most important, there must be an understanding of the component function and the construction. With this information it is easier to get an overview of the most important characteristics. The report contains descriptions about eight components, bulbs, LED lamps, relays, linear solenoid actuators, stepper motors, PMBLDC motors, NTC sensors and PTC sensors. Some of the components, for example relays and motors contain a magnetic field, created when a current flows through the component. Even though they have similar constructions and properties do they not have the exact same important characteristics because the components utilize the properties in different ways.

2.1 Lamps

Two types of lamps used in the trucks are incandescent lamps (bulbs) and Light Emitted Diode (LED) lamps. Which type of lamp used depends on where the component is positioned and the function of the lamp at the specific position. Sometimes it is desirable to change a bulb to a LED lamp or vice versa and then it is important to know how the characteristics of the two components differs.

2.1.1 Incandescent lamp (Bulb)

An incandescent lamp is still a common light source in today's trucks. The basic design is the same today as it was 135 years ago and it has the lowest efficiency, converting energy to visible light, which means it consumes a lot of energy related to the amount of light emitted (Lamptech [2011]). The term used for an incandescent lamp in a truck is bulb hence that name will be used in this report.

The light source in a bulb is filament and the most common filament is Wolfram. Wolfram is a metal element, which withstands high temperatures because of its high melting point. For example inside a 60 W bulb, the length of the filament can be as long as 2m with a thickness of 0.254mm. To be able to implement the filament in a bulb, it is constructed as a coiled coil (Harris [2013]).

The filament operates as a resistor in a circuit and the resistor value depends on the component temperature. The filament behaves like a blackbody, when a current passes it emits visible light when it heats up. The emission of the visible light will not start until the temperature of the filament exceed 500℃ but to be able to obtain the useful amount of white light it needs to exceed a temperature of 2500℃.

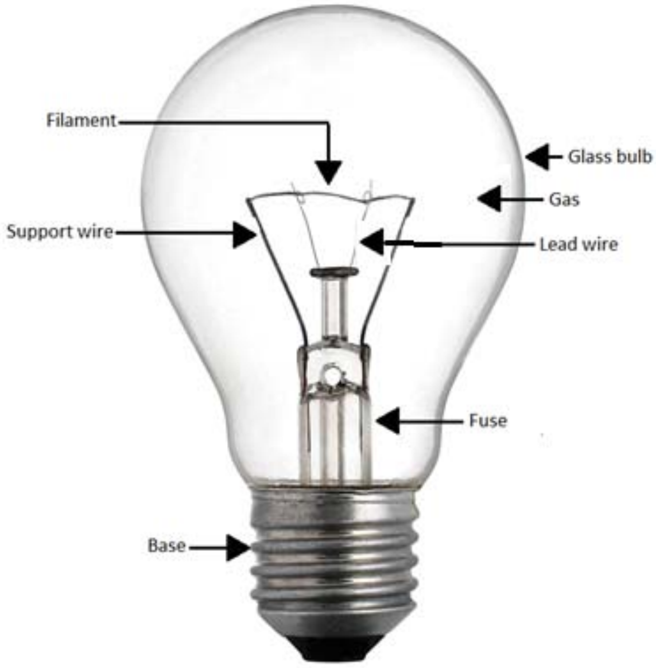

Figure 1 the construction of a bulb

The Filament in the bulb is fixed to conductive wires (support wire and lead wire), which is fixed in the other end on the base, it usually consists of aluminum or brass. The purpose of the base is to cement the bulb and the most regular cement failure due to overheating, see figure 1.

The filament is surrounded by a protective gas or vacuum. The purpose of the gas is to prevent the filament from evaporation, which occurs because of its high temperature. The most common gas is argon. Argon is an element from the Periodic System (Ar) and has position number 18, noble gases. Argon exists in the atmosphere, which makes it easy to use and cheaper than other types of gases. The gas is enclosed by a glass fixed to a metal base, containing two metal contacts. In the base of the bulb a fuse is positioned to ensure a safe end of life of the bulb. The fuse consists of glass filled with balloting, which melts if the filament overheats. The purpose of the fuse is to prevent accidents from happening (MacIsaac, Kanner and Anderson [1999]).

As previously mentioned a bulb behaves as a temperature dependent sensor. When the component is cold, the resistance (R_{cold}) is only 1/5 of the resistance (R_{hot}) in the component, when it is hot, see equation 1. The filament in the bulb is the temperature dependent part, because the bulb will not start to emit light until a certain filament-temperature is reached and if R_{cold} and R_{hot} are known, a temperature difference in the bulb can be calculated by equation 2.

$$R_{hot} = R_{cold} + R_{cold}\alpha(t2 - t1)\ [\Omega] \qquad (1)$$

$$\Delta t = (t2 - t1) = \frac{R_{hot} - R_{cold}}{R_{cold}\alpha}\ [K] \qquad (2)$$

t1: cold incandescent bulb

t2: hot incandescent bulb

R_{cold}: resistance at t1

R_{hot}: resistance at t2

α: The temperature coefficient of the material

When the supplied power is turned on, the bulb has a low temperature and a high inrush current. As the filament temperature increases, the current through the lamp will decrease, according to ohm´s law, and the current will than settle on a stable level, see equation 4, shown in figure 2 (Lamptech [2011]).

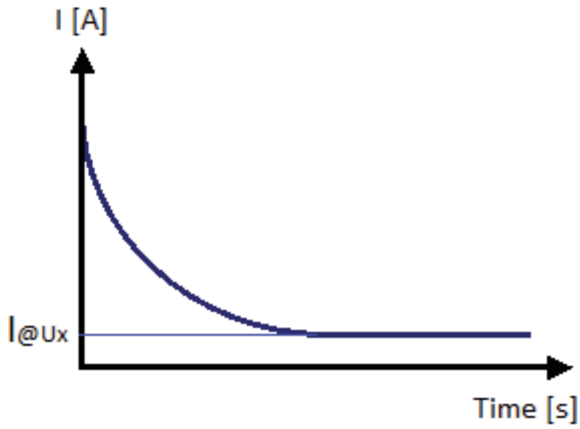

Figure 2 the current vs time characteristics for a bulb.

The absolute (ABS) maximum current is another important characteristic. The ABS maximum current through a component should never be exceeded, though it can short cut the bulb and the entire electrical system. The value of the ABS maximum current is usually higher than the maximum recommended current for a bulb. To get the most reliable ABS maximum value, it´s better to do tests, instead of using calculated values (Nuffield Foundation [2011]). When bulbs are considered it often discussed if it is better to leave he power on or turn it off. If one or the other is the best way depends on duration of the "on time", see equation 3. The bulb should be turned off if the current consumption, caused by inrush current, is smaller than the energy consumed at stationary current for the time duration. If the inrush current causes larger energy consumption it is better to keep the light on (Lamptech [2011]).

$$I_{rms} = \lim_{T\to\infty} \sqrt{\frac{1}{T}\int_0^T i(t)^2 dt} \quad [A] \qquad (3)$$

As previously discussed, it is very important not to exceed the maximum current, since it will reduce the lifespan. Equation 4 is used to calculate the current at the bulbs rated voltage. To be able to calculate the current, two other important parameters are the nominal voltage (U_{nom}) and the nominal power (P_{nom}) of the incandescent lamp (Nuffield Foundation [2011]).

$$I_{@v_x} = \left(\frac{V_x}{V_{nom}}\right)^{0.5505} * \left(\frac{P_{nom}}{V_{nom}}\right) \quad [A] \quad (4)$$

$I_{@v_x}$: The calculated stationary bulb current at voltage V_x

V_x: The rated voltage used for calculate the bulb current

V_{nom}: The nominal voltage of the bulbs, for which the bulb − power is defined.

P_{nom}: The nominal power of the bulbs at the nominal voltage

Figure 3 shows the bulbs different current ranges. The values that separate the current-levels for different bulbs are not the same because the nominal voltage and nominal power are different for different types of bulbs.

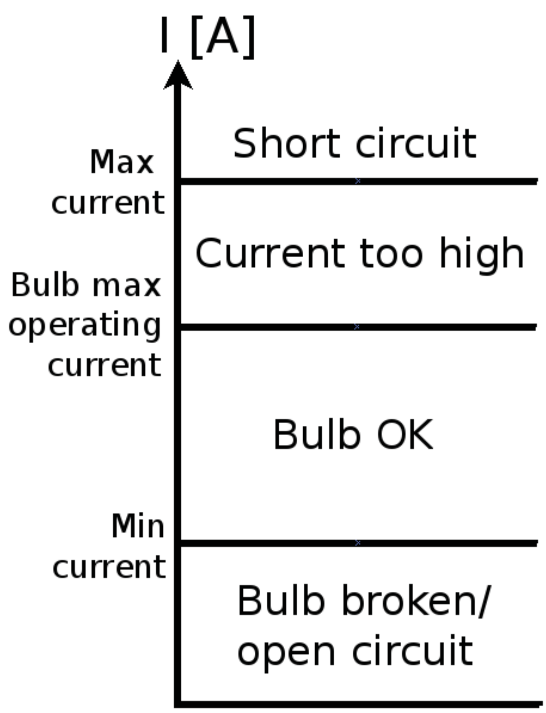

Figure 3 the current different stages for a bulb.

The luminous flux (Φ) for a bulb is often listed in the bulbs datasheet from the manufacturer and it is often named initial lumens. The value of the luminous flux from the manufacturer is often based on laboratory testing. The luminous flux has the unit lumen (lm) and the average luminous efficiency has the unit lm/W. Though the filament is the source of the emitted light, the calculation of the light must be calculated based on information about the filament. The radiated energy ($P_{radiation}$) can be calculated by equation 5.

$$P_{radiation} = P_{low\ pressure\ out} = e(T)S\sigma T^4 \quad [W] \qquad (5)$$

S: Surface [m^2]

σ: Boltzmans constant $= 5.670373 \cdot 10^{-8}$ [$kgs^{-3}K^{-4}$]

T: Temperature of filament [K]

T_0: Room temperature [K]

When the filament temperature is constant, the input energy will be the same as the output energy. For a bulb at 12V approximately 25% of the filament radiation is not transmitted and compared to other types of light sources, the efficiency of a bulb is very low. To be able to calculate the output energy and the radiation energy of the component, the temperature (T) of the filament must be known. The temperature of the filament can be calculated in equation 6.

$$T = T_0 \left(\frac{R}{R_0}\right)^{5/6} \quad [K] \qquad (6)$$

T_0: ambient temperature

R: filament resistance

R_0: Reference resistance of the filament

The input energy (P_{input}) can be calculated by equation 7, it depends on the supplied voltage (U), current (I) and background radiation, but the background radiation is negligible when input energy is discussed. The output energy (P_{output}) can be calculated using equation 8 and is the radiated energy added with the direct energy transfer but for a bulb the direct energy transfer is negligible. The input energy in a bulb don´t depend on the gas in the bulb, but how the gas effects the output energy depending on if it is a low pressure gas or a high pressure gas inside the bulb. Equation 5 also describes the calculation for a lamp with a low-pressure gas $P_{low\ pressure\ out}$, where the output energy from the bulb is the same equation as the radiation energy. For a bulb with a high pressure gas $P_{high\ pressure\ out}$ the energy also depends on the ambient temperature T_0 and can be calculated by equation 9.

$$P_{input} = VI + \text{background radiation} \quad [W] \qquad (7)$$

$$P_{output} = e(T)S\sigma T^4) + \text{direct energy transfer} \quad [W] \qquad (8)$$

$$P_{high\ pressure\ out} = e(T)S\sigma T^4) + v(T - T_0) \quad [W] \qquad (9)$$

The flux and the luminous efficiency is two other important characteristics for a bulb. The flux and the luminous efficiency describes the light of the bulb and how the light depends on the wavelength, The two characteristics are describes in appendix B (Illyam [2013]).

2.1.2 Light Emitted Diode (LED) lamp

LED lamps are common light source in different industries today; the truck industry is not an exception. A LED lamp is a good replacement for a bulb where the industry is in need of high mechanical stability, low operating voltage and where the lower luminous performance is compensated by a longer lifespan (Scaleter, [1999]). By changing a bulb to a LED lamp the energy savings will be almost 80% and the lifespan is 40-50 times longer, which is equal to 20 000-50 000 hours. Compared to a bulb, the LED lamp only has 5% of its heat radiated when an ordinary bulb has a radiation of 90% (Beaty and Flink, [2013]). In the Volvo trucks today there are a lot of LED lamps, for example the position light, the daytime running light and the trailer fog light are LED-lamps (Hidealight [2014]).

Even though a LED lamp has a long lifespan there are some factors that have a higher impact on the lifespan than other. One of the factors is the ambient temperature and the critical temperature is 25^{o}C, a higher temperature has a negative impact on the lifespan. A high ambient temperature during a short amount of time can have an impact on the color of the LED lamp. If the temperature is increases in the long-term the light loss will reduce the lifespan of the lamp. Two other parameters that have effects on the lifespan are the current and the heat dissipation (Hidealight [2014]). When a bulb breaks its the end of the life, a LED lamp doesn´t work in the same way. The longer a LED-lamp is active, the amount of light emitted will decrease. When only 70% of the initial luminous output is emitted, a LED-lamp reaches the end of life status.

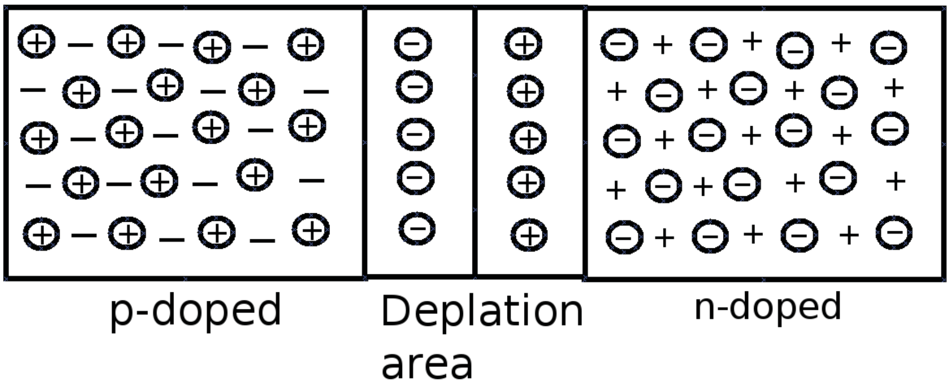

Figure 4 a p- and n-doped material.

With reverse bias a positive outer voltage is connected to the n-doped side of the semiconductor related to the p-doped side. The depletion area will broaden and negative charged electrons in the depletion region will gravitate towards the n-doped region. Theoretically no current will flow through the diode in the beginning but in reality there will be small leakage current. When the reverse bias is further increased the amount of current flowing through the diode will increase exponential, see figure 5 (Molin, [2009]). With forward bias electron-hole pairs recombined in the PN transition region and energy emits in form of light or luminous intensity (scaleter, [2009]).

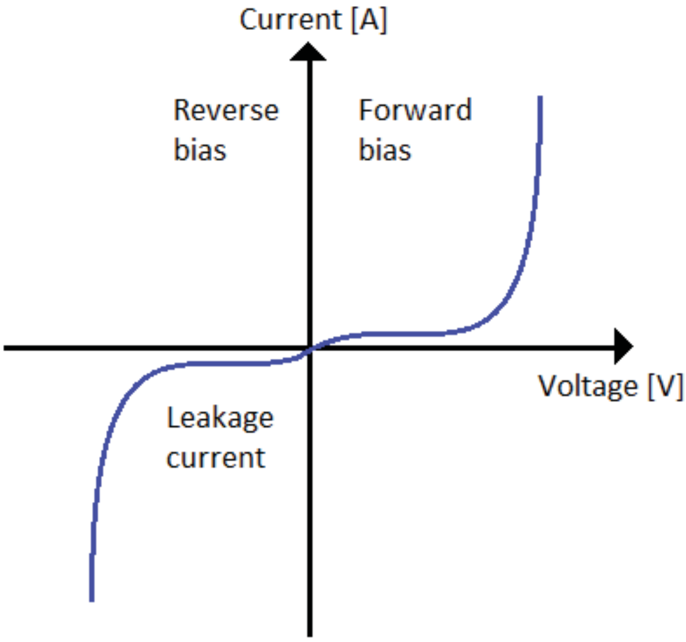

Figure 5 the relationship between the current and voltage in a LED-lamp.

A LED lamp has two connections, an anode and a cathode, see figure 7. For the lamp to act like requested it is important for the anode to be connected to the plus side and the cathode connected to the minus, called forward bias. An ordinary current range for a LED lamp is 1mA-100mA with a voltage range from 22V to 30V e.g. for a functional 24V LED lamp the current consumption should be grater then 50mA and in the failure mode shall have a current consumption less than 20mA, see figure 6.

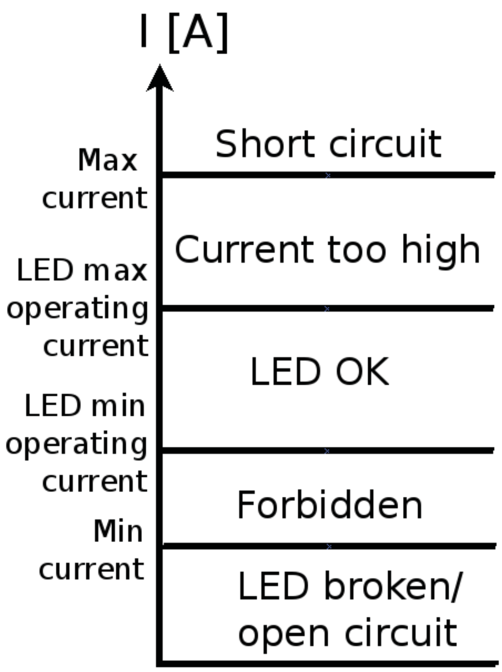

Figure 6 the diagnostics for LED lamps.

Max current is the level where the output will be shut off and the maximum load on the output caused by normal LED lamps. The forbidden area should only be reached by broken lamp electronics (Technical report [2012]). The terminal voltage (V_T) is an important characteristic for a LED lamp, see equation 10. When the terminal voltage is known, it is possible to calculate the current through the LED-lamp, see equation 11.

$$V_T = \frac{kT}{q} \quad [V] \qquad (10)$$

$$I = I_0(e^{V/V_T} - 1) \quad [A] \qquad (11)$$

I_0: Leakage in reverse bias current [A]

q: $1.60 \cdot 10^{-19}$ [As] magnitude of charge of a electron

k: $1.38 \cdot 10^{-23}$ $[J/K]$ Boltzmanns constant

T: Absolute temperature [K]

Reverse bias is when the LED lamp is connected in the wrong way, the cathode is connected to the plus side and the anode is connected to the minus side. It is important to know the maximum reverse bias because if the LED lamp is connected that way a very small leakage current will flow through the diode and there is no light emitted. If the supplied voltage increases and passes the maximum reverses voltage, the LED lamp will break. This means that it is very important to control the current through the LED lamp before adding it to the electrical system; figure 7 shows the bone description of a LED lamp.

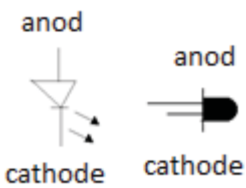

Figure 7 is a description of the pins on a LED lamp.

If the forward maximum current is exceeded for too long, the lamp will break. To prevent that type of accident a LED lamp could never be connected directly to the voltage source, which means that there needs to be a series resistance (Park and Huh, [2012]). The series resistance can be calculated by equation 12 and the series resistance is one of the most important part of the LED lamp circuit. LED lamps do not typically fail like a bulb; the failure is often caused by electrical or terminal overloads. Another common failure is mechanical failure with the optical systems (Beaty and Flink, [2013]).

$$R_S = \frac{V_s - V_L}{I} \quad [\Omega] \qquad (12)$$

V_s: Supplied voltage

V_L: LED-lamp voltage

I: current

One equation used to calculate the terminal resistance is equation 13, which depends on temperature and transferred energy, see equation 13 and 14.

$$R = \frac{T_j - T_a}{Q} \quad [\Omega] \qquad (13)$$

$$E = qA = K * A \cdot \frac{T_j - T_a}{L} \quad [J] \quad (14)$$

T_j: junction temperature

T_a: ambient temperature

E: terminal transfer energy, which is flux (q) per unit area or temperature difference divided by the terminal transfer difference between two materials.

If it is requested to have more than one LED lamp in a circuit, they have to be in series and they have to be of the same type.

As for a bulb, the flux and the luminous efficiency for a LED lamp is two important characteristics used to describe the light emitted from the lamp and there for, there is a description of the two characteristics in appendix B.

2.2. Relay

A relay is a simple electromagnetic switch and it has several functions in the truck. The main function is to supply a 24 voltage to an Electric Control Units (ECU´s) and/or electrical components like lamps, motors and resistors in the vehicle. A relay can be placed anywhere in the truck but most common locations are in the cab and in some cases on the chassis. When a relay is part of a circuit it will be seen as an inductance in series with a resistance, which will increase when the temperature of the relay increases (Technical report [2013]). Appendix A describes how the magnetic field in an inductive component works. Figure 8 shows how a common relay locks like.

Figure 8 how a relay in the truck locks like.

A relay consists of a coil, a parallel resistor/diode, a switch and contacts shown in figure 9.

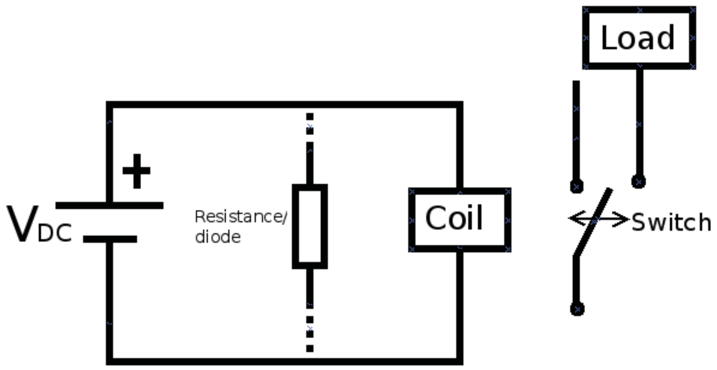

Figure 9 an example of a relay circuit configuration.

The coil is an inductance in series with a resistance, shown in figure 10. At t=0 there is a voltage applied to the circuit, the switch S1 is closed and a current starts to flow through the circuit. Equation 15 is Kirchhoff's law, which describes the voltage division in the circuit. The result from equation 15 can be used to calculate the current in the circuit, see equation 16 (Ostrom [2010]).

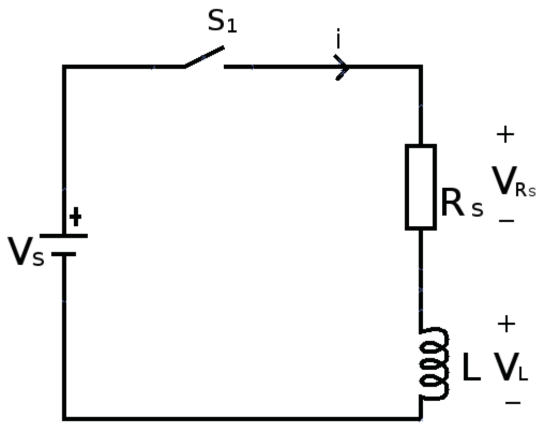

Figure 10 a schematic of a switch in series with a resistance and an inductance.

$$V_s + V_{R_s} + V_L = 0 \quad [V] \qquad (15)$$

$$V_{R_s} = -R_s I \quad [V]$$

Faradays law: $L\frac{dI}{dt} \quad [V]$

$$V_L = -L\frac{dI}{dt} \quad [V]$$

$$\rightarrow V_s - R_s I - L\frac{dI}{dt}$$

$$\tau = {}^{L}/_{R_s} \quad [s]$$

$$I = I_0\left(1 - e^{-\left({}^{R_s}/_{L}\right)t}\right) = I_0(1 - e^{t/\tau}) \quad [A] \qquad (16)$$

V_s: Voltage supply

V_{R_s}: Resistance voltage

V_L: Inductance voltage

R_s: Series resistance

I: Current

T: Time constant

I_0: Stationary current

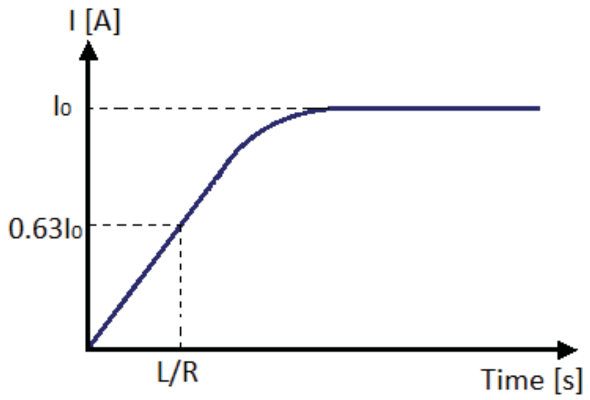

Figure 11 the Current verses time characteristic for a relay.

Figure 11 shows the current verses time characteristic of the circuit. Coils often have a parallel resistance or a parallel diode. The purpose of the resistance/diode is to prevent the voltage to increase to extreme levels when there is no voltage supplied. When switch S1 is closed and a DC current floats through the circuit and there is a parallel resistance/diode it calls reverse-bias. Reverse-bias means that when the coil is energized the diode/resistance will conduct no current. If there is a big change in the current, for example when switch S1 is opens and switch S2 closes, see figure 12, can cause the inductor voltage (V_L) to become enormous, called kickback energy. When there is no power supplied, the inductor will induce a voltage with reverse polarity to maintain current at the same magnitude and in the same direction. This means that the current will float through the diode instead and the stored energy will dissipate slowly rather than suddenly (All about circuits, [2012]).

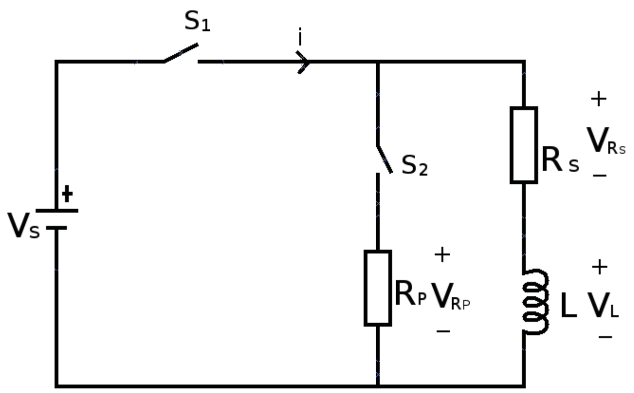

Figure 12 the circuit with a parallel resistance and two switches S1 and S2.

Figure 13 describes the voltage change in the circuit. The blue line is the supplied voltage (V_s) over time in the circuit. At position A the current is nearly constant and is approximately equal to the current described in equation 17.

$$I(t) = \frac{V_s}{R_s + R_L} \quad [A] \qquad (17)$$

When the power supply changes there will be a change in the voltage over the inductor (V_L), because the voltage over the inductance depends on the current in the circuit, see equation 18. The voltage change over the inductance will change the current in the circuit rapidly. Figure 13 shows how the voltage change can produce an enormous voltage change over the inductance, V_L.

$$V_L = L\frac{dI}{dt} \qquad (18)$$

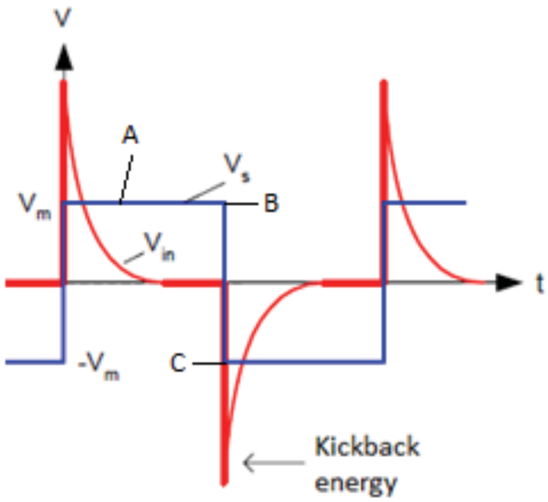

Figure 13 the kickback energy when the voltage changes.

The kickback energy can produce arcing in the switches when the power is turned off. The resistance/diode is added to the circuit to prevent the kickback energy from getting distributed to other parts of the circuit. In sensitive electronic circuits kickback energy can be catastrophic and burn out other components for examples transistors (Keith, [2006]). Figure 14 describes the current characteristic when the voltage supply is turned off. In Some relays the resistance/diode is embedded and when choosing between a diode or a resistance, depends on the circuit and how fast the kickback energy is needed to be taken care of. A resistance decreases the kickback energy faster but it has a higher impact on the circuit when the voltage supply is connected to the relay. A diode affects the kickback energy at a slower pace but don´t affect the circuit when the voltage supply is connected (Ostrom [2010]).

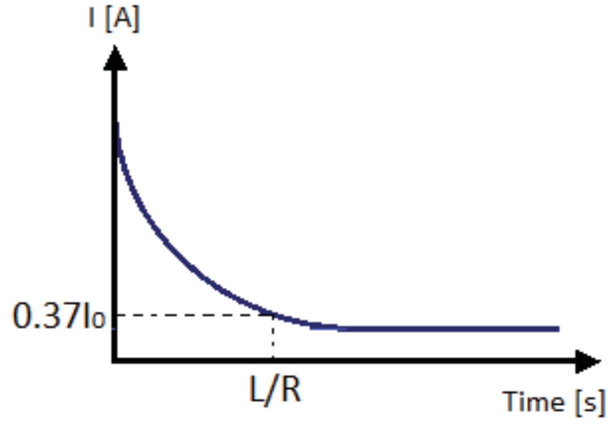

Figure 14 the current verses time characteristic when the voltage supply is turned off and the kickback energy is decreasing.

Equation 19 describes the voltage distribution in the circuit shown in figure 12 and with information from equation 19, it is possible to calculate the current in the circuit, see equation 20.

$$RI + L\frac{dI}{dt} = 0 \quad [V] \qquad (19)$$

$$\frac{dI}{I} = -\frac{R}{L}dt$$

$$\ln\left({}^{I}/_{I_0}\right) = -Rt/L$$

$$I = I_0 e^{-Rt/L} = I_0 e^{-t/\tau} \, [A] \qquad (20)$$

In the truck the purpose of a relay is to distribute current to different ECUs and components at different time, when they don’t need to be activated at the same time. In other systems relays is used to distribute a higher voltage to other component though a relay is operating at a lower voltage (Ostrom [2010]).

The voltage energizes the coil and when the minimum amount of current is reached, the coil will start to work as a magnet, described in appendix A. Depending on the amount of supplied voltage the magnet will have different effect on the switch, which has two positions: inner or outer, see figure 15.

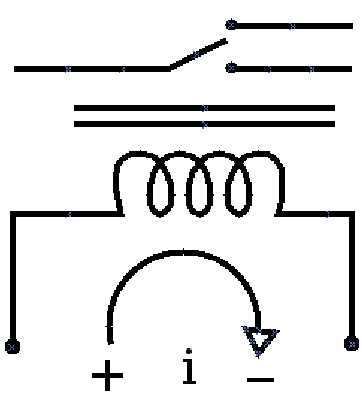

Figure 15 the switch position.

The load is not always located on the outer position; it can also be on the inner position. When there is a supplied voltage the coil will be energized and a magnetic field will affect the switch so it changes position. When the current is turned off, the magnetic field decreases and a spring change the position of the switch.

There can be different types of load connected to a relay and the most common types in a truck are lamps (bulb or LED lamp), resistance or DC motors e.g. the wiper motor (Singh Sandhu, [2009]). Figure 16 illustrates a circuit of an ECU that controls two relays and thus affects the wiper motor. Depending on the switch position in the relays the wipers will work at a high pace or a low pace.

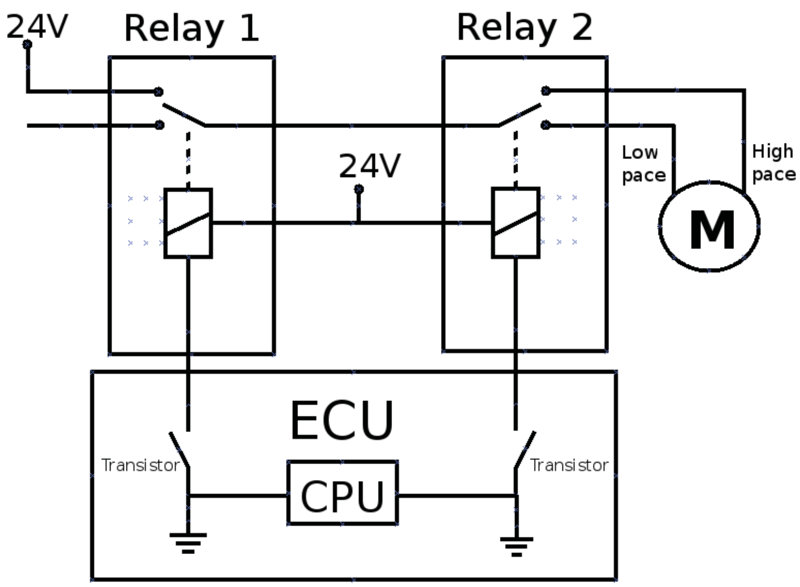

Figure 16 a circuit with an ECU, which controls the motor through two relays.

The circuit in Figure 16 includes several parts. An ECU contains a Central Processing Unit (CPU). The CPUs controls two transistors that are low-side driver though they are connected to ground, if they were connected to a power supply they would have been called high-side driver. Another part is relay1, which is connected to a 24V source. If the ECU activates the relay a current will start to flow and the wiper motor will start. The next step is relay2, which affects the speed of the wiper motor depending on the switch position. The last part is the wiper motor, which is a brushless permanent magnet DC motor, described in section 2.4.2 (Werlinder [2014]). Figure 16 contains two transistors and two relays in the circuit. The guideline for a circuit in a truck is if the current is greater than 10A a transistor is used otherwise a relay is used.

2.3 Actuators

A solenoid can be used as an electromechanical actuator that converts electrically energy into mechanical motion. A linear solenoid actuator, also called Linear Electro-Mechanical Actuator (LEMA), is one of the most common used linear actuator because it is a low-cost and rugged component (Electronics tutorials [2014]). Other types of actuators used in today's electrical systems are the rotary solenoid and the stepper motor. The stepper motor is discussed in section 2.4.1 in this document. A solenoid actuator is often used to control valves and works on the same basic principles as a relay, discussed in section 2.2. In trucks linear solenoid actuators is often used to control different types of valves, such as front wheel diff lock valve, front sinusoidal valve, 5th wheel valve, front wheel drive and PTO1/PTO2 (Technical report [2013]).

Major input parameters for a solenoid are the voltage, external load and temperature. A DC voltage commonly powers a sinusoidal; the industry often uses 24V DC and draws a few hundred mA. There are different ways to control a sinusoidal actuator and for small DC type components transistors or MOSFET switches are often used (Electronics tutorials [2014]).

2.3.1 Linear solenoid actuator

A linear solenoid actuator uses a principle of position-dependent reluctance that converts an electrical energy into a mechanical energy from a pulling or a pushing movement. The solenoid consists of a copper wire shaped as a coil. When a current floats through the coil there will be a magnetic field B and a magnetic flux Φ created, see equation 21 and 22.

$$B = \mu_0 \mu_r \frac{NI}{l} \quad [T] \qquad (21)$$

$$\Phi = \mu_0 \mu_r \frac{N^2 A}{l} \quad [Wb] \qquad (22)$$

μ_0: Permititivity of vacuum

μ_r: Permittivity of the material inside the solenoid

N: Number of turns

I: Current

l: Solenoid length

A solenoid is an inductive device and it is the magnetic flux in the coil that creates the inductance (L), which means that the magnetic flux (Φ) = solenoid inductance (L). More details about the magnetic flux are described in appendix A (Technical report [2013]). Inside the solenoid there is a piston and because of the forces created by the magnetic field in the coil, the piston is pulled-in or pulled-out (Grimm, [2009]). Some actuators are able to be both pull-types and push-types but they are not as common used as the linear solenoid actuators that just pulls or pushes (Sclater, [1999]).

<u>Pull-type:</u> Figure 17 below shows a pull-type linear solenoid. When a voltage is applied it energizes the coils, which creates a magnetic field in the coil. When the component is energized it pulls the piston with the connected load towards itself, into the center of the coil. The pull-type component is very common when a system requires an open or a closed type of motion and are commonly used in pneumatic or hydraulic control valves, electrical activated door locks and automotive engine managements.

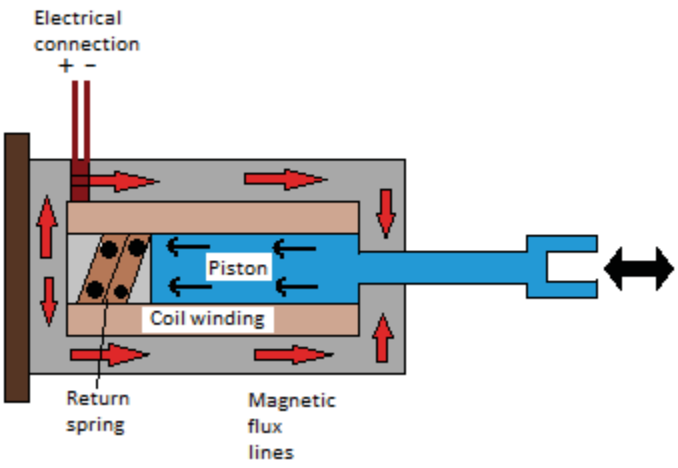

Figure 17 a cross-section of a pull-type linear solenoid actuator.

Push type: The push-type linear solenoid acts in the same way as the pull-type actuator except that the coil is wired in another way, which gives a different direction of the magnetic field. The piston is than pushed out of the coil when energized instead of pulled-in. Another difference is that the return spring is not located in the same position as it is in the pull-type actuator (Electronics tutorials [2014]).

The linear solenoid actuator is an inductive device and as discussed in the relay section 2.2 of this document, there will be a kickback energy produced in the circuit. By adding a diode/resistance parallel to the solenoid, it is possible to prevent the kickback energy from spreading to other parts and damage other component in the circuit, shown in figure 18. Commonly a ‘flyback’ diode is used parallel to the solenoid but it is also possible to use zener-diodes or small value varistors.

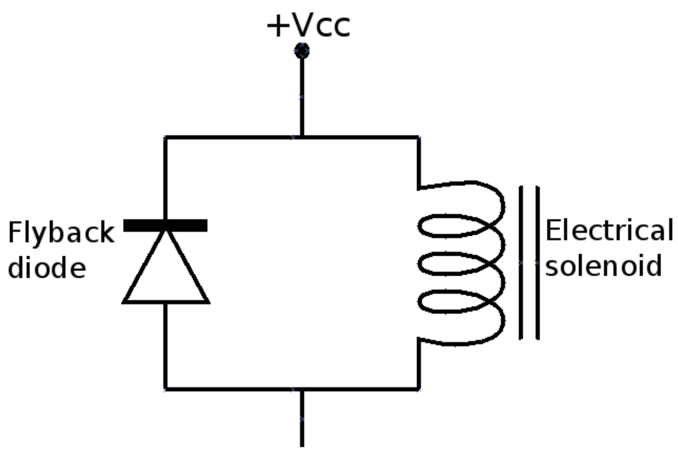

Figure 18 the ‘Flyback’ diode parallel to the solenoid whose purpose is to prevent the effects of kickback energy.

A linear solenoid actuator has one major disadvantage and it is that it gets hot when constant power is supplied to the component. The longer the solenoid is connected to a constant power source, the hotter it will be and as the temperature increases the resistance in the component will increase. When there is a constant power supplied to the solenoid, it will not be able to cool down and the temperature will continue to increase. There are two main ways to decrease the temperature in the solenoid and it is to reduce the supplied current by adding a holding resistance or by using intermittent duty cycle (Grimm, [2009]).

Figure 19 shows the circuit of a solenoid with an added holding resistance R_H and a switch.

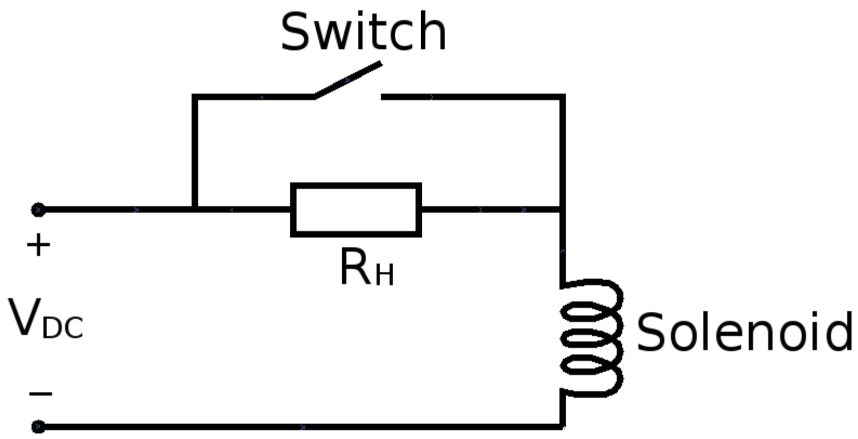

Figure 19 a circuit design with a solenoid in series with a holding resistance.

The holding resistance is positioned in series with the solenoid and works as a current limiting component, with a switch placed parallel to the holding resistance. When the switch is closed the current will flow through the switch and all the current will reach the solenoid and energize the windings in the coil. When the coil is energized the switch will open and the current has to flow through the holding resistance, which means that there will be a lower current supplied to the solenoid. By using a holding resistance the supplied voltage (V_{DC}) can be arbitrary but there will still be a reduction of temperature in the solenoid, if the suitable resistance is chosen there can be a temperature reduction up to 90%. To take in consideration is that the holding resistance also generates a heat (I^2R_H) (Electronics tutorials [2014]).

Using intermittent duty cycle means that power supplied to the solenoid is switched ON and OFF in intervals. Figure 20 shows the characteristic for an intermitted duty cycle. In a circuit where an intermittent duty cycle is used, the power will be turned ON for a particular timer period and than turned OFF. The winding in the solenoid has to be energized long enough to activate the piston and when the power is turned OFF the winding has to be de-energized before the power can be turned ON again. The square wave created by the different power levels is shown in figure 20, where T_{ON} is the time period when the power is switch ON and T_{OFF} is the time period when the power is turned OFF.

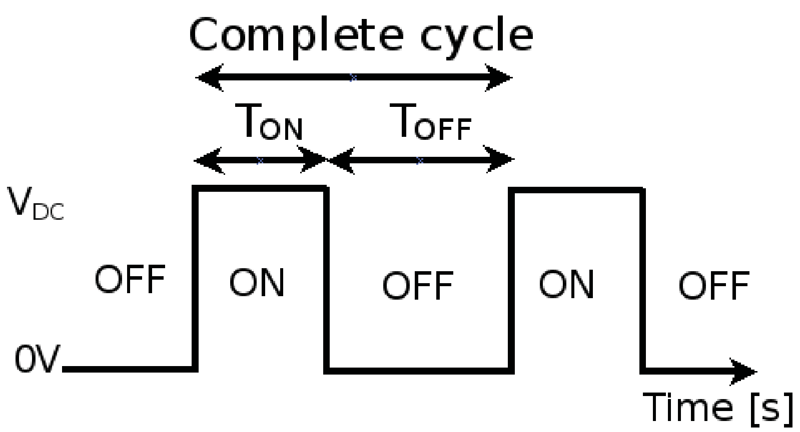

Figure 20 an intermittent duty cycle for a linear solenoid actuator.

To be able to calculate the total duty cycle, the complete cycle needs to be known. The complete cycle is the time when the power is turned ON one time and turned OFF one time, see equation 23. By dividing the time when the power is switched ON with the complete cycle and multiply the result by 100, the duty cycle is calculated, see equation 24 (Electronics tutorials [2014]).

$$\text{Complete cycle} = T_{ON} + T_{OFF} \quad [s] \qquad (23)$$

$$\text{Duty cycle} = \frac{T_{ON}}{\text{Complete cycle}} \quad [s] \qquad (24)$$

2.4 DC motors

Many functions in the truck that earlier were controlled mechanically is controlled by electrical devices today. Using an actuator, discussed in section 2.3, is one way to control systems and functions in the truck. Another way to control electrical components and systems is to use DC motors where for example a stepper motor can be used to work as an actuator. A permanent magnet brushless DC motor (PMBLDC motor) is also a common used motor in the truck though they are reliable and requires no maintenance. A PMBLDC motor can for example be used to control the sunroof or the wiper motor and other functions in the truck. The stepper motor is for example used in the bending lights in the truck.

2.4.1 Stepper motor

A stepper motor looks like a conventionally motor and compared to a totally enclosed motor with the same dimension and speed, it has similar produced torque and power. A stepper motor is a brushless synchronous motor, which converts a DC voltage to discrete mechanical movements. The motor is manufactured based on steps per revolution where 12, 24, 72, 144, 180 and 200 steps per revolution are common. The different number of steps for different motors results in different stepping angles: 30, 15, 5, 2.5, 2 and 1.8 degrees. A stepper motor with 1.8 degrees is the most common one.

The stepper motor is classified by two things, the stepping angle and the frame size, which corresponds to the frame size of the motor. For example a stepper motor with size 11 has a body size of approximately 1.1 inches (=26.84mm) (Davies, [2003]).

Stepper motors are attractive in different systems and industries today because of its high reliability; accuracy and that they can be controlled directly by a computer or microcontroller. Stepper motors are good choices when controlling rotating angle, speed position and synchronism are important. Stepper motors are commonly used in different industries today for example in the automotive and microcomputer industry. Common uses of a stepper motors are as actuators and as position transducers in different electrical components (Solarbotics, [2012]), (Hughes [2006]). The stepper motor has two major disadvantages, their loud noise and vibration. Because of the loud noise from the motor pulsed with modulation (PWM) is often used to decrease the noise. The vibrations created by the steps can cause damages on surrounding mechanics, which is why it is important to dimension the motor correctly (Calmon, [2014]).

Advantages:

- The only fully digital engine.
- Easy to control from all types of digital systems though the rotor angle is proportional to the input pulse.
- Cost-effective.
- Brushless which means no service is needed.
- Has full torque at stand still if the windings are energized.
- Has an accuracy of 3-5% of a step and the error is not cumulative from one step to the next.
- Can never be overloaded mechanically
- Requires no feedback

Disadvantages:

- Not easy to operate at a very high speed.
- Sensitive to external inertia.
- Can lose position without warning.
- Rarely manage revs above 1500 rpm.
- Drops torque when speed increases.
- Fairly loud noise.

The stepper motor is very popular in the industry today because it can be controlled by a microcontroller and it can be part of an open loop system, which means that no information about the stepper position is needed. With no position control needed there is no need of expensive position sensor or an optical encoder. Common stepper motors consist of a motor and a drive circuit. The motor works like an electromagnet with windings in the stator and a magnetic rotor, see figure 21. There are three different types of motors: Variable Reluctance (VR) motors, Permanent Magnet (PM) motors and Hybrid (HB) motors. Next there will be a description of the three types of motors with focus on the HB motor because it is the most common type. Depending on which type of motor used the rotor and stator can be with or without teeth. When the windings are energized, it will magnetize the rotor and it will start to step.

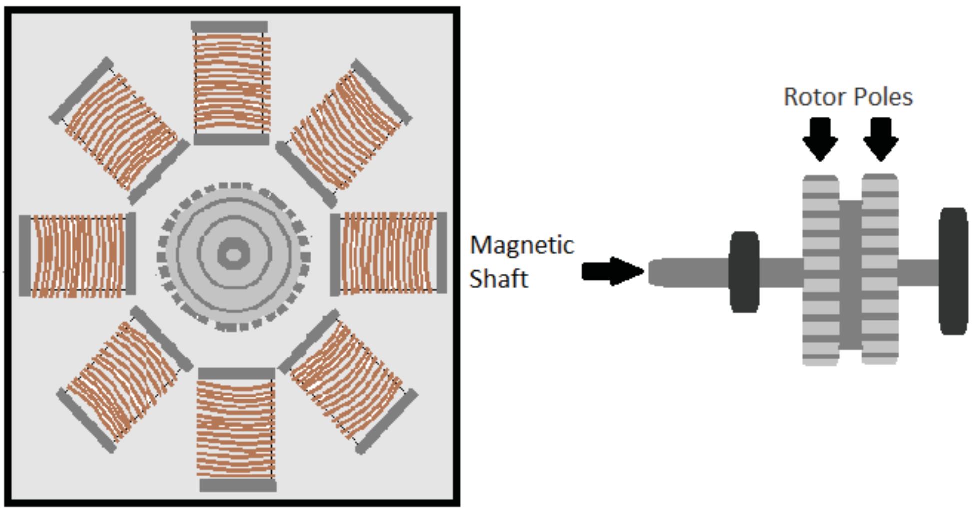

Figure 21 an overview of a stepper motor with 4 poles.

Variable Reluctance (VR) motor: The VR motor is the oldest type of stepper motor and relatively uncommon today. The VR motors are capable of operating at high speeds and provides small to medium sized step angles, it has a wired stator with a number of poles and a multi-teeth rotor made of soft iron. The stator windings are energized from DC current, which is provided by the stepper controller. When the windings are energized a rotation will occur when the magnetic stator poles attract the rotor teeth. The step angle in the motor is determined by the number of teeth on the rotor, the stator and the winding configurations (Davies, [2003]), (Solarbotics, [2012]).

Permanent magnet (PM) motor: The PM motor is also referred to as the 'thin can' or 'can stock' motor and is the easiest to manufacture of three stepper motors. The stator contains coils with windings and the rotor consists of a circular permanent magnet mounted on the shaft with alternating south and north poles, which will create the torque. The PM motor is a low cost and large steps motor (45 to 120 degrees), which makes it quite common even if it is a low power and low-resolution type of motor.

Hybrid (HB) motor: The stepper motor that dominates the industry today is the HB motor. The HB motor is suitable for high resolution, about 200-500 steps per revolution and is available in power ranges up to 3kW. A HB motor is a combination of the Permanent Magnet motor and the Variable Reluctance motor but is more expensive and has better performance with respect to step resolution, torque and speed than the other two types of stepper motors (Shiniano, [2010]). The HB motor has a step angle from 0.9 to 5 degrees where 1.8 degrees is the most common one, therefor the description of the HB motor will be based on a motor with a 1.8 step angle (Davies, [2003]), (Solarbotics, [2012]).

A HB motor with a 1.8 degrees step angle is a 4-phase motor. The stator in the motor has, like a 4 pole VR motor, eight wired poles separated by 45 degrees.

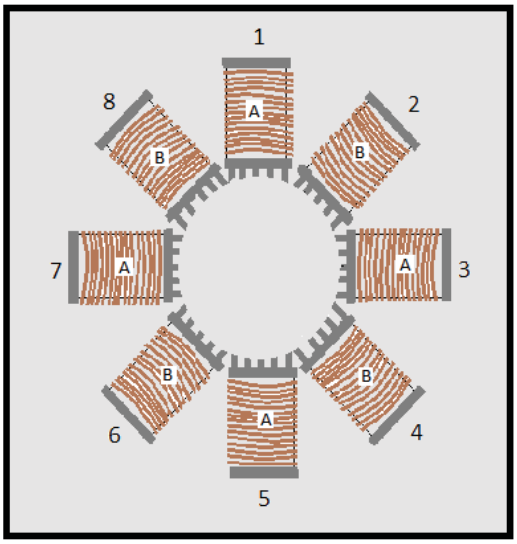

Figure 22 the stator in a 4-phase hybrid stepper motor.

Figure 22 shows a 4-phase stepper motor with 8 poles. Each phase in the motor is equipped with five teeth, separated by 7.2 degrees, which means that there are a total of 40 teeth on the stator. The rotor in a HB motor is multi-toothed like the VR motor and has a cylindrical magnet around the shaft, like the PM motor (Solarbotics, [2012]). There are a total of 96 teeth on the rotor, equally divided on two laminations with an offset of ½ tooth compared to the stator. Between the laminations there are a permanent magnet axially magnetized, which makes half of the teeth magnetized as north poles and the other 48 teeth are magnetized as south poles, see figure 23 (Hughes [2006]). There is no power supply on the rotor, which makes it robust and reliable. The current in the stator windings is the only power supplied to the motor. Compared to the rotor in the VR motor and the PM motor, the teeth on the rotor provides an even better path which helps to guide the magnetic flux to the preferred locations in the air gap. This increases the holding, detent and dynamic torque in the HB motor compared to the PM motor and the VR motor.

Figure 23 the structure of the rotor in a hybrid (HB) motor.

In figure 22 there are eight poles, numbered from 1 to 8. The poles 1, 3, 5 and 7 are called phase A and the poles 2, 4, 6 and 8 are called phase B. If phase A carries a positive current, pole 1 and 5 are magnetized as South Pole and phase 3 and 7 are magnetized as North poles. The rotor will rotate when the offset tooth at the north end and of the rotor are attracted to pole 1 and 5 in the stator, while the offset tooth at the south end of the rotor are attracted to pole 3 and 7 in the stator. To make another step, the positive/negative current in phase A is switched off and the positive/negative current in phase B is switched on. Pole 2, 4, 6 and 8 will then be affected by the magnetic flux created by the stator windings and the rotor rotates. Equation 25 can be used to calculate the step angle in a hybrid stepper motor (Hughes [2006]).

$$\text{Step angle} = \frac{360^{\circ}}{(\text{rotor teeth})\times(\text{stator phases})} \quad [\text{Degrees}] \qquad (25)$$

Like discussed earlier, there are three common types of motors but independently of which type of motor used, they can be controlled in the same way. Figure 24 shows the different parts in a stepper motor, which consists of a motor and a drive unit (Drivteknik, [2014]). The drive unit contains two parts, a stepper controller and a power supply. The power supply provides the circuit with a constant, rated DC voltage and the stepper controller controls the function of the stepper motor.

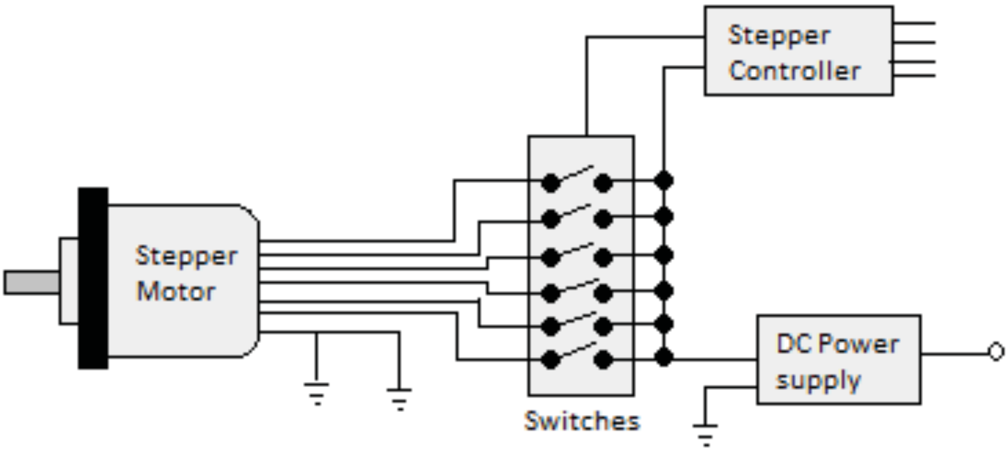

Figure 24 the different parts of a stepper motor.

The stepper controller contains several different parts; it is multifunctional and controls the motor speed, steps and the rotation of the motor (Elliott, [2007]). Today it is possible to control the stepper motor with both software and hardware units and a microcontroller is the most commonly used when high performance is sought. The microcontroller feed pulses and direction signals to the stepper controller. The signals from the microcontroller create pulses where the frequency determines the motor speed, number of pulses and motor position (Drivteknik, [2014]). The number of pulses is directly proportional to the length of the rotation and the speed of the motor; the motor will not run when it is feed with resonance frequency (Shiniano, [2010]).

A stepper motor is based on taking one step at a time and there are a couple of common stepping modes used to get the optimal stepping function, see figure 22:

<u>Wave drive:</u> has one phase energized at a time. A disadvantage with the wave drive is that only 50% of the motor windings are used and the maximum torque is not obtained. The stator is energized according to the sequence $A \rightarrow B \rightarrow A \rightarrow B$ and the rotor steps in the sequence $8 \rightarrow 2 \rightarrow 4 \rightarrow 6$.

<u>Full step drive:</u> This stepping mode has two phases energized at the same time but have the same angular movement as the wave drive, but with an angular offset by one half. The stator is energized as follows $AB \rightarrow AB \rightarrow AB \rightarrow AB$ and the rotor step positions are $1 \rightarrow 3 \rightarrow 5 \rightarrow 7$. The big difference between the Wave drive and the full step drive is that the full step drive uses all of the windings in the stator.

<u>Half step drive:</u> The half step drive combines the two previous stepping modes, wave drive and full step drive and has periods with one phase energized and periods with two phases energized. The stator windings are energized according to the sequence $AB \rightarrow A \rightarrow AB \rightarrow B \rightarrow AB \rightarrow A \rightarrow AB \rightarrow B$ and the rotor steps in the sequence $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 6 \rightarrow 7 \rightarrow 8$. When the half step drive mode is used, it only use half of the angular movements compared to the other two stepping modes.

<u>Microstepping:</u> In the Microstepping mode, the current in the windings is varying. The mode allows the motor to take smaller steppes, which decreases the risk of oscillation in the motor (Solarbotics, [2012]).

If a stepper motor in a system requires 48 pulses to rotate a complete revolution and there is an input signal with 96 pulses per second, the motor will rotate at 120 rev/min. The stepping range in a stepper motor needs to be increased gradually from sleep to full speed and cannot be ramped (accelerated) to a higher speed too fast, see figure 25 (Hughes [2006]). If the stepping range increases to fast, it may create sharp oscillations in the system ant the motor cannot stay 'in step' and it will stall (Calmon, [2014]). There for it is better to ramp the stepper speed slowly though a stepper motor is constructed to work for a long period of time and not to start/stop rapidly with high stepping ranges.

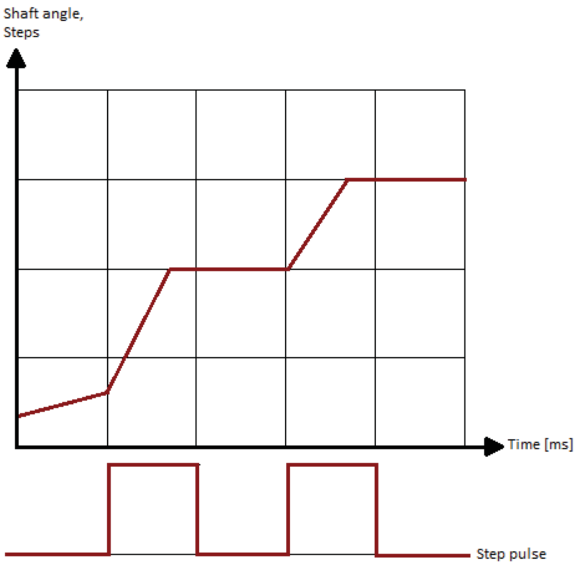

Figure 25 how the step pulses affects the stepper motor.

Because the stator contains coils, there will be a time delay before the motor starts, because the teeth in the motor have to be magnetized. There also is a minimum amount of current needed to make the rotor rotate. The time it takes for the rotor to move from one pole to another is called the step-time and can vary from 5-100ms. A stepper motor with a high stepping rate becomes more similar to an ordinary motor and when it operates at a high speed it is referred to as 'slewing' (Hughes [2006]). Figure 26 shows a single step resolution in a stepper motor. The time t is the time it takes for the rotor angle (θ) to rotate to the next stator pole and the time T is the time it takes to reduce the oscillations, which are undesirable, during a stepping. Using the microstepping method reduces the oscillation in a stepper motor.

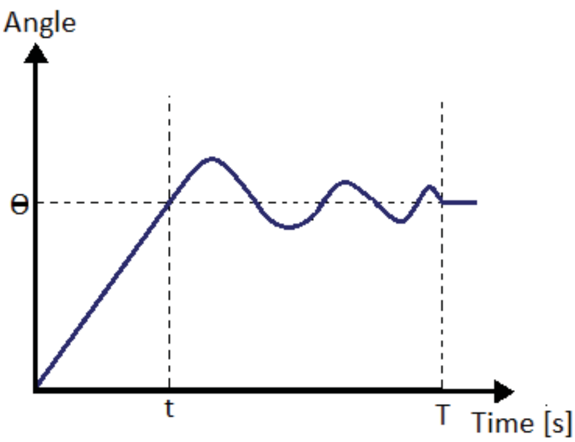

Figure 26 the angle verses time for a single step in a stepper motor.

As discussed earlier, the step angle has an accuracy of 3-5% and there are three types of common stepping errors. The accuracy is often represented when full step drive mode is used and the accuracy can be reduced by using a higher stepping range, for example microstepping (Calmon, [2014]).

Step position error: Equation 26 describes the step position error, which is the maximum positive or negative error caused when the rotor has rotated one step.

$$\text{step position error} = \text{measured stepangle} - \text{theoretical stepangl} \qquad (26)$$

Position error: The number of motor steps N are calculated by equation 27 and the position error is the calculated angular error $\Delta\theta_N$ minus the number of steps N and the measured angular in each step θ_N, shown in equation 28.

$$\text{N} = \frac{360^{\circ}}{\text{step angle}} \qquad (27)$$

$$\Delta\theta_{\text{N}} = \Delta\theta_{\text{N}} - \text{N}\theta_{\text{N}} \text{ [Degrees]} \qquad (28)$$

The position error is often expressed like follows: stepangle $\pm(\Delta\theta_{\text{max}} - \Delta\theta_{\text{min}})$

Hysteresis position error: Is the value that is obtained when the position error were measured in both directions (Solarbotics, [2012]).

Another part of the stepper motor is the pole switch, whose main task is to switch on/off the poles by supply the windings in the stator with positive or negative current (Drivteknik, [2014]). The switches are often power transistors connected to the stepper controller and when they are active they direct the current from the DC power supply to the appropriate phase, shown in figure 24 (Elliott, [2007]).

The torque produced by a stepper motor varies from 1µNm to 40Nm and depends on:

- Drive design
- Step rate
- Voltage
- Drive current in the windings

The torque in the motor is produced when the magnetic flux in the motor creates a rotor movement from one stator pole to another. The intensity of the magnetic flux in the motor is proportional to the torque output and a movement of the rotor, which creates an angular change (Calmon, [2014]), (Hughes [2006]).

Two important characteristics for a stepper motor are the torque vs. angular position characteristics and the torque vs. speed characteristics.

Torque vs. angular position: The relationship between the two units is the offset between the rotor and the torque. For an ideal stepper motor the characteristic is sinusoidal, shown in figure 27.

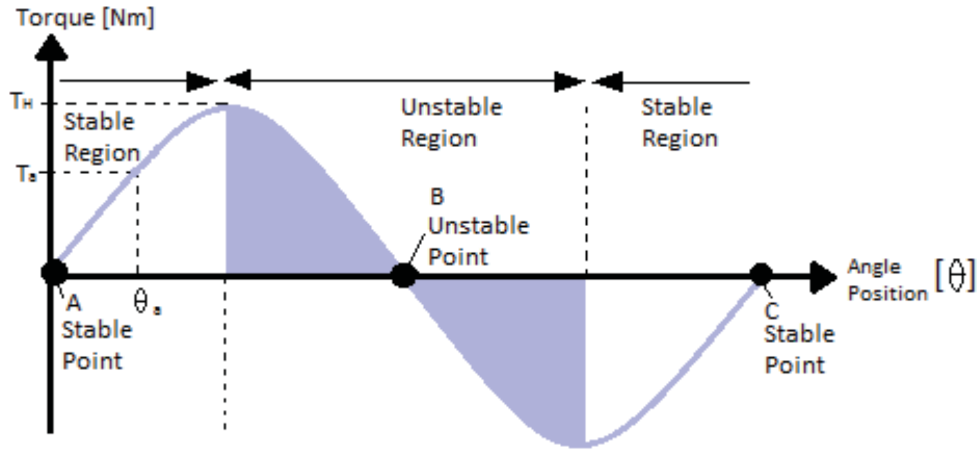

Figure 27 the torque vs. angle characteristics for a stepper motor.

In figure 27 there are three important designated points A, B and C. Point A and C are called the stable points and B is the unstable point.

The stable points A and B are the equilibrium points where there is no external load applied to the rotor. If a load is applied on the rotor shaft it will create an external force F_a in the motor and with a new force added to the motor, the rotor will come to rest at another angular position θ_a. To object the created angle θ_a, the motor creates a torque T_a that opposes the changed angular position though the created torque is equal to the external force in the motor (T_a=F_a). The motor will only stay in the stable region as long as the increased load on the motor shaft, which increases the angle position, not creates a torque greater than the maximum holding torque T_h. If T_h exceeds, the motor will enter the unstable region where point B is located. In the unstable region the torque will decrease until it once again enters a stable region. The displacement angle X in the motor can be calculated by equation 29 where Z is the rotor tooth pitch.

$$X = \left(\frac{Z}{2\pi}\right)\sin\left(\frac{T_a}{T_h}\right) \quad \text{[Degrees]} \qquad (29)$$

Earlier different angular errors of a stepper motor were discussed and a solution that would decrease/eliminate the problem would be to increase the maximum holding torque ($T_{H,max}$) in the motor [7].

<u>Torque vs. speed:</u> Figure 28 shows the torque vs. speed characteristics for a stepper motor. To be able to select the right stepper motor for a specific purpose, the torque vs. speed characteristic is very important.

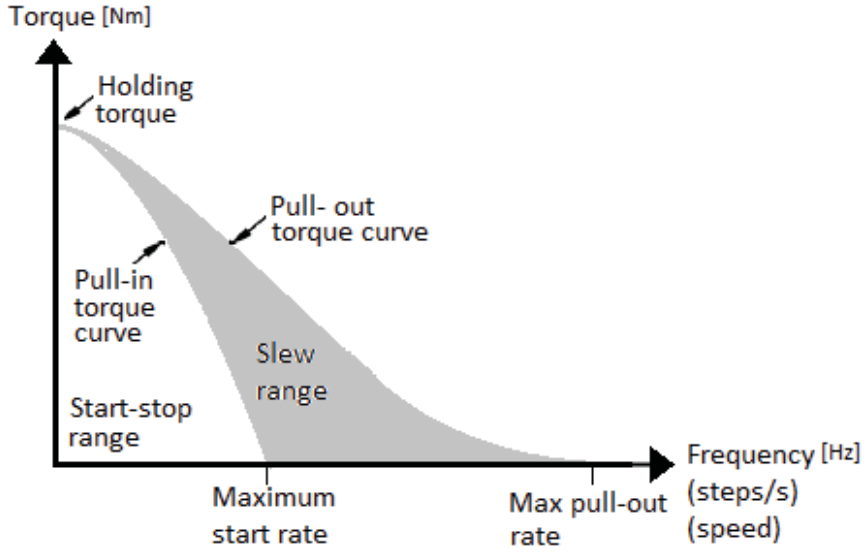

Figure 28 the torque vs. speed characteristics for a stepper motor.

Different types of stepping modes have been discussed and with an increased stepping range the torque in the motor will be decrease. Next, the different parts of the torque vs. speed characteristics will be discussed (Solarbotics, [2012]), (Shiniano, [2010]):

Holding torque (T_h): The holding torque is discussed earlier and is the maximum steady torque produced by the motor without causing rotation.

Pull-in torque curve: The curve, which separates the start-stop range and the slew range. It is the maximum frequency at which the motor can start/stop without losing synchronism.

Start-stop range: The speed range where the motor can start/stop and reverse the direction of the rotation without losing step.

Slew range: The range between the pull-in torque curve and the pull-out torque curve. In this area the motor can run without losing step when it is increased/decreased gradually and the slew range is reached by ramping.

Maximum start rate: The maximum start frequency when no load is applied to the motor.

Pull-out torque curve: The curve defines the maximum torque at which a stepper motor can start and run synchronized without losing step at constant speed.

Max pull-out rate: the maximum rate at which the motor can run and remain synchronized.

The output torque and the output power for a stepper motor are functions of the motor size, working duty cycle, motor windings and the type of driver used. The output torque and the output power can be reduced by the resonance in the motor and the resonance can arise at all frequencies. A motor with a constant motor drive has problems with resonance within the lower frequency regions but using half stepping or microstepping can eliminate resonance problems. Equation 30 describes the resonance frequency f where p is the number of pole pairs in the motor, T_h is the holding torque and J_r is the rotor inertia.

$$f = \frac{100}{2\pi}\sqrt{\frac{2pT_h}{Jr}} \quad [\mathrm{Hz}] \qquad (30)$$

2.4.2 Permanent Magnet Brushless Direct Current (PMBLDC) motor

A permanent magnet brushless DC (PMBLDC) motor is a common component in today´s electronics for example when components with speed control, pumps or fans needs to be controlled. The PMBLDC motor is often used when reliability, low costs and low maintenance are important (Hughes, [2006]). Compared to conventional DC motors the PMBLDC motor has no brushes and the windings are positioned on the stator instead of on the rotor, which means it is like a conventional DC motor turned inside out. Because of how the PMBLDC motor is constructed, it is more similar to an AC self-synchronized permanent magnet motor, than a DC motor. An advantage of having the windings on the stator is that there will be no arcing, which is why the PMBLDC motor often is used where explosive or flammable materials are presented. The main parts in a PMBLDC motor are the stator, the rotor and the position sensor. The position sensor is the big difference between the AC motor and the PMBLDC motor; figure 29 shows the construction of a PMBLDC motor. The position feedback is used to detect the rotor position, which affects the whole system (Haider, [2011]). Depending on the type of magnet used in the rotor, the motor can handle different temperature levels (Davies, [2003]).

When the PMBLDC motor started to appear in the electronics, a common problem was that the magnet got demagnetized. The reason was the high inrush current during start and because of the high temperatures in the motor. Buy changing the type of magnets used in the motor during the 1970s decreased the problem and today it does not affect the function of the motor.

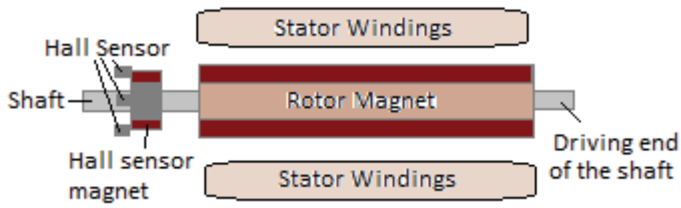

Figure 29 shows an overview picture of a PMBLDC motor.

Like discussed earlier, the best way to describe a PMBLDC motor is to compare it with an AC self-synchronous permanent magnet motor, not with a conventional DC motor. A PMBLDC motor has a stationary armature on the stator and the rotor is a rotating magnet (Beaty and Fink, [2013]). For a given size, the efficiency for a PMBLDC motor is the highest compared to any other electrical motors today. This means that it produces the highest output power with the least input power and the efficiency remains high during the entire speed range in the motor, equation 31 shows how to calculate the efficiency of a PMBLDC motor (Karassik, Messina, Cooper and Heald, [2008]). A PMBLDC motor is most commonly used for applications lower than 5kW. If the system needs a higher power output, it is no longer a cost benefit to use a motor with a permanent magnet compared to other types of motors.

$$\eta = \frac{\text{input electrical power} - \text{power losses}}{\text{input electrical power}} * 100\% = \frac{\text{output power}}{\text{input power}} * 100\% \text{ [lm]} \quad (31)$$

η: Efficiency

The permanent magnet in the PMBLDC motor can vary from two to eight pole pairs, which alternates between north poles (N) and south poles (S). The windings are positioned on the stator with no current in the rotor, which means that there is to no power loss in the rotor. The permanent magnets can be embedded into the rotor structure or it can be assembled onto the surface of the rotor, the position depends on the size of the motor. Regardless of how the permanent magnet is positioned, the rotor is very robust and has a long operating life (Narmadha, [2010]).

There are three different types of magnets, which can be used in a PMBLDC. It is the required magnetic field in the rotor that decides the type of magnet used in the motor. The Ferrite is the most traditional used magnet; it is the cheapest of the three magnets but can only be used in PMBLDC motor with more than 50hp to keep the cost competitive to the other magnets. Another drawback is that it has low flux density for a given volume. The magnetic flux output is only one third or one half compared to the other two magnets. The other two magnets are Samarium Cobalt and Neodynium Iron Boron. These two magnets can be used from 1 to 50 000 hp. Samarium Cobalt is the most expensive one but can withstand higher temperatures than the other two magnets (Karassik, Messina, Cooper and Heald, [2008]).

Like discussed earlier, the main difference between a conventional dc motor and a PMBLDC motor is the winding and magnet position in the motor. In a PMBLDC motor, the stator contains fixed armatures, windings and position sensors where the Hall sensor is the most common used (Haider, [2011]).

An important component in the PMBLDC motor is the position sensor, which make it possible for the motor to operate. The commutation in the motor is performed electrically by transistors, which are controlled by position sensors on the stator (Davies, [2003]). There are often three sensors in a motor, which are embedded in the stator. The positions of the sensors are very critical and each sensor has to be positioned exactly in the middle between two windings, so the current in the windings are turned on/off at the exact right time. The sensor provides high or low electrical signal that indicates if it is a north pole or a south pole, passing near the sensor (Narmadha, [2010], Haider, [2011]). The information from the sensor, about the rotor position, is fed to a logical network where the information is used to decide which of the windings that should be energized next (Sandqvist, [2014]).

In a PMBLDC motor there are three common used sensors:

Hall sensors:

- Most common
- Magnetic field sensitive
- Low cost
- Low resolution
- Temperature sensitive

Resolver:

- High resolution
- Need ADC
- High Costs

Optical encoder:

- High resolution
- Low reliability
- Higher cost than Hall sensor

Most PMBLDC motors have three windings connected on the stator, positioned in star fashion, see figure 30. Each coil is an inductor in series with a resistance, which induces a back electromagnetic field (EMF) when the rotor passes the winding. The EMF is described in appendix A.

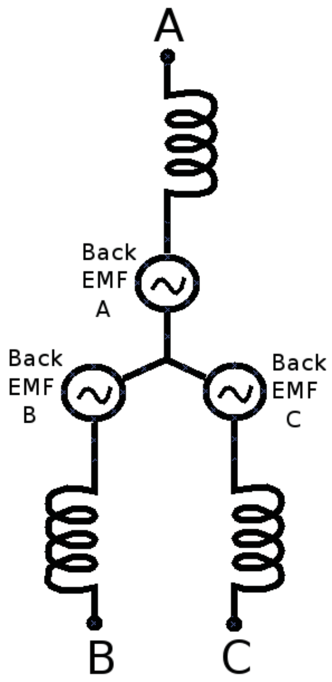

Figure 30 the stator configuration, with three coils.

In a PMBLDC motor there can be two types of stator windings, Trapezoidal and sinusoidal. The trapezoidal is the most common one in the motors though the sinusoidal is more expensive because it needs extra windings. Figure 31 shows a PMBLDC motor and the back EMF, phase currents and the signal to the positions sensor. The motor in the figure is winded as trapezoidal and the back EMF, phase currents and signal to the position sensor are in trapezoidal fashions. If the figure illustrated a motor with sinusoidal winding there would have been sinusoidal output signals to the system (Narmadha, [2010], Haider, [2011]).

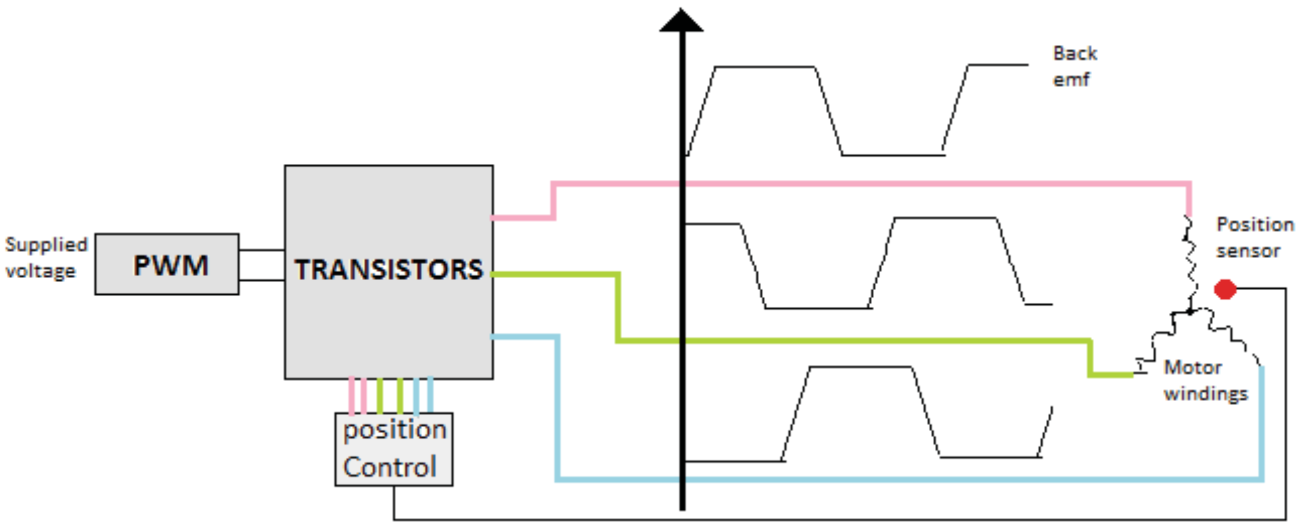

Figure 31 the entire control system of a PMBLDC motor.

The windings in a PMBLDC motor are fed with current pulses and as described earlier they can be trapezoidal or sinusoidal. The transistors in the PMBLDC circuit gets information about the rotor position from Hall sensors and can than provide the current pulses to the right windings (Beaty and Fink, [2013]).

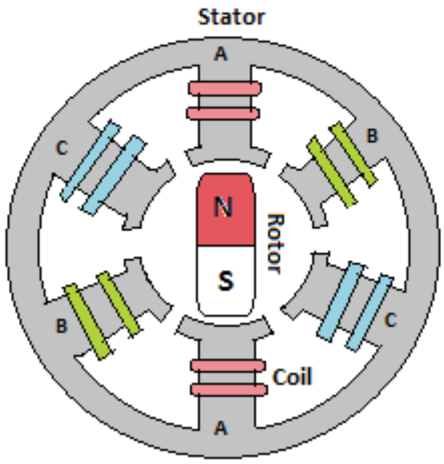

Figure 32 a six-step inverter which generates the three phase supply.

Figure 32 shows a PMBLDC motor with three poles, A is one pole pair, B is one pole pair and C is one pole pair, the different pole pairs have different polarity (Narmadha, [2010]). To get the rotor to rotate it has to chase the electromagnetic field, which appears when the windings are energized. Two of the windings can only be energized at a time and the rest needs to be in a non-energized condition (Haider, [2011]). The magnet chases the opposite polarity and that is how the torque in a PMBLDC motor is created. When the magnet is positioned like it is in figure 32, pole pair A is energized and the rest are non-energized. To get the rotor to change position, the current in pole pair A is turned off and the current in pole pair B is turned on. The magnet will than rotate though one of the windings in pole B is energized with negative polarity, which attracts the North Pole on the magnet and the other winding in is energized with a positive polarity, which attract the South Pole. When the magnet has rotated to pole pair B, it will be turned off and pole pair C will be turned on and this regulation will continue. It is important that all the coils have the same number of turns because the current is constant in all phases and as described in appendix A, the magnetic flux is increased with a higher number of turns on the coil so if the number of turns varies; the magnetic flux in the motor will vary. The timing to turn on/off the current in the windings is very critical, though the purpose is to maximize the torque in the motor. If the current is affected to early/late, the motor will get performance issues. The current is turned on/off 6 times before the rotor has rotated 360 degrees, the amount of laps the rotor rotates in one minute is called Revolutions Per Minuit (RPM).

Figure 31 shows an overview of the PMBLDC electrical system with three phases and Trapezoidal signals. The mechanical commutation in a motor is replaced by electrical commutation to provide the torque in the motor. The position sensors between the rotors are used to inform the system about the rotor angular position (θ). The rotor position feedback has different values depending on if it is the north pole or the south pole of the magnet, passing the sensor. The information about the rotor position is then transported to the inverter. A PMBLDC motor is used in a closed loop control system with a DC input signal. The system uses a Pulse Width Modulation (PWM) power controller to provide a variable voltage to the inverter. Inside the inverter the electrical commutation are performed by switching transistors. Like discussed earlier, the inverter is affected by the rotor position and depends on the information from the position sensors, the transistors will be affected in the inverter. The output signals from the inverter are the signals that affect the windings in the stator. Depending on the rotor position, the windings in the stator will be energized or de-energized (Narmadha, [2010], Haider, [2011]).

Ones the motor is designed properly, the number of turns on the windings and the rotor magnetic field remains constant. The motor is constructed in the way that if the rotor is running on at its rated speed, the potential difference between the back EMF and the supplied voltage will be sufficient for the motor to draw the rated current and deliver the rated torque. The only way to affect the back EMF is than to change the angular velocity or the rotor speed. If the speed increases, the back EMF will increase.

The PMBLDC motor has three important variables: torque, induced voltage and magnetic flux. The magnetic flux is discussed in appendix A.

All PMBLDC motors have a voltage constant K_B, where B is the back EMF. The K_B constant relates the voltage (V_{DC}) to the resulting idle speed (n) of the motor, see equation 32. The voltage constant can be calculated as a DC measurement, which is used in equation32, but it can also be calculated as an AC measurement, see equation 33. Which type of measurement that is most suitable depends on if the motor contains electronics or not. The DC measurement is used without electronics; otherwise the AC measurement should be used. In an AC measurement the peak voltage ($\hat{V}$) between two lines and the resulting ideal speed (n) are measured, see equation 33 (Sandqvist, [2014]).

$$K_B = \frac{V_{DC}}{n} \quad [V/rpm] \qquad (32)$$

$$K_B = \frac{\hat{V}}{n} \quad [V/rpm] \qquad (33)$$

Another constant is the torque constant K_T. The constant gives the relationship between the torque (T) and the current from the power supply (I), see equation34.

$$K_T = \frac{T}{I} \quad [Nm/A] \qquad (34)$$

With the information from equation 32, 33 and 34 it’s possible to calculate the torque and motor speed of the motor. An important fact is that the two constants K_B and K_T are not independent of each other, see equation 35. $\frac{60}{2\pi}$ is the conversion factor between V/rpm and $V/(rad/s)$.

$$K_T = K_B \frac{60}{2\pi} \quad [Nm/A] \qquad (35)$$

<u>Torque and speed:</u> Torque (T) is one of the main variables while discussing the PMBLDC motor. Torque is produced because of the interaction between the permanent magnet and the magnetic field created by the energized windings on the stator (Narmadha, [2010]). The torque is produced by the input current (I) and the torque constant K_T, see equation 34. Figure 33 shows a two-pole PMBLDC motor whit a rotor rotating to the right.

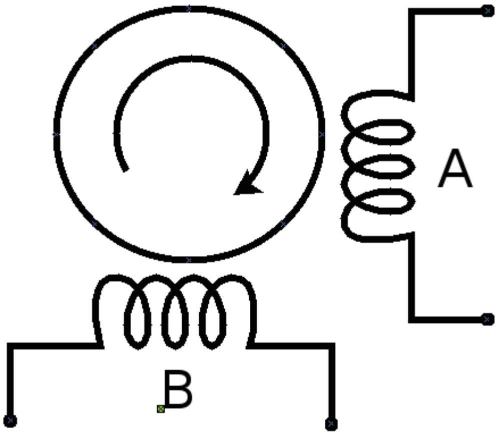

Figure 33 a part of an illustration of a PMBLDC motor with two poles.

With information from equation 36 and 37 it is possible to see how the torque in the two-phases (T_A and T_B) and the current (I_A and I_B) are linked together with sinusoidal signals. Equation 36 and 37 describes the output torque for phase A and B. Because the signals are sinusoidal the equations contains sinusoidal components.

$$T_A = I_A K_{T(A)} \sin\left(\frac{p\theta}{2}\right) \ [\mathrm{Nm}] \quad (36)$$

$$T_B = I_B K_{T(B)} \sin\left(\frac{p\theta}{2}\right) \ [\mathrm{Nm}] \quad (37)$$

T: Torque in phase A or B

I: Current in phase A or

p: Number of poles

θ: Angular position of the rotor

$$I_A = I\sin\left(\frac{p\theta}{2}\right) \ [\mathrm{A}] \qquad (38)$$

$$I_B = I\cos\left(\frac{p\theta}{2}\right) \ [\mathrm{A}] \qquad (39)$$

The total torque (T) for the two poles is obtained when the torque for phase A and phase B are added. By adding equation 38 and 39 to equation 36 and 37, the total torque is shown in equation 40. The maximum torque archives when the two magnetic fluxes are perpendicular to each other (Ngabonziza Nyampame, [2011]). With sinusoidal signals and perpendicular magnetic fluxes, the Pythagorean theorem can be used to eliminate the sinusoidal parts and the torque will only be affected by the armature current and the total torque constant K_T.

$$K_T = K_{T(A)} + K_{T(B)} \ \left[{}^{V}/_{rpm}\right]$$

$$T = T_A + T_B = IK_T\sqrt{[\sin^2(\theta) + \cos^2(\theta)]} = IK_T 1 = IK_T \ [\mathrm{Nm}] \qquad (40)$$

Discussed earlier is that the torque is directly proportional to the polarity of the armature current. Figure 34 shows the torque characteristics when the rotor rotates one lap. The simulation in the figure is ideal which is impossible to achieve in a proper motor because there cannot be an exact uniformed magnetic field. Figure 34 shows that the polarity of the torque change when the polarity of the current changes.

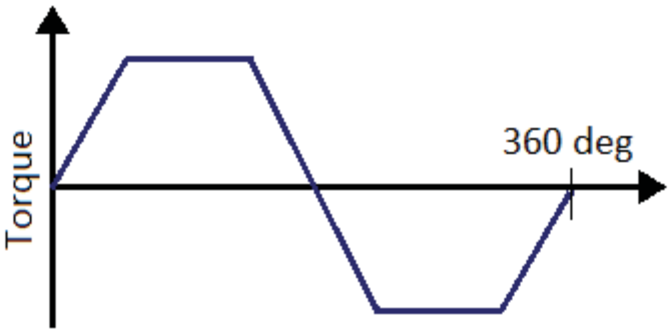

Figure 34 the Torque characteristics during one rotor rotation.

The ratio between the torque and the speed are linear in a PMBLDC motor, see figure 35. There are three torque parameters used to describe the PMBLDC motor, it is the peak torque (T_P), the rated torque (T_r) and the electromagnetic torque (T_e), the electromagnetic torque will be discussed later.

Figure 35 contains two zones, continuous torque zone and intermittent torque zone. When the motor is running in the continuous torque zone, the torque can be loaded up to the rated torque and the torque remains constant up to the rated speed. Because the torque appears when there is an interaction between the armatures and the permanent magnet [10]. The peak torque will occur when the two magnetic fields are perpendicular to each other. When the motor is operating in the intermittent torque zone there will be a tradeoff between torque and speed, to get a higher torque, the speed will have to operate at a lower speed than the rated speed. The maximum speed occurs when the rated voltage is fed to the motor [8]. The maximum speed can be up to 150% of the rated speed but as can be seen in figure 35, the torque will continue to drop outside the continuous torque zone and when the maximum speed is reached there will be no torque produced in the motor (Davies, M. [2003]).

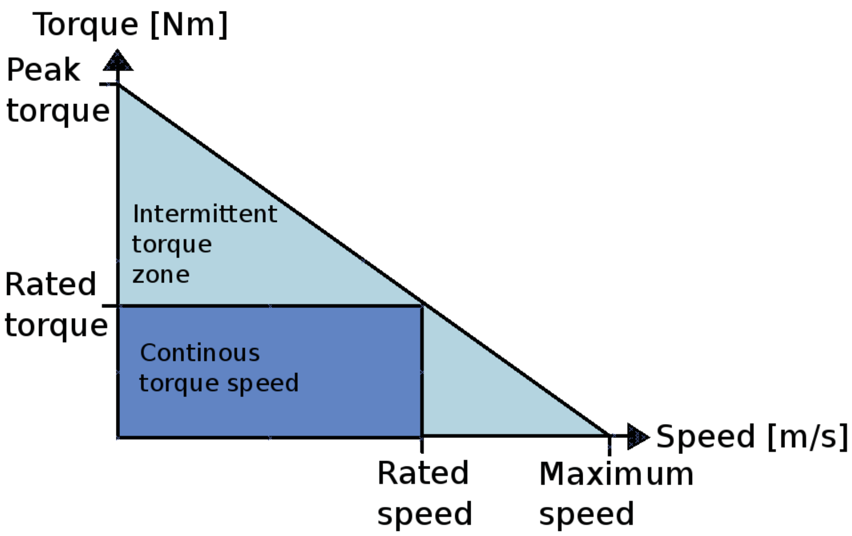

Figure 35 the Torque VS speed characteristics.

To do calculations of a PMBLDC motor an equivalent circuit is often used, see figure 36.

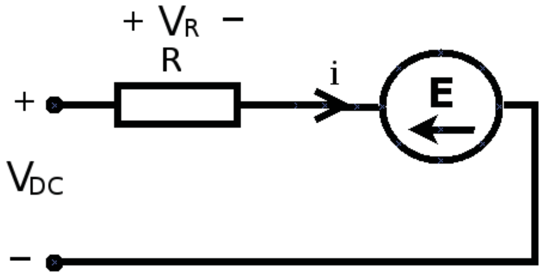

Figure 36 an equivalent circuit for PMBLDC motor.

In a three-phase PMBLDC motor each winding has an input voltage. How to calculate phase voltage for a PMBLDC motor with trapezoidal signals are shown in equation 41-43.

$$V_a = R_a I_a + L_a \frac{dI_a}{dt} + M_{ab} \frac{dI_b}{dt} + M_{ac} \frac{dI_c}{dt} + e_a \ [V] \quad (41)$$

$$V_b = R_b I_b + L_b \frac{dI_b}{dt} + M_{ba} \frac{dI_a}{dt} + M_{bc} \frac{dI_c}{dt} + e_b \ [V] \quad (42)$$

$$V_c = R_c I_c + L_c \frac{dI_c}{dt} + M_{ca} \frac{dI_a}{dt} + M_{cb} \frac{dI_b}{dt} + e_c \ [V] \quad (43)$$

The stator resistance (R_s) and the inductance (L_s) in all the phases assume to be equal though they are not affected by the rotor position in the motor. This means that the stator resistance per phase is R=R_a= R_b= R_c and the stator inductance per phase is L=L_a= L_b= L_c. not even the mutual inductance (M) between the three phases depends on the rotor position M=M_{ab}= M_{ac}= M_{ba}= $M_{bc\ Mca}$= M_{cb}. With the new information about the stator resistance, inductance and actually neglecting the mutual inductance in the motor, it is possible to rewrite the equation 41-43, which gives the new phase voltage, see equation 44-46 (Narmadha, [2010]).

$$V_a = RI_a + L\frac{dI_a}{dt} + e_a \ [V] \quad (44)$$

$$V_b = RI_b + L\frac{dI_b}{dt} + e_b \ [V] \quad (45)$$

$$V_c = RI_c + L\frac{dI_c}{dt} + e_c \ [V] \quad (46)$$

As discussed earlier, a back EMF is generated every time the rotor rotates in the motor. For a PMBLDC motor with three phases, the phases are located 120 degrees apart. The total back EMF in a PMBLDC motor can be calculated by equation 47, which is a function consisting of two variables, the rotor position (θ) and the mechanical speed (ω). Because the back EMF depends on the rotor position equation 48-50 shows the back EMF for different rotor positions for each phase in the motor, when the speed is known.

$$E = K_E \omega \qquad (47)$$

$$e_a \begin{cases} \frac{6E}{\pi}\theta & (0 < \theta < \frac{\pi}{6}) \\ E & (\frac{\pi}{6} < \theta < \frac{5\pi}{6}) \\ -\frac{6E}{\pi}\theta + 6E & (\frac{5\pi}{6} < \theta < \frac{7\pi}{6}) \\ -E & (\frac{7\pi}{6} < \theta < \frac{11\pi}{6}) \\ \frac{6E}{\pi}\theta - 12E & (\frac{11\pi}{6} < \theta < 2\pi) \end{cases} \qquad (48)$$

$$e_b \begin{cases} -E & (0 < \theta < \frac{\pi}{2}) \\ \frac{6E}{\pi}\theta - 4E & (\frac{\pi}{2} < \theta < \frac{5\pi}{6}) \\ E & (\frac{5\pi}{6} < \theta < \frac{9\pi}{6}) \\ -\frac{6E}{\pi}\theta + 10E & (\frac{9\pi}{6} < \theta < \frac{11\pi}{6}) \\ E & (\frac{11\pi}{6} < \theta < 2\pi) \end{cases} \qquad (49)$$

$$e_c \begin{cases} E & (0 < \theta < \frac{\pi}{6}) \\ -\frac{6E}{\pi}\theta + 2E & (\frac{\pi}{6} < \theta < \frac{\pi}{2}) \\ -E & (\frac{\pi}{2} < \theta < \frac{7\pi}{6}) \\ \frac{6E}{\pi}\theta - 8E & (\frac{7\pi}{6} < \theta < \frac{9\pi}{6}) \\ E & (\frac{9\pi}{6} < \theta < 2\pi) \end{cases} \qquad (50)$$

If the back EMF E=1 in the motor, there will be a function called back EMF function $f(\theta)$. The variable $f(\theta)$ is a function, which represents the rotor positions. Though there are three phases there are three different back EMF functions that can be represented, one for each phase, see equation (51-53).

$$f(\theta)_a \begin{cases} \frac{6}{\pi}\theta & (0 < \theta < \frac{\pi}{6}) \\ 1 & (\frac{\pi}{6} < \theta < \frac{5\pi}{6}) \\ -\frac{6}{\pi}\theta + 6 & (\frac{5\pi}{6} < \theta < \frac{7\pi}{6}) \\ -1 & (\frac{7\pi}{6} < \theta < \frac{11\pi}{6}) \\ \frac{6}{\pi}\theta - 12 & (\frac{11\pi}{6} < \theta < 2\pi) \end{cases} \qquad (51)$$

$$f(\theta)_b \begin{cases} -1 & (0 < \theta < \frac{\pi}{2}) \\ \frac{6}{\pi}\theta - 4 & (\frac{\pi}{2} < \theta < \frac{5\pi}{6}) \\ 1 & (\frac{5\pi}{6} < \theta < \frac{9\pi}{6}) \\ -\frac{6}{\pi}\theta + 10 & (\frac{9\pi}{6} < \theta < \frac{11\pi}{6}) \\ 1 & (\frac{11\pi}{6} < \theta < 2\pi) \end{cases} \qquad (52)$$