# DIMENSIONING OF ELECTRO-HYDRAULICS FOR A BATTERY ELECTRIC LOADER

Lappeenranta-Lahti University of Technology LUT

Electrical engineering, master's thesis

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ABSTRACT

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**Dimensioning of electro-hydraulics for a battery electric loader**

Electrical engineering, master’s Thesis

72 pages, 17 figures and 4 tables

Examiners: D.Sc. Prof. Juha Pyrhönen and D.Sc. Ilya Petrov

Supervisors: M.Sc. Sami Haikio

Keywords: BEV, electrical machine, mobile hydraulics, hydraulic pump, VFD, wheel loader

This thesis describes a dimensioning process of electro-hydraulic and power electronic control components for an underground wheel loader. The purpose of the work is to establish basic principles regarding energy efficiency and mechanical and electrical protection for responsible industrialization of the product.

Comparisons between different hydraulic pumps, AC electrical motors and control methods are made to select components that as a whole fulfill the set requirements for the loader. In addition, energy efficiency and prime cost of production are in balance. Another major importance of any battery electric vehicle is balancing of batteries so that the actuators can work at maximum power at all times when needed and to prolong their total lifetime.

The result of this thesis is to provide a progressive dimensioning manual for hydraulic pumps, electrical motors and frequency converters. The dimensioning of motor power cables is described. In this vehicle, additional EMC protections are of no importance because of short cabling.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

School of Energy Systems

Sähkötekniikka

Janne Siivonen

**Akkukäyttöisen kuormaajan sähköhydrauliikan mitoittaminen**

Sähkötekniikan diplomityö

72 sivua, 17 kuvaa ja 4 taulukkoa

Tarkastajat: TkT Prof. Juha Pyrhönen ja TkT Ilya Petrov

Ohjaajat: DI Sami Haikio

Avainsanat: hydrauliikkapumppu, mobiilihydrauliikka, pyöräkuormaaja, sähkökone, taajuusmuuntaja, työkone

Työssä mitoitetaan sähköhydrauliikan ja sitä ohjaavien tehoelektroniikan komponentteja maanalaiseen kaivokseen soveltuvaan pyöräkuormaajaan. Työssä on tarkoitus esittää energiatehokkuuteen ja osien mekaaniseen ja sähköiseen suojaukseen liittyviä perusperiaatteita, jotta kuormaajan tuotteistus olisi mahdollisimman vastuullista.

Vertailun kohteena on muun muassa eri hydrauliikkapumpputyypit, sähkömoottorityyppit ja ohjausstrategiat. Näitä vertaamalla on tarkoitus löytää komponentit ja metodit, joilla kuormaajalle asetettujen vaatimuksien ehdot täyttyvät. Sen lisäksi hyötysuhteen ja kokonaisuuden hinnan tulee olla tasapainossa. Erityisen tärkeä asia akkukäyttöisessä kulkuneuvossa on myös akkujen tasapainottaminen, jotta kone saa aina tarvittavan maksimimäärän tehoa toimilaitteisiin, jolloin myös akkujen käyttöikä pitenee.

Työn tuloksena on askelittainen suunnittelumenetelmä hydrauliikkapumpulle, sähkömoottorille ja taajuusmuuntajalle, jotka ovat kaikki liitoksissa toisiinsa. Moottorin voimakaapelien pituuteen liittyvään EMC-suojaukseen vaadittavia suotimia ei ole tarvetta asentaa lyhyiden johtojen takia.

**ACKNOWLEDGEMENTS**

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Janne Siivonen

Turku, October 26, 2021

# NOMENCLATURE

## Symbols

| | |
|---|---|
| *A* | Area |
| *C* | Speed of light |
| *c* | Capacitance per unit length |
| *f* | Frequency |
| *I* | Current |
| *l* | Length |
| *N* | Rotational speed |
| *n* | Rotational speed |
| *P* | Power |
| *p* | Pole-pair number, pressure |
| *Q* | Liquid flow |
| *R* | Resistance |
| *s* | Length |
| *T* | Torque |
| *t* | Time |
| *U* | Voltage |
| *V* | Displacement, volume |
| *v* | Velocity of progressive wave |
| $\alpha$ | Resistance temperature coefficient |

| | |
|---|---|
| $\eta$ | Efficiency |
| $\varepsilon$ | Relative permittivity |
| $\mu$ | Relatively permeability |
| $\Theta$ | Temperature rise |

Subscripts

| | |
|---|---|
| cef | Effective cooling |
| cr | Critical |
| DC | Direct current |
| ef | Effective |
| in | Incoming |
| max | Maximum |
| N | Nominal |
| off | De-energized |
| on | Energized |
| peak | Peak value |
| req | Required |
| RMS | Root mean square |
| r | Rise |
| s | Synchronous |
| tot | Total |
| tot,max | Total, maximum |

Abbreviations

| | |
|---|---|
| AC | Alternating-current |
| BEV | Battery electric vehicle |
| BMS | Battery management system |
| C-rate | Battery allowable current compared to capacity |
| CAN | Controller area network |
| CE | Conformité Européenne |
| DC | Direct current |
| DIN | Deutsches Institut für Normung |
| DOL | Direct on-line |
| EDM | Electric discharge machining |
| EMC | Electromagnetic compatibility |
| EMF | Electromotive force |
| EMI | Electromagnetic interference |
| ETL | Electronic torque limiting |
| FEM | Finite element method |
| HF-CM | High-frequency common-mode |
| IE | International Efficiency (Standard) |
| IEC | International Electrotechincal Commission |
| IGBT | Insulated-gate bipolar transistor |
| IM | Induction machine |

| | |
|---|---|
| IP | Ingress protection |
| ISO | International Organization for Standarization |
| Li-ion | Lithium-ion |
| $LiFePO_4$ | Lithium iron phosphate (battery type) |
| LS | Load sensing |
| LVDT | Inductive position transducer |
| MDG | Mining design guideline |
| MOSFET | Metal oxide semiconductor field effect transistor |
| MTPA | Maximum torque per ampere |
| NEMA | National Electrical Manufacturers Assosication |
| PC/LS | Pressure compensated, load sensing |
| PMa SynRM | Permanent magnet assisted synchronous reluctance machine |
| PMSM | Permanent magnet synchronous machine |
| PRV | Proportional relief valve |
| PWM | Pulse width modulation |
| RMS | Root mean square |
| SAE | Society of Automotive Engineers |
| SFS | Finnish Standards Association |
| SI | Système international d'unités |
| SoC | State of charge |
| SRPM | Synchronous reluctance assisted permanent magnet |
| SynRM | Synchronous reluctance machine |

| | |
|---|---|
| VFD | Variable frequency drive |

# Table of contents

# 1 INTRODUCTION

Because of recent changes in international regulations, battery electric vehicles (BEVs) are becoming more attractive in the industrial scene. Replacing diesel motors with alternating-current (AC) motor drives has serious positive impacts on environment and demand for such vehicles has started to boom. This thesis describes the dimensioning process of hydraulic system used in a real-world BEV mining loader and is mainly concerned with articulated steering and hydraulic boom devices even if the machine has numerous other hydraulic functions. Proper dimensioning of the hydraulic circuit is important to keep the vehicle's price tag within reason and enabling it to fulfill the requirements. Selection of components is limited by factors such as pre-selected battery packs, dimensions and weight of the components, standards and regulations. In addition, high energy efficiency is essential for the longevity of the battery capacity and environmental impact.

## 1.1 The loader

The electric loader under development (figure 1) is designed to operate in underground tunnels with minimum heading of 4.5 meters. It is capable of loading 18 tonnes of rock material in its bucket and tramming at 24 km/h with full payload (set value for maximum tramming speed is 30 km/h). The loader is powered by two 353 kWh lithium iron phosphate ($LiFePo_4$) batteries contained within a single battery pack that can be swapped in a few minutes. Batteries are swapped using automated functions on the rear side of the vehicle and on the battery pack itself (locking hooks and electro-hydraulically actuated kickstands in battery pack). The loader itself carries two 12 volt batteries connected in series that power a separate 24 volt circuit for certain auxiliary and emergency functions.

Figure 1 The electric underground loader. Fig. courtesy Sandvik Mining and Construction.

## 1.2 Goals

This study mainly focuses on selection of electric motors, frequency converters and hydraulic pumps for a Sandvik heavy loader. Motor’s and frequency converter’s cooling will also be studied in detail. Another important topic is electromagnetic compatibility as it is closely related to frequency converters. In addition, other relevant topics, such as battery monitoring, torque limitation and energy regeneration are discussed. The work should conclude on which type of motor and hydraulic pump is best for this application and what kind of a frequency converter is required to supply them. It should also give a bottom line on how to avoid electrical problems such as frequency converter trips and component deradation. To achieve compilance of standards, they need to be studied as well during the dimensioning process. This document is organized so that it can be used in future projects inside the organization.

## 1.3 Standards and regulations

The vehicle is designed to comply with standards such as ISO and MDG (Mining design guideline, Australia) that enforce personnel safety, sustainability and customer benefits. The standards and regulations that are directly linked with this thesis are as follow.

- EN ISO 19296: Mining – Mobile machines working underground mines – Machine safety
- EU 2006/42/EC: Machinery directive
- EU 2006/95/EC: Low voltage directive
- EU 2014/30/EU: Electromagnetic compatibility directive
- CE marking
- MDG 15: Guideline for mobile and transportable equipment for use in mines
- EN ISO 13850: Emergency stop push button
- Others

The requirements for compliance are discussed in sections where appropriate.

# 2 DIMENSIONING OF THE HYDRAULIC SYSTEM

The hydraulic cylinders and batteries are not dimensioned in this work, however, all the main components between them are. This means that the dimensioning workflow starts with selecting the hydraulic pumps capable of supplying enough hydraulic flow in sufficient pressure to the cylinders to meet the process requirements. Once the pumps are selected, the motors that drive the pumps need to be selected. In motor selection, studying the battery properties is important to select a motor with compatible parameters, such as the voltage and current. The parameters of the motor and battery pack, and additionally specifications for control, determine which motor converter is suitable for the vehicle. Figure 2 depicts the hydraulic circuit of the loader under development.

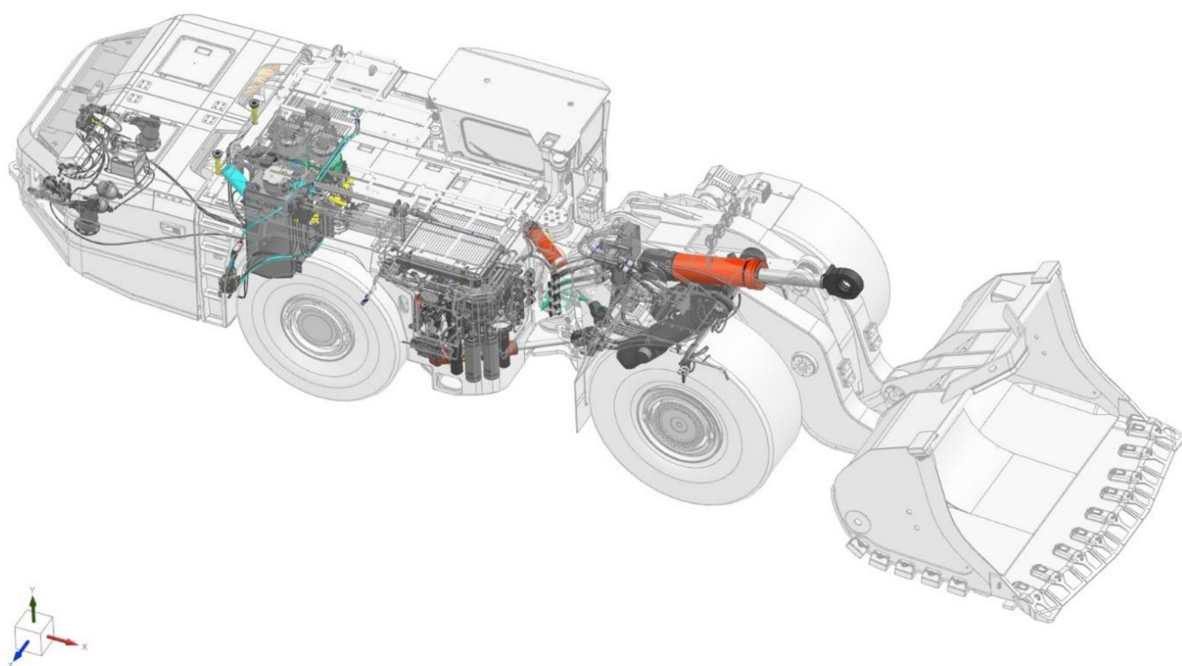

Figure 2 Loader’s hydraulic system. Fig. courtesy Sandvik Mining and Construction.

## 2.1 Hydraulic actuators

This thesis focuses on three of the main hydraulic functions in the vehicle, the boom, bucket and articulated steering. All of them are actuated by linear hydraulic cylinders.

To begin dimensioning the pumps, their requirements must be known accurately. Because the hydraulic actuators are already selected, their parameters and actuation periods characterize the actual requirements for pumps. The actuators for boom, bucket and steering functions, as well as their parameters, are listed in table 1.

Table 1 Hydraulic cylinders used in boom and steering system.

| | Rod-side diameter (mm) | Piston-side diameter (mm) | Stroke length (mm) | Working pressure (bar) | Number of cylinders |
|---|---|---|---|---|---|
| Boom (lifting) | 110 | 180 | 1045 | 317 | 2 |
| Bucket (tilting) | 140 | 220 | 686 | 318 | 1 |
| Steering | 70 | 100 | 522 | 290 | 2 |

Hydraulic pump dimensioning is based on pumps' ability to generate required hydraulic oil flow to actuate the cylinders within required time. Cylinder flow rates need to be calculated first using cylinder dimensions and process requirements.

$$Q = Av = \frac{As}{t} \tag{1}$$

where $Q$ is hydraulic fluid flow into piston [$m^3/s$], $A$ is the area that the oil pushes [$m^2$], $s$ is stroke length [m] and $t$ is stroke period [s].

This equation is used to calculate hydraulic flow in SI units. However, SI units are not the industry standard in hydraulics. Hydraulic component manufacturers use l/min instead of $m^3/s$ as the unit of hydraulic flow. The unit must be converted for easier comparison.

$$Q = \frac{As}{t} 60 \cdot 10^3 \tag{2}$$

where $Q$ is volumetric flow in [l/min].

### 2.1.1. Articulated steering

The articulated steering system uses two linear hydraulic cylinders to rotate the front and rear axles relative to the central pivot point (articulation hinge). When the machine steers left, the front body of the loader body points left and the rear body points right as shown in figure 3.

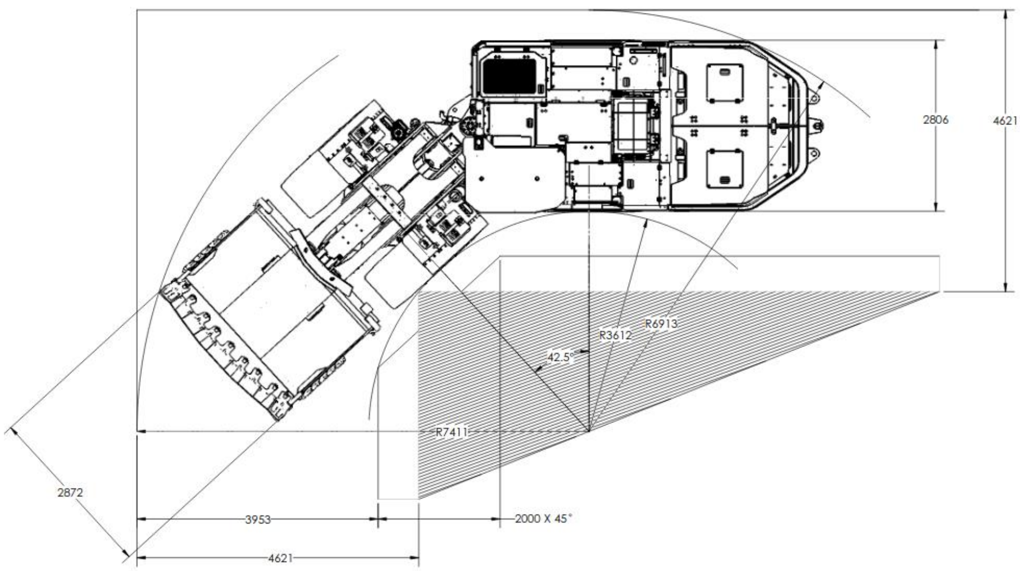


Figure 3 Geometry of the loader. Fig. courtesy Sandvik Mining and Construction.

This can be achieved by extending the right linear actuator and retracting the left actuator proportionally. When the operator maintains a straight line in tramming, both cylinders are extended to an equal span and locked in place (by hydraulic valves) to avoid unwanted movement of the axles. In practice, the piston side of the left cylinder is connected to the rod side of the right cylinder and vice versa to achieve proportional extension and retraction of the cylinders. The steering system must be capable of turning the wheels from lock to lock in 3.5 seconds. Angle between neutral position and lock is 42.5° (articulation angle).

When turning the body, frictional forces under each tyre resist the movement. Thus, the mechanical force of the steering cylinders must overcome the friction to achieve turning. The frictional force is relative to the mass that each tyre is supporting. When the bucket is loaded, the front wheels are carrying more weight than the rear tyres and the steering actually gets lighter because the rear section is significantly less burdened.

The axles are equipped with limited slip differentials that allow the loader to gain enough traction to move when the other side is on a slippery surface.

The system that primarily steers the vehicle is one of the two main hydraulic pumps. However, according to ISO 5010, an international standard that this machine is built to comply with, all wheeled earth-moving machines whose maximum speed is over 20 km/h shall be equipped with a secondary system for steering should a malfunction occur. (International Organization for Standardization, 2019)

MDG 15/2018 also has a section corresponding to the forementioned clause that is somewhat more specific. It states that the emergency steering system must be able to power the hydraulics enough to turn the wheels 1.5 times from lock to lock after engine shutdown. (Department of Regional NSW, NSW Resources Regulator, 2020).

While this loader is not powered by an internal combustion engine and the expression “engine shutdown” does not mean the same thing in electric vehicle applications, the specification was interpreted so that a reserve hydraulic pump capable of powering the steering system enough to turn the wheels 1.5 times from lock to lock after the steering motor is de-energized must be installed. This emergency hydraulic pump can be far smaller than the main pump for cost saving purposes and can be wired onto the on-board 24-volt circuit.

Steering uses two cylinders but they are cross connected together. The flow rate for both the piston side and rod side must be calculated and added together. The diagram for steering circuit is shown in figure 4.

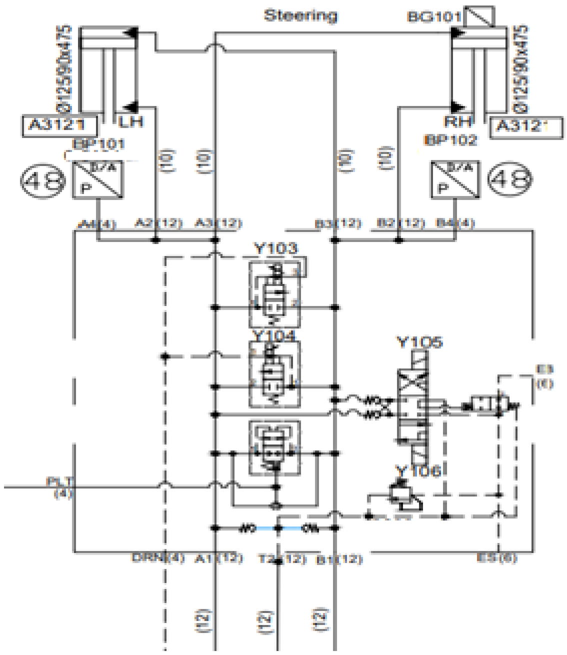


Figure 4 Hydraulic schematic for steering. Fig. courtesy Sandvik Mining and Construction.

The requirement for turning the wheels from lock to lock is 3.5 seconds. According to equation (1), the flow rate for steering at full power is $1.75\times10^{-3}$ $m^3/s$ or 105 l/min.

### 2.1.2. Bucket

In addition to lifting the boom, the bucket can be tilted using a single hydraulic cylinder. Bucket tilting is useful when loading and unloading the bucket. Bucket cylinder is also used in bucket shake function, where bucket cylinder is moved back and forth rapidly to unload the contents of the bucket cleanly. Bucket shake function is implemented by quickly varying the displacement of the hydraulic pump. Tilting the bucket from one extreme to another must not take more than 2.0 seconds. When the bucket is actuated hydraulically, the rod side area is being pushed and when the bucket tilts in the other direction, gravity does the work. Thus, flow required by bucket tilting is $5.3\times10^{-3}$ $m^3/s$ or 317 l/min.

### 2.1.3. Boom

The boom (figure 5) has two hydraulic cylinders to position itself vertically. The control of boom cylinders is coupled so that they are always extended to an equal span.

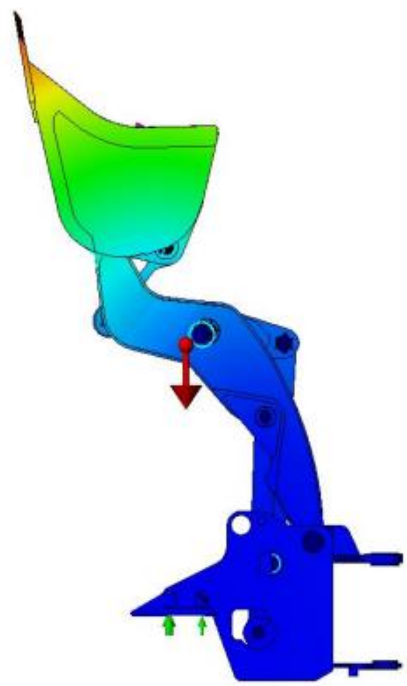

Figure 5 Boom. Fig. courtesy Sandvik Mining and Construction.

According to specification, the hydraulics need to be capable of lifting the boom from ground to its peak in 8.3 seconds and lowering the boom in 5.2 seconds. Boom's upward motion is powered by the hydraulic pumps, however when lowering, it is allowed to fall gravitationally.

The required flow rate for boom motion is $3.2\times10^{-3}$ $m^3/s$ or 192 l/min. Because two cylinders are used to move the boom this value must be doubled to get flow rate required for the pump, which is 6.4×10$^{-3}$ m$^3$/s. Boom's hydraulic diagram is shown in figure 6.

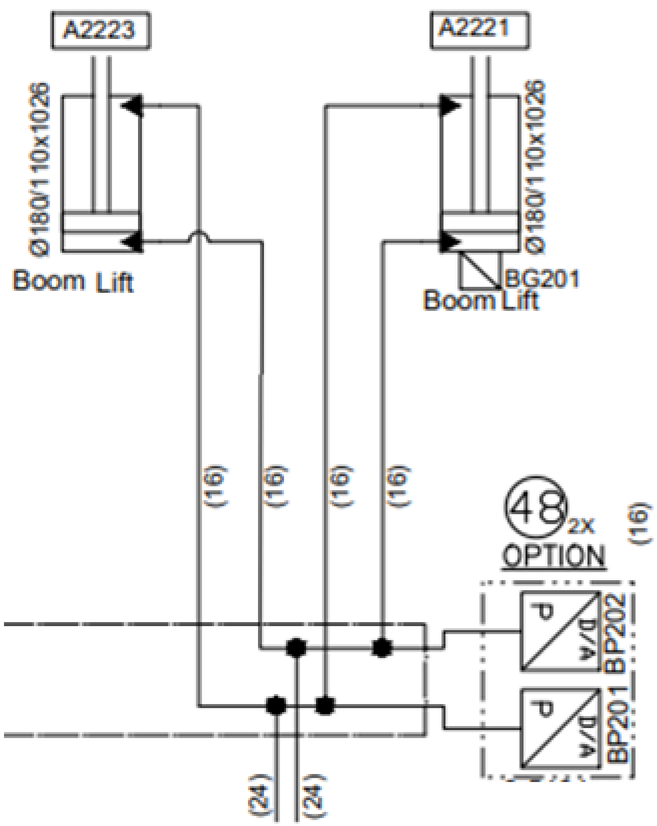


Figure 6 Hydraulic schematic of boom. Fig. courtesy Sandvik Mining and Construction.

## 2.2 Selection of hydraulic pumps

There are numerous different hydraulic pump manufacturers around the globe but because of the strict deadlines and quality control, only a certain group of suppliers can be considered for this project. It is important not to undersize the pump as the actuator will not get its full benefit and the hydraulics become underpowered and prone to failures. Oversizing the hydraulic pump allows for optimal performance of the entire system, but it will lead to unnecessarily high cost of components as not only the pump will be more expensive but also other components because of higher pressure tolerances of the components.

Large hydraulic pumps often come in the form of either axial piston pumps or gear pumps. While the details of their internal design are outside of the scope of this thesis, it is worth mentioning that piston pumps can be variable-displacement (hydraulic torque can be adjusted by varying the oil displacement per revolution) while gear pumps are always fixed-displacement. At the same time piston pumps have significantly higher pressure ratings and better efficiency than gear pumps, making them suitable for heavy-duty applications. Displacement of the pump can be adjusted by changing the angle of the swashplate against the pistons inside the pump, varying the stroke length of pistons. Bigger angles result in higher oil flow through the pump. In modern implementations, the swashplate is tilted using a servo piston. The position of the servo is fed back into the control loop by LVDT (inductive position transducer). (Parker, 2000)

Selecting a fixed-displacement piston pump would be a more inexpensive solution because varying pump displacement is not necessary in fully electrohydraulic applications. Displacement control is useful in diesel vehicles because the energy for hydraulics comes from a single source that powers traction and hydraulics, and the energy coming to a hydraulic pump can not be controlled independently. Electrohydraulic pump’s oil flow can and should be controlled with varying the shaft speed rather than its displacement because of significant efficiency savings. However, variable displacement pump has another significant benefit, that is the ability to limit load torque acting on the drive. This topic is further discussed in chapter 2.7.

Due to cost and size constraints, only two pumps can be installed. Because the boom requires so much oil flow, a single mobile-sized pump is not enough to operate it alone. Therefore two pumps must be connected so that either hydraulic function (boom or steering) can use both pumps when the situation demands it, or alternatively, reserving the other pump only for steering and using both pumps for the boom when needed. This also means that both functions can not be used at full power concurrently. Due to safety reasons, it is important that the operator always has control of steering and it must be prioritized. This can be achieved with load sensing valves in the steering circuit that signal the boom valves to not open fully (or forcing them to close when power to steering is needed if valves are already open) to allow full power for steering.

It is wise to pick two identical pumps to simplify control and installation. There is no way to calculate an optimum pump configuration (without over or under sizing) for this system so different pumps need to be compared and checked that hydraulics work as intended with selected components. The requirement for a single pump is

$$Q_{\text{pump}} = \frac{Q_{\text{tot,max}}}{2} \tag{3}$$

where $Q_{\text{tot,max}}$ is previously calculated flow values added together ($13.45\times10^{-3}$ $m^3/s$).

Flow rate for a single pump is then 6.7 $m^3/s$. Using the same logic, power out of single pump should be about 175 kW. The pump's efficiency must also be taken into account. Pump must, therefore, be rated 175 kW ÷ $\eta$. Efficiency of piston pumps is usually in the range of 80-90% (ExxonMobil, 2018).

The values calculated above are for case where the vehicle is both steering and lifting at full power at the same time. Dimensioning the components this way would not be favourable because this type of operation is not a requirement and flow rate of this magnitude requires extreme component sizing. If for some reason the machine needs to be steered while lifting the boom, it is acceptable to reduce the power to the boom momentarily. Sizing the components for borderline cases that are not required for the project results in excessive cost of the system.

A better approach at pump sizing is to select pumps that are capable of lifting the load within the required time interval when the vehicle is not moving. That is, using pumps, whose combined fluid flow equals to boom motion's flow calculation. As mentioned before, if the steering unit must be used, it will be prioritized and the boom will slow down but not stop. Thus, better values for the flow and power are $3.2\times10^{-3}$ $m^3/s$ and 102 kW (ignoring efficiency) respectively.

Figure 7 shows the cylinder pressures in a typical loading session. The selected pump must be able to maintain flow at these pressures to generate the required torque. Load torque in this session barely hits 480 Nm and the pressure stays under 280 bar.

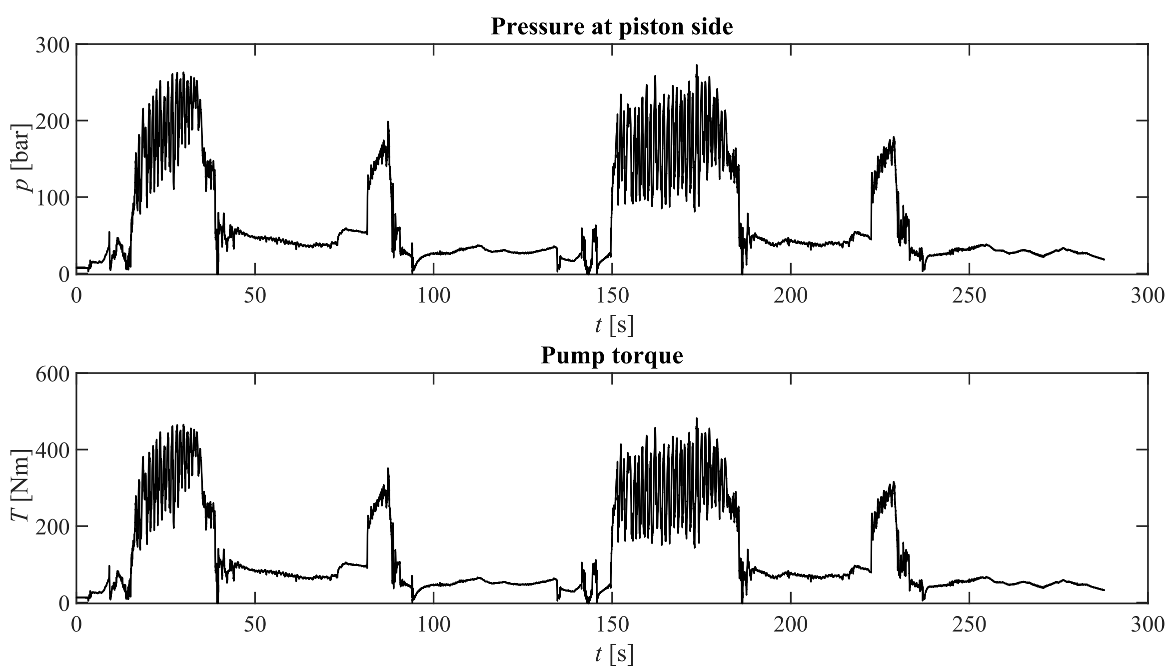


Figure 7 Piston side pressure measured on a similar sized Sandvik diesel loader.

Different pumps that meet the requirements need to be compared to find the optimal pump. Usually standard hydraulic components can be found in different manufacturers' catalogues and it becomes easier to find a component matching the required parameters. For example, Danfoss has "Open circuit pump series 45" line of hydraulic pumps that includes pumps ranging from displacement of 25 $cm^3$ to 147 $cm^3$. These pumps are said to be designed specifically for off-highway mobile applications (this likely means that these components tolerate vibration better and are small enough to be installed in moving vehicles). Series 45 size 100 pump (maximum displacement of 100 $cm^3$) meets the requirements according to previous calculations. Its theoretical maximum flow is 245 l/min and continuous working pressure is 310 bar (maximum is 400 bar). Its nominal speed is 2450 rpm. Size 90 has a theoretical maximum flow of 198 l/min, which is higher than the requirement, but the term theoretical maximum likely means that its efficiency is neglected. (Danfoss, 2021) Hydraulic pumps' efficiency is usually no more than 90% at nominal speed, which makes this size incapable of producing the required flow, whereas size 100 variant should be adequate. The torque production of a hydraulic pump can be derived using following equations

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

where $P$ is the pumping power [W], $p$ is the pressure inside the pump [Pa] and $\eta$ is the volumetric efficiency of the pump and

$$Q = Vn \tag{5}$$

where $V$ is pump's displacement [$m^3$] and $n$ is the pump's rotational speed [1/s], resulting in

$$T = \frac{Vp}{2\,\pi\,\eta} \tag{6}$$

The hydraulic industry often, somewhat misguidedly, uses l/min, $cm^3$ and bar in place of SI standard units $m^3/s$, $m^3$ and Pa. By converting the units ($1\ cm^3 = 1\cdot10^{-6}\ m^3$ and $1\ bar = 1\cdot10^5$ Pa, whose multiplication is $\frac{1}{10}$, hence the coefficient 20 in place of 2 in the denominator), the same equation can be written as

$$T = \frac{Vp}{20\,\pi\,\eta} \tag{7}$$

where $V$ is the displacement in [$cm^3$] and $p$ is the pressure in [bar].

(Bosch-Rexroth, 2021) Assuming 90% efficiency, its torque at nominal speed and maximum displacement is 550 Nm.

Another pump that could likely be sufficient is Bosch-Rexroth A10VZO size 100. Its flow at nominal speed (2300 rpm) is 230 l/min and requires 445 Nm of torque for full power. The reason why this pump’s load is smaller compared to the Danfoss pump is that this pump has nominal pressure of only 280 bar (maximum is 350 bar). (Bosch-Rexroth, 2021)

## 2.3 Driving the pump with an electric motor

Main method of controlling pump is varying the speed of the electric motors and controlling the directional valve spools. The rotor and pump shaft rotate at the same speed (if the input shaft of the pump is directly connected to the output shaft of the motor without gear reduction), and therefore the motor speed dictates shaft speed of the pump. A simple diagram of a hydraulic system is shown in figure 8, with controls abstracted out.

In this loader, the hydraulic system used to lift or lower the boom is controlled by a joystick. Essentially, the joystick angle controls motor's speed and directional valve's position and opening, effectively controlling pump's flow rate and direction of oil flow. The joystick may be moved in two directions from the neutral position, one direction extends the hydraulic cylinders and the other retracts it allowing the operator to lift or lower the load. The 4/3 (4-port, 3 position) directional valve block in figure 9 illustrates its operating principle: hydraulic fluid can be moved straight-way or cross-way, allowing movement of the cylinder both ways. This type of directional valve can also be set in a position where no oil flows through it, which locks all actuators in place (if valve leaks are neglected). When the high-side of the pump (P in Figure 9) is connected to the bore side (A) of the cylinder, the cylinder will extend and vice versa.

Hydraulic systems connected to internal combustion engines usually have the hydraulic pump shaft rotating at a constant speed but the hydraulic flow is throttled with directional control valves or in the case of variable displacement pumps, the pump's displacement is changed to adjust flow. In direct electrohydraulic systems, throttling and displacement variation is not strictly necessary as the pump can be turned at whatever speed the application demands at each point in time, whereas in diesel equipment the single traction engine drives the pump via timing belt or via other means of rotational energy transfer. The most efficient way to control hydraulic fluid flow in electrohydraulics is simultaneously opening the directional valve orifice and sending a signal to the frequency converter to start supplying the electrical motor at a given speed, achieving an accurate amount of flow to actuators.

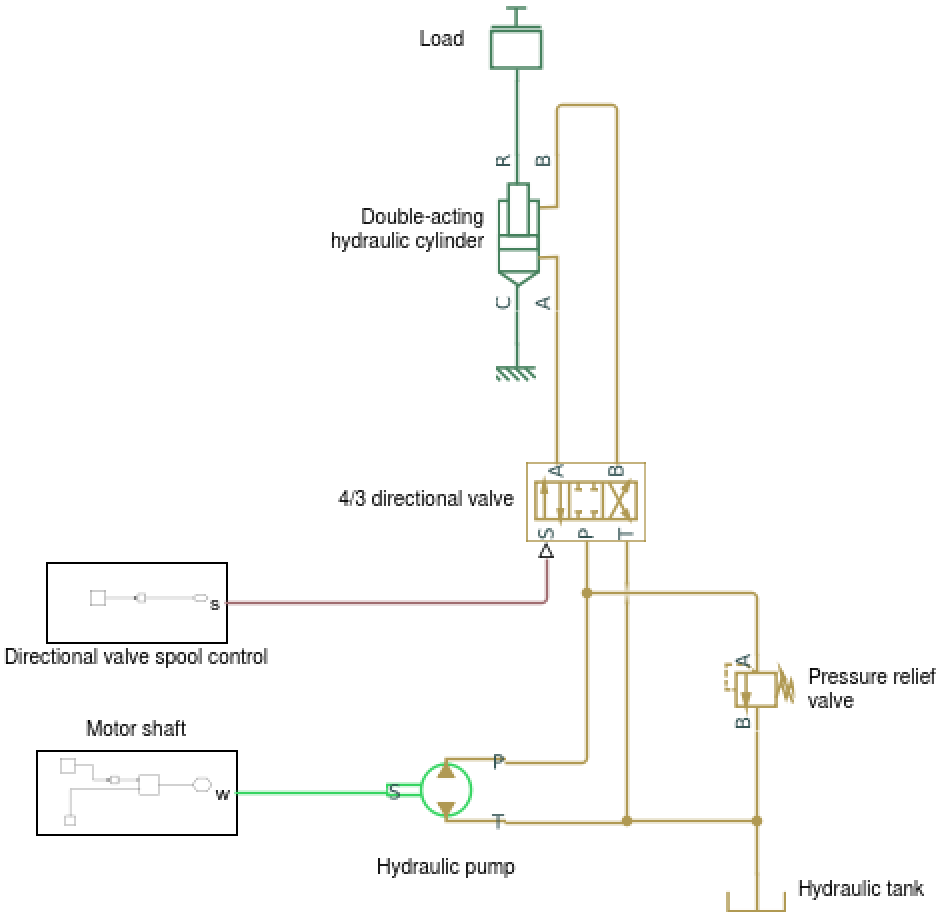


Figure 8 A simple hydraulic circuit showing a mass being lifted.

The control of the hydraulics becomes a bit more complicated because the hydraulic power comes from two pumps and the boom cylinders are coupled with both. Not to mention that steering also uses one of the two pumps and full power must be reserved for steering. A simple method of achieving power on demand is to only use one pump for the boom if the vehicle's hydraulic equipment does not demand a great deal of power. Only when the demand reaches a certain threshold, should the other pump be turned on. This raises a question regarding delay in control because starting the pump from stand-still to certain speed is not instantaneous. This is due to inverter start-up delay and load inertia. The delay of the boom’s or articulated steering’s cylinders’ response should not exceed a certain period of time. Empirical testing conducted by Sandvik shows that a delay of 250-300 ms is the period of time at which the operator notices unresponsiveness. If this delay is not exceeded on pump activation, this type of control is adequate.

If this period is exceeded on turning on the pump, some other type of control must be employed. It is possible to keep the motor rotating while the swashplate of the other pump connected to it remains at zero degrees. In this situation, no fluid flow occurs in the pump because of no piston stroke and the load to the motor is as low as it gets. This results in minimal losses, yet keeping the motor turning, and should the demand for hydraulic power peak, delay should not be as high as starting the motor from stand-still. This however means that variable displacement pumps must be installed and swashplate control implemented. (Parker, ei pvm)

However, a bachelor’s thesis by Jani Heinonen shows that turning off the inverter in a certain Sandvik loader and restarting it does not cause a significant delay in case of steering. This means that the inverter turns on and the motor starts fast enough and the valve delay is in fact greater than the delay of inverter turn-on. (Heinonen, 2021, p. 26) That study however involves another, much smaller machine, LH307B. The frequency converters of that loader are not planned to be installed in this loader and it is wise to verify turn-on delay for whatever frequency converter is going to be installed in the heavier loader.

A question arises during the development of this loader regarding how exactly should the pumps be controlled to achieve required system flow on demand while keeping the hydraulic system as efficient as possible.

Joysticks are the main interface to actuators. They send signals to both the directional valves and the hydraulics control module, a micro circuit that decides which power unit to use based on which power pack (combination of AC motor and hydraulic pump) is connected to the healthier battery. If the flow demand exceeds the maximum oil flow of one pump, the module will start both pumps to achieve demanded flow. The control module knows the parameters of the pumps and the electric motors so that it can signal the frequency converter exactly how fast the motor should rotate. If only one pump is needed, the power pack with higher state of charge will be utilized. The most straight-forward method of turning both pumps is to turn them at exactly the same speed, effectively halving the work. This however does not take into account optimization of efficiencies because pump's speed affects efficiency. The relation between pressure, shaft speed and efficiency is shown in figure 9.

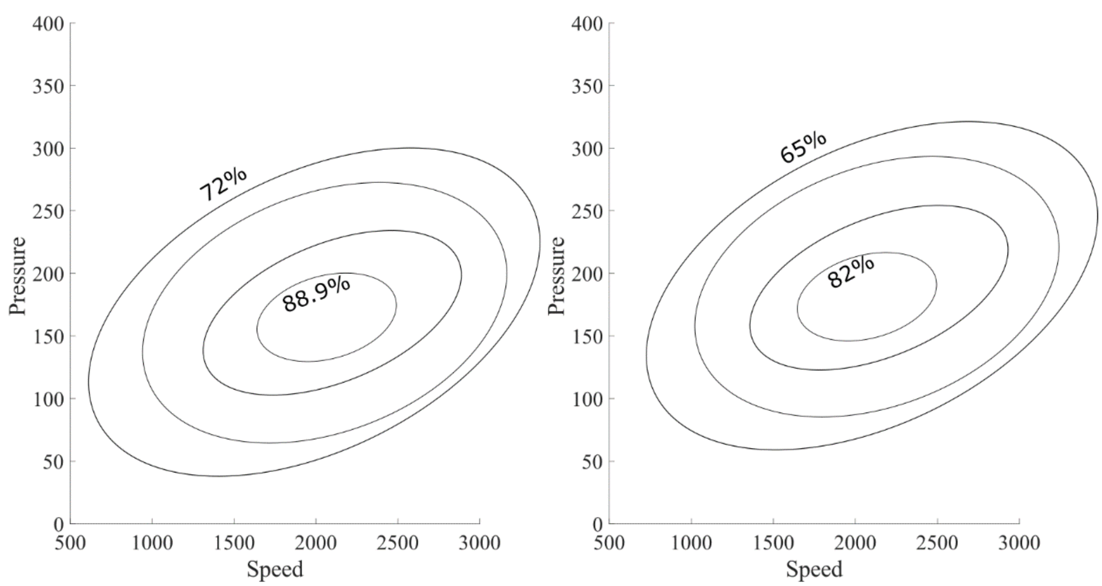


Figure 9 Example contour plots of a pump running at 100% and 50% of its maximum displacement.

Since one power pack is not powerful enough to lift the boom at maximum speed, there needs to be a control scheme that uses both power packs for lifting. There are many ways to achieve this but the simplest methods in electronic control perspective are generating half the flow request at both pumps or generating maximum flow at the primary power pack and generating enough additional flow at the secondary power pack to reach the requested flow. If the second method is adopted, primary power pack will rotate at pump's maximum speed and the secondary power pack will rotate at a speed dictated by

$$n_{\mathrm{sec}} = 60\frac{\eta_{\mathrm{tot}}}{V}\left(Q_{\mathrm{req}} - Q_{\mathrm{max}}\right) \tag{8}$$

where $n_{sec}$ is the pump's speed control reference in [1/min], $Q_{req}$ is the requested flow [$m^3$/s], $Q_{max}$ is the maximum flow one pump can generate and $V$ is the displacement of the pump [$m^3$].

The control should also be adjusted so that neither of the pumps ever run at less than minimum speed. Frequency converter's and motor's temperature need to be monitored as well. If either temperature approaches derating temperature, the pump's torque must be decreased (by torque limiter) to reduce temperature. Figure 10 shows a flow graph on how this hydraulics control should be implemented in the perspective of frequency converters' speed control.

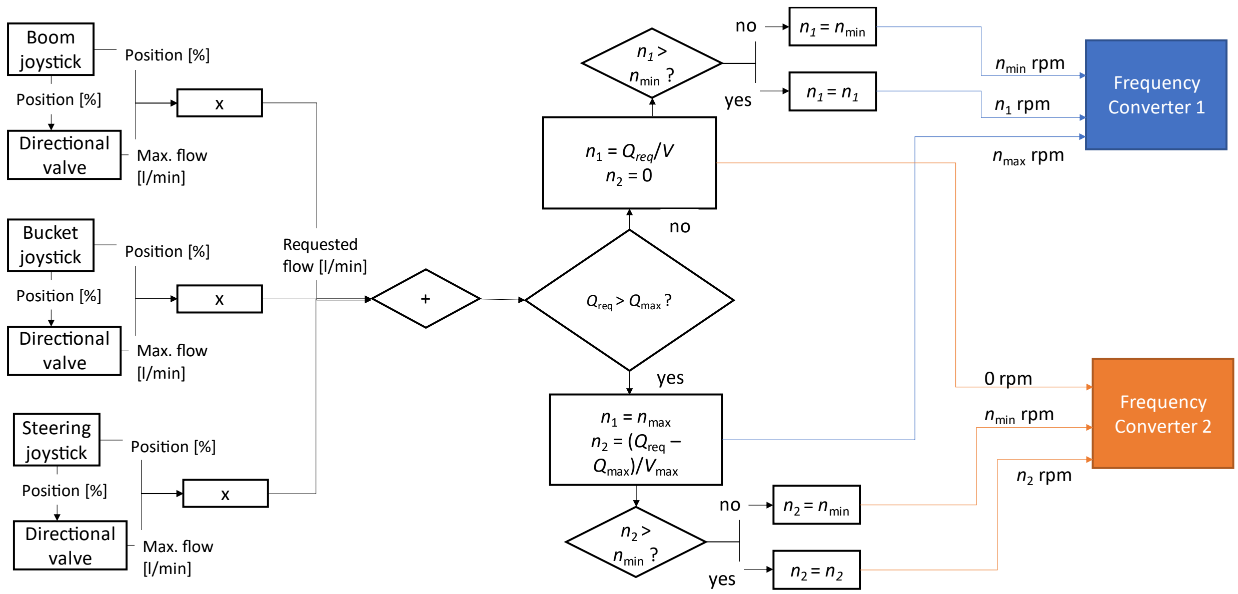


Figure 10 Flowchart that describes how pump speeds are determined in order to supply specific hydraulic fluid flows to the cylinders.

When two pumps are running at the same time, the logic should determine at which speed to run each pump to achieve maximum combined efficiency. The same type of contour curves are available for electric motors as well so their combined efficiency must be considered. Pump’s curves can be simplified by using a constant pressure. For example, drawing a straight line on 280 bar eliminating a variable completely. Pump always has better efficiency when it is rotated at its maximum displacement.

## 2.4 Choosing the electric motor for the pump

Usually in medium to high power electro-hydraulic applications, the hydraulic pump is driven by either a 3-phase IM (induction machine) or a 3-phase PMSM (permanent magnet synchronous machine).

Induction machines, or more specifically squirrel-cage induction machines, work by creating a rotating magnetic field to the air-gap and the squirrel-cage rotor induces current in its bars. This induced current produces torque in the same direction as the rotating magnetic field, rotating the rotor. Induction machine’s rotor does not turn at the same frequency as the magnetic field (unless there is no load) due to slip, which makes the rotor lag the magnetic field by a certain percentage. The slip characteristics and low power factor are the main reason induction motors have relatively low efficiency compared to some other types of 3-phase AC motors. Induction motors are however by far the most common type of AC motors in the industry due to their low price. IMs do not require very expensive materials to manufacture and they have a fairly simple construction.

Construction of PMSM is similar to that of an induction motor. In the most basic form, the squirrel cage rotor is replaced by a permanent magnet rotor (rare-earth magnets are either embedded in the rotor core or mounted on its surface). The stator creates a rotating magnetic field in the air gap which attracts the magnets. A PMS motor’s rotor rotates at synchronous speed with no slip. In a PMSM the permanent-magnet flux linkage is fixed and therefore the internal back EMF increases as the rotational speed increases. Therefore, the converter must be capable of controlling the field weakening of the PMSM in a clever way (Danfoss, 2019) The losses of PMSMs can be as much as 40% less than in IMs (Pyrhönen, et al., 2016, p. 296). This means that a PMSM, while significantly more expensive, may result in bigger savings over time, more powerful actuation and prolonged battery life.

Some manufacturers use the term SRPM (synchronous reluctance assisted permanent magnet motor) to describe a salient-pole PMS motor with permanent magnets inset in a special configuration to increase reluctance torque resulting in increased efficiency and power factor. (Pyrhönen, et al., 2016, p. 300)

The reason why PMS machines are so expensive is rare-earth magnets' relatively high cost. SynRMs (synchronous reluctance machines) are similar to PMS machines but they have a salient-pole rotor construction and do not require permanent magnets. Instead of magnets, SynRM's rotor tries to align to an angle that has the least amount of magnetic energy and the highest inductance. SynRM's main drawback compared to PMSM is lower power factor. Another major difference to induction and PMS machines is the fact that SynRM's torque producing method is reluctance. (Zekic, 2016) On the other hand, SynRM can be equipped with permanent magnets, making it a PMa SynRM (permanent magnet assisted SynRM). The difference between PMa SynRM and SRPM is the fact that the former is dominated by reluctance torque and the latter is dominated by permanent magnet torque. (Pyrhönen, et al., 2016, pp. 37, 451)

When selecting a motor for this type of application, it is naturally important to pick one with a specific power to lower the total mass of the vehicle. Electrical machines can often be categorized into mobile and industrial machines. There is no clear distinction between the two, in fact industrial motors are sometimes utilized in mobile applications, but mobile motors have usually at most a few hundred kilograms mass while industrial motors of the same kilowatt rating may have a mass as much as thousands of kilograms as there is much more space in an industrial setting (such as a factory) and in practice no mass limit. Industrial motors are, however, significantly more inexpensive and more customizable as they are produced in higher quantities. The vast majority of industrial motors are induction machines.

In applications where motor loads and speeds are highly variable, it is important that the motor can be controlled efficiently and accurately with a frequency converter. Motors designed to be supplied by frequency converters are called *inverter-duty motors*. Most of the time, motors designed for mobile operation are inverter-duty. While standard motors can be supplied by frequency converters, motor insulation breakdown may become an issue. Since frequency converters create steep voltage wave fronts, have high switching frequencies and increased voltage (as a result of neutral shift effect), a strengthened insulation is needed. Insulation between phases needs to be strengthened by inserting *phase paper*. The phase voltage propagation in a winding can cause high turn-to-turn voltage stresses and in some cases the first turn is, therefore, separately insulated.

Above the speed at which the converter has reached its maximum output voltage the motor has to go into field weakening area. The motor must be designed to handle the higher speeds and voltages that occur in the field weakening area (mechanics and insulation need to be protected from extreme conditions). (Yusivar & Wakao , 2011) Field-weakening affects motor torque severely but allows the motor to rotate at higher speeds. Field-weakening's principle in a DOL IM is shown in figure 11.

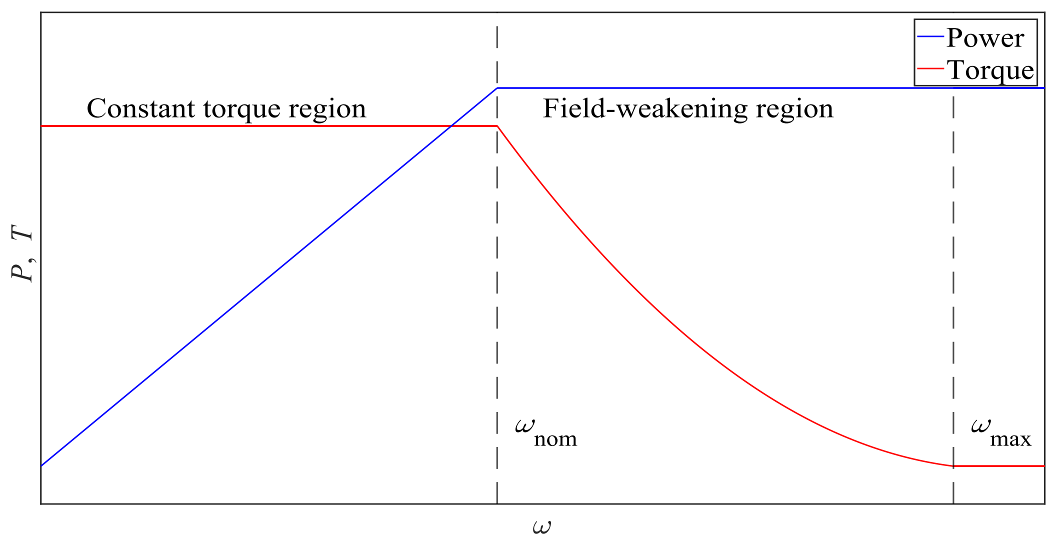


Figure 11 Field-weakening characteristics of a DOL induction motor. Field-weakening region is also known as constant-power region.

Motor needs to be appropriately protected from external objects and liquids. Component frame protection is usually described with IP (ingress protection) codes, that are specified in IEC 60034-5 standard. For underground environments, especially underground mines, the components need to be completely dust proof. This means that the component frames must be rated so that the first IP rating digit is 6, which is strongest protection from physical objects and particles. The second digit represents protection against liquids where 0 is no protection against liquids and 8 is protection from water sink, or in other words, airtight. German standard DIN40050 additionally has IP69K code which means protection from high temperature and pressured water. (Omron) Due to condensed water in mines this loader is specified to have electronics enclosed in IP67 frames or higher, but IP69K is recommended due to regular intense cleaning.

High efficiency of motors leads to cost savings over time. PMS motors' and induction motors' efficiencies in power range of 0.12 to 1000 kW are roughly categorized into four classes as per IEC 60034-30-1:2014 standard where IE1 is "standard efficiency" and IE4 is "super premium efficiency". The classification depends on pole pair number and rated power but for reference a 1 pole pair 90 kW machine rated IE1 must have nominal efficiency at least 93% and 95.8% if IE4. (ABB, 2018) All motors with output power between 75 and 200 kW sold in the EU must reach efficiency class of at least IE3 according to EU regulation 2019/1781 (that entered into application in 1 July 2021). However, these classes are mainly concerned by DOL started motors and not necessarily frequency-controlled motors, that only have 2 classes of efficiency: IE1 and IE2. AC motors sold for frequency-controlled drives are required to reach IE2 according to the same regulation. (European Union, 2021)

Application's duty cycle and thermal loadability are key factors in motor selection. Figure 12 shows measurement data of two subsequent mining loader work cycles where the values represent pump torque and boom's joystick control signal.

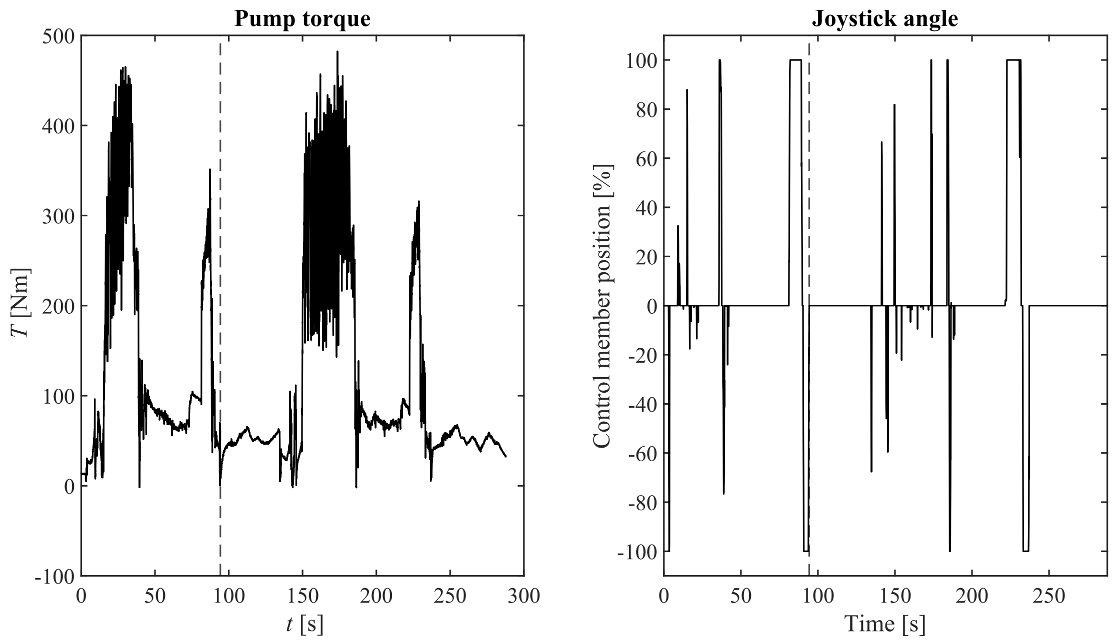


Figure 12 Measurement data of pump torque and boom's control signal in two back to back loading cycles with tramming in between them. Measurement data is recorded from a Sandvik diesel loader of similar size class. A dotted line at 94 seconds represents the end of the first work cycle.

This duty type matches the description of IEC 60034-1 S10, "duty with discrete constant loads". A motor with this duty cycle is loaded for short periods of time, far shorter than the motor's thermal time constant. This type of motors may be overloaded intermittently if the losses during a cycle are not greater than the rated losses.

To protect the motor, it needs to be sized accordingly relative to loading. When a motor is overloaded, its power dissipation gets significantly higher. Installing a bigger motor means that its cooling can tolerate heavier loads without overheating but with appropriate dimensioning, the cost of components can be minimized. As motor pricing is usually directly related to their nominal torque, a motor with the lowest torque should be chosen. To dimension motor power regarding to its thermal capacity, its currents must be observed during a work cycle, in other words, effective load current $I_{ef}$ must be lower than motor's nominal current $I_N$.

$$I_{\mathrm{N}} \geq I_{\mathrm{ef}} = \sqrt{\frac{1}{t_{\mathrm{cef}}} \int_{0}^{t_0} I^2(t)\mathrm{d}t} \tag{9}$$

where $I(t)$ is the motor current, $t_o$ is the operating period and $t_{cef}$ is the effective cooling period (Pyrhönen, et al., 2016, p. 393).

Effective cooling period is dependent on duty cycle ratio and motor cooling power at rest $P_C$. Determining the motor’s cooling power at rest is complicated but it can be approximated to 20% of its nominal cooling power. Effective cooling period $t_{cef}$ can be calculated as follows

$$t_{\mathrm{cef}} = \frac{t_{\mathrm{on}}}{t} + P_{\mathrm{c}} \frac{t_{\mathrm{off}}}{t} \tag{10}$$

where $t_{on}$ is time energized, $t_{off}$ is time de-energized and $P_c$ is the motor’s relative cooling power at rest.

In order to calculate thermal loadability of the motor using equation 10, motor current’s relationship to the shaft torque must be known. As an example, a permanent-magnet motor whose nameplate values include $T_N$ = 200 Nm, $I_N$ = 122 A and $T_{max}$ = 500 Nm was chosen for the following calculation. Because in case of a PM electrical machine’s torque can be roughly assumed directly proportional to the supply current (assuming field-weakening region is not reached), $I_{max}$ is then 305 A corresponding to 500 Nm load. In this case, supply current is therefore approximately $0.61 \times T(t)$.

Since the exact data points of pump torque were available, this integral was calculated using root mean square method with computational software

$$I_{\mathrm{ef}} = \sqrt{\frac{1}{t_{\mathrm{cef}}} \sum_{i=1}^{t_{\mathrm{o}}} I_i^2} \tag{11}$$

Because this equation deals with currents, it is appropriate to look at the torque plot instead of the joystick plot. Torques in figure 13 represent the hydraulic pump’s torque, and because the pump is directly powered by the AC motor, these values are the shaft torques of the motor as well. Effective cooling period is 0.99, as the motor does not become de-energized during this duty often. This effectively means that liquid cooling is working at its full power at all times. The root mean square calculation equals to 99.2 A, which is far less than the nominal 122 A current of the motor in question, and it can therefore be regarded as a suitable machine for this type of duty.

It is worth noting that in electric motors generally, a 10 °C rise in temperature halves the lifetime of insulation. This means that overloading the motor above its nominal point has a serious effect on its life span.  However since the overloading periods in this duty are relatively short, the insulation damage is very minimal, if not negligible. (Pyrhönen, et al., 2016, p. 383)

Motor type and make do not inherently limit the choice of motor converters, but it may be beneficial to choose the motor and converter from the same manufacturer. This is mainly because converter manufacturers make it easy to install the combination without additional configuration of products. Also the technical support is usually better if both the converter and motor come from the same manufacturer. This instead does limit the number of choices because not all motor manufacturers make motor converters and not all motor converter manufacturers make motors. Entire drive systems (motor and motor converter) are produced by, for example, ABB, Dana, Danfoss and Inmotion, although ABB is mostly known for industrial drives.

Motor voltage is another key selection criteria. This loader has battery packs rated at 614 volts. Minimum voltage of the battery packs is 480 VDC resulting in theoretical 339 VAC. Once the battery reaches the minimum voltage, it is then deactivated until it is charged again. This means that hydraulics must work at full power up until this point. By taking into account drive efficiency, the required motor voltage is established. Drive efficiency is frequency converter's efficiency multiplied by motor's efficiency and possibly speed reductor's (gearbox) efficiency.

The frequency converter is a source of significant loss in the drive system. Since the switching frequency caused current ripple is at relatively high frequency in IGBT inverters, skin effect in stator windings is increased. Skin effect can however be reduced notably by using thinner wire strands in windings. High-frequency current ripple also causes transients in air-gap flux of the motor which causes increased iron losses. These losses are reduced in an inverter-duty induction motor by changing the shape of rotor slot openings to reduce leakage flux and eddy currents. Due to these factors, the induction motor efficiency is typically reduced by about 1 percent per unit and the frequency converter's efficiency at the rated supply frequency is approximately 96...97%.  (Pyrhönen, et al., 2016, pp. 396-398) Permanent magnet motors suffer similarly of the switching frequency caused losses. However, rotor losses in PMSMs usually remain small. It is, however important to take care of the PM material cooling as some high-frequency losses take place also in them.

Danfoss EM-PMI machines are 500-volt PMS motors that come in the range from 2200 to 8800 RPM. If we assume that the converter is capable of 90% of the corresponding theoretical maximum voltage a 500 V motor needs at least 500×√2/0.9 V = 786 V battery DC voltage. The hydraulic pump's (Danfoss Series 45) nominal speed is 2880 RPM and the 2200 RPM motor variant is not strong enough because it should be used in the field-weakening area. Because the battery voltage is lower than what is needed to produce full motor voltage, the motor's nominal speed drops in relation to the ratio of the voltages

$$n_{\mathrm{m}} = n_{\mathrm{m,nom}} \kappa_{\mathrm{d}} \frac{U_{\mathrm{b}}}{U_{\mathrm{m}}\sqrt{2}} \tag{12}$$

where $n_{\mathrm{m,nom}}$ is the nominal speed of the motor (as specified in technical sheet), $U_{\mathrm{b}}$ is the battery DC voltage, $U_{\mathrm{m}}$ is the motor's nominal AC voltage and $\kappa_{\mathrm{d}}$ is converter maximum modulation ratio.

The peak value of 500 VAC is comparable to 707 V and therefore, in principle about 710 VDC is needed to produce the AC voltage. However, converter modulation rarely goes to overmodulation range and therefore the maximum modulation ratio $\kappa_{\mathrm{d}}$ is typically about 0.9. Looking at equation 9, it can be concluded that the 2200 RPM variant is only driven at about 1050 RPM at minimum battery voltage and 1350 RPM at nominal voltage, which leads to very low pump efficiency. If a 4400 RPM motor was instead chosen, the speed would be about 2100 RPM at minimum voltage and 2700 RPM at nominal battery voltage. Due to LiFePO4 batteries' discharge profiles (more about this in chapter 4), the motor is powered at close to nominal voltages most of the time and the minimum voltages are only applied at the very end of battery's lifecycle, and it is apparent that this motor's 4400 RPM variant should be a viable machine for this application. These speeds are somewhat less than pump's nominal speed and the motor will need to go to field weakening slightly.

EM-PMI motors come in various sizes based on their torque producing capability. As calculated earlier, the hydraulic pump requires the motor to drive loads at 550 Nm. The smallest of these motors, the EM-PMI240-T180-4400 produces 500 Nm of peak torque. While this does not reach the initial requirement, it still comes close and can be considered for this application. However, depending on how important it is to reach the requirement, a bigger motor might be the correct solution. The second smallest motor of this product line, EM-PMI300-T310 produces peak torque of 700 Nm. This motor however does not have a speed configuration that matches the load. Its highest speed variant is 3200 RPM. This means that with this voltage source, the motor’s nominal speed is actually 1920 RPM making this motor a bad choice for pumps whose nominal speeds are 2880 RPM. The rest of the motors in this product line are far too powerful (nominal torque production is in thousands of newton-metres) for this application and the best solution is likely to pick the EM-PMI240-T180 4400 RPM variant.

It is however imperative that if the load torque goes over 500 Nm, the torque limiter must be engaged so that the motor does not stall. If position control is required, this motor can be ordered with resolver installed. Female spline matching Series 45 axial piston pump’s input shaft is available. The motors in this product line are rated IP67. (Danfoss, 2021)

Another possible motor for this application is Parker GVM (global vehicle motor) 6 pole pair PMSM. Depending on the winding configuration, the nominal voltage is 24 to 800 VDC. The GVM210-400-DPW has nominal voltage of 480 VDC which is the battery pack’s minimum voltage and has rated torque of 336 Nm and maximum torque of 710 Nm. This motor’s nominal speed is 3900 RPM. Its rated current is 281 $A_{RMS}$ and maximum current is 695 $A_{RMS}$. The GVMs are IP67 by default but IP69K are available upon request. (Parker, 2021) This motor may only be installed vertically which must be taken into account in design. The GVM is better for the loader out of the two when looking at the specifications but price difference and converter compatibility must be checked. Cost comparisons will not be done in this thesis because the prices are only available on request.

Temperature class (or insulation class) of motors refers to the change in winding temperature from ambient temperature when the full load is applied. Previously discussed motor comes in insulation classes F and H corresponding to 155 and 180 °C respectively. If this temperature is exceeded, insulation failure becomes an issue. Because the thermal loadability for the smaller Danfoss motor is validated earlier, temperature limits should not be reached with either of the two motors.

## 2.5 Frequency converter

Motor speed is controlled by a frequency converter. The converter control may be closed or open-loop (with or without motor position/speed feedback) type. In this application, controlling the pump's oil flow, it is important to increase energy efficiency and to better control hydraulic processes. Throttling a positive displacement hydraulic pump is not viable because it only increases the pressure in the hydraulic circuit without reducing the flow. Using a pressure-regulating valve can accomplish some degree of control in flow, however it is inefficient as using it as the main method of control leads to significant losses. Using a pressure-regulating valve and varying the displacement of the hydraulic pump is traditional when it comes to hydraulic control in systems that are powered by internal combustion engines. The most energy efficient way of hydraulic control when electrical machines power the system is to carefully control the shaft speed of the pump. Because the pump shaft is coupled with the AC motor's output shaft, the motor needs to be controlled electronically to manipulate the pump output. (Hydraulic Institute, 2004)

The synchronous speed of the motor is determined by

$$n_s = \frac{60f}{p_{\text{pair}}} \tag{13}$$

where $f$ is network supply frequency and $p_{\text{pair}}$ is the pole-pair number of the stator.

This means that varying the supply current frequency will control the motor speed directly. The most common way to achieve high controllability of motor speed is using frequency converters. Variable frequency drive (VFD) is a term that describes systems including a frequency converter and a motor. The converter can change the frequency of the power that is supplied into the motor. It is however important to notice that running a pump with speeds outside of its nominal speed can lead to decreased efficiency. Industrial frequency converters take in AC power (1 or 3 phase) and rectify it so it becomes DC power. This DC power is routed from the DC link of the converter to the 3-phase inverter circuit which is modulated in a way that the resulting frequency is whatever it was set to. But since this application is energized by batteries that are DC voltage sources by nature, the battery terminals are connected to the DC link of the converter. The working principle of variable frequency drive is shown in figure 13.

Depending on the converter, other parameters can also be controlled in place of speed. The most common alternative control parameter is output torque. Control's dynamic adjustment is achieved with PI controllers within the converter. The VFD has other benefits, including overload detection (when the machine runs above the nominal torque) and it can provide live information about the drive to on-board computer systems via controller area network protocols, such as CANopen or SAE J1939. This information may include system status, temperatures, system faults, warnings, resolver offset, motor speed, motor torque, currents, voltages and other status information.

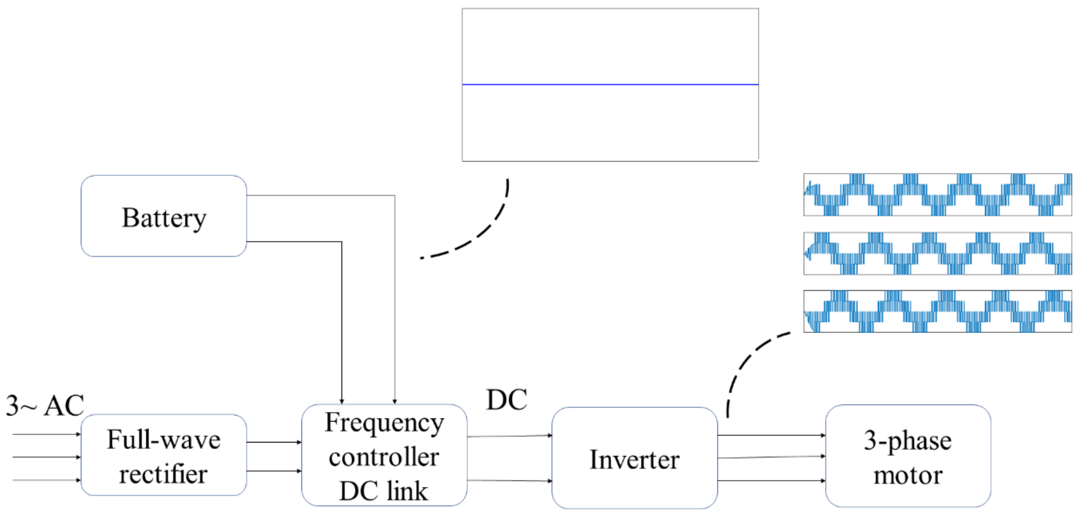


Figure 13 Variable frequency drive that can be powered by either a DC voltage source (battery) or a three-phase voltage source (grid).

Modern frequency converter's DC to AC conversion is almost exclusively operated by IGBTs (insulated gate bi-polar transistors) due to their relatively low turn-on and turn-off times like in the case of MOSFET (metal oxide semiconductor field-effect transistor), enabling higher carrier frequencies and making inverters more efficient. However, unlike MOSFET, IGBTs' gates are voltage controlled which results in simpler low voltage controlled circuit. (Saunders, et al., 1996)

High-end frequency converters are built-in with different methods of control for compatibility with different types of motors. Control methods can be categorized into scalar control and vector control. Scalar control operates by changing the voltage supplied to motor to change its speed as the synchronous speed is directly dependent on the voltage. *U*/*f* ratio of the motor describes how much a change in voltage corresponds to the speed. For example, if the motor's nominal nameplate voltage is 480 V and nominal frequency is 50 Hz, the *U*/*f* ratio is 11.6 V/Hz. Therefore a 11.6 V increase in the supply results in 1 Hz increase in synchronous speed of the motor, and this is how scalar control in most cases operates. Scalar control is sometimes accompanied by PI controller for dynamic operation but scalar control can only be used as a speed controller whereas vector control can control torque as well as speed. Vector control, also known as space vector control, is a more sophisticated control method and the mathematics behind it are not described in detail here. It is better suited for more dynamic duties as its delay can be as short as 20 ms whereas scalar control can take 200 to 500 ms for state changes. (Pyrhönen, et al., 2016, p. 116) PMSMs that produce some reluctance torque (such as an SRPM) are often controlled using a particular vector control method, MTPA (maximum torque per ampere) algorithm. This control type utilizes both PM and reluctance torque to maximize motor's shaft torque. (Pyrhönen, et al., 2016, pp. 318-324)

Motor's speed can be increased as long as back EMF of the motor does not exceed converter's maximum voltage. When the back EMF gets to that point, the converter must switch to *field weakening* mode. Field weakening reduces stator flux linkage, resulting in reduced torque production, but allows the motor to be driven at higher speeds. Field-weakening usually begins when the supply frequency to the motor is 90% of its nominal frequency. This means that field-weakening is applied when a 480 V motor is supplied 432 V. This is beneficial because when torque production needs to be increased quickly, a 10% *voltage reserve* can be utilized. (Pyrhönen, et al., 2016, p. 64) This, naturally, means that the converter must be capable of producing a 480 V output.

In case of industrial induction motor drives, all motor parameters can be manually programmed in the frequency converter which handles the tuning and safety precautions of the motor. The VFD also compensates for different phenomena such as load-independent start (optimum starting torque), load-dependent starting torque (for highly variable loads), load compensation (voltage boost on low frequencies) and slip compensation (avoiding too high slip that would otherwise stall the motor, applicable to IMs). In the case of motors whose parameters are highly customizable and individual (nameplate values do not always refer to the particular motor, but a range of motors in the same product line), it becomes cumbersome to program a variety of motor attributes into the drive so many frequency converter manufacturers offer automatic identification functions (such as Danfoss Automatic Motor Adaption) that can automatically measure and program the motor data. (Danfoss, 2019)

Automatic motor identification in synchronous motors works by defining motor type, number of pole pairs and some nameplate values in the frequency converter. The converter is then connected appropriately to the motor, after which the converter begins to measure some of the internal motor parameters such as the DC resistance, d-axis and q-axis subtransient inductances and no-load direct synchronous inductance at various voltage steps. Other important parameters, such as synchronous inductance and magnetizing inductance, are then computed mathematically by the converter. Identification programs calculate motor parameters using simplified mathematics that results in crude values in a set of discrete steps. This is however much less complicated and laborious compared to FEM (finite element method) analysis and the motor can possibly be commissioned faster. (Pyrhönen, et al., 2016, pp. 210-217)

For product safety purposes and as per product requirements, the frequency converter must be equipped with STO (safety torque off) function that disables signals going into semiconductors in the inverter circuit of the converter, so that the converter is prevented from energizing the motor. STO must be engaged during maintenance work and cleaning of non-electrical parts so that there is no way for the motor to be energized. STO is intended for short-time maintenance work where switching off the power supply is not required. (ABB, 2014) Standards relating to STO functionality include SFS-EN 12100 (Finland), IEC 60947-5-5 and ISO 13850. These standards state that STO should be installed on all machinery, excluding hand tools and machinery where this type of safety function would not reduce danger (for example, if STO does not moving parts faster than standard shutdown). The STO manual switch must be easily accessible. (Sesko, ei pvm)

Usually, manufacturers of mobile motors recommend certain frequency converters to be used with their motors. Danfoss and Parker, for example, have converters that are specifically designed to drive their motors. This makes inverter dimensioning easy, but there should be no reason why a specific inverter-duty motor could not be used with an arbitrary converter that is not specifically designed for them given their parameters are compatible. However, to simplify dimensioning and commissioning, vehicle manufacturers try to buy their converters and motors from the same company, which may sometimes lead to reduced cost of the drive.

The critical parameters in frequency converter selection are rated current and voltage, both of which must match the motor's nameplate values. The converter's amperage range should include motors full load amperage to allow overloading for peak loads. Selecting a frequency converter based only on the power rating is not sufficient. The control type plays a role as to which type of motor can be driven with a certain converter but many converters have various control methods programmed in such as $U/f$ scalar control and vector control. The enclosure protection class should also match the motor's protection class.

Danfoss EC-C1200-450 liquid cooled heavy-duty converter with DC link voltage range from 0 to 850 V can output up to 560 VAC. From this value we see that $\kappa_{\mathrm{d}} = 0.93$. The biggest variant of this frequency converter is the 350 A variant which is recommended for the EM-PMI240-T180 motor if peak torque is required. The maximum full load amperage of the motor happens to be said 350 A. This converter's schematic is shown in figure 14.

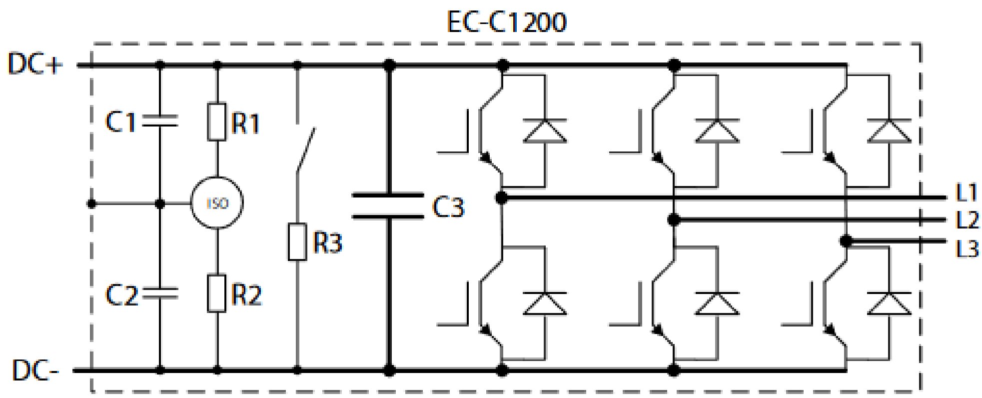


Figure 14 Danfoss EC-C1200 frequency converter. DC+ and DC- are battery terminal connections and L1-L3 are the AC signal ports. (Danfoss)

In DC applications power can be transmitted both ways, from battery to 3-phase terminals or the other way. This means that when the AC machine is working as a generator (machine is turned by external physical events and not because it is energized by the converter) the inverter circuit should supply power to the DC link terminals that now charge the battery.

On the other hand, Parker GVI (global vehicle inverter) converters are designed to be compatible with the GVM motors. This converter has peak current of 500 $A_{RMS}$. (Parker, 2021) This converter however does not become available early enough to make it into mass production of this loader.

## 2.6 Component cooling

This section is concerned with cooling of electrical components. While the hydraulics are suspect to overheating as well, the hydraulic oil itself works as a coolant. Hydraulic oil needs is cooled in the reservoir.

Air cooling is common for constant speed operation motors due to its simplicity. The rotor is simply constructed in a way that it circulates air when it is rotating. This is usually achieved with cooling fins or blades in the rotor, providing air flow in magnitude proportional to its speed. Rotor fins produce losses due to increased air resistance.

For applications where motor speed is highly dynamic such as in a wheel loader, air cooling is not sufficient for the electrical drive components, which refers to motor and frequency converter here. The battery packs are not cooled during mining operation, only when they are being charged. Since the losses of PMSM, IM and frequency converter account for multiple percentages of the total input power, heat dissipation is in the magnitude of kilowatts. Coil temperature of motors needs to be kept as low as possible because higher temperatures mean higher resistance in coils according to

$$R_1 = R_{1,\mathrm{ref}}(1 + \alpha\,\Theta) \tag{14}$$

where $R_1$ is the resistance of the winding [Ω], $R_{1,\mathrm{ref}}$ is the resistance of the winding in reference temperature (25 °C), α is resistance temperature coefficient of the windings (0.0043) and $\Theta$ is the temperature rise [°C].

Coil resistance is the source of copper losses in motors, biggest losses in most types of electric motors

$$P_{\mathrm{Cu}} = 3I^2R \tag{15}$$

where $I_1$ is current per phase flowing through a stator coil and $R_1$ is the coil resistance of each phase.

In induction motors, rotor losses also increase as the temperature rises due to greater rotor bar resistance. In electric machines with permanent magnets, the polarization of the magnets is reduced in high temperatures causing the motor to lose power. In addition to reduced efficiency, high temperatures cause thermal stress to components resulting in reduced lifetime and insulation damage in the long run. Usually, electronic components in the power range of hundreds of kilowatts are liquid cooled to combat this. Motor cooling is standardized in IEC 34-6 in which cooling categories are codified into three parameters as shown in tables 2–4. The code is given in form ICxyZ according to the tables.

Table 2 First digit in IEC 34-6 cooling standard coding.

| Digit | Description |
|---|---|
| 0 | Free circulation |
| 1 | Inlet duct ventilated (one inlet duct) |
| 2 | Outlet duct ventilated (on outlet duct) |
| 3 | Inlet and outlet duct ventilated |
| 4 | Frame surface cooled |
| 5 | Integral heat exchanger |
| 6 | Machine mounted heat exchanger |
| 7 | Integral mounted heat exchanger |
| 8 | Machine mounted heat exchanger |
| 9 | Machine with separate mounted heat exchanger |

Table 3 Second digit in IEC 34-6 cooling standard coding.

| Digit | Description |
|---|---|
| 0 | Free convection |
| 1 | Self-circulating |
| 2 | Integral component mounted on separate shaft |
| 3 | Dependent component mounted on the machine |
| 4 | Not defined |
| 5 | Integral independent component |
| 6 | Independent component mounted on the machine |
| 7 | Independent and separate device or cooling system |
| 8 | Relative displacement |
| 9 | Any other device |

Table 4 Coolant in IEC 34-6 cooling standard coding.

| Letter | Fluid |
|---|---|
| A | Air |
| F | Freon |
| H | Hydrogen |
| N | Nitrogen |
| C | Carbon dioxide |
| W | Water |
| U | Oil |
| S | Any other fluid |
| Y | Fluid has not yet been selected |

For example, IC 71W (valid for Danfoss SRP machines) cooling method means water cooled machine in which water self-circulates via an integrally mounted heat exchanger. Sometimes motors are assigned cooling method codes consisting of multiple different cooling types, for example IC 8 A1 U9, where the first part (A1) is the cooling method of the primary circuit and the second part (U9) is that of the secondary cooling circuit. (Rajapakshe, 2014)

Water is the most common coolant in electrical equipment of this size range. Water can however refer to water-based coolants in general, usually water ethylene glycol mixture ("antifreeze") to prevent corrosion and reduce the freezing point.

## 2.7 Torque limiter

Torque limiting enables the operator to limit hydraulic pump's torque electronically to allow maximum torque at any motor speed, increasing the efficiency of the hydraulics. Torque limiter control consists of PRV (proportional relief valve) that is integrated into a PC/LS (pressure compensated, load sensing) control. This circuit, in addition to swashplate angle sensor and microcontroller with motor's torque vs. speed curve programmed in, forms the ETL (electronic torque limiting) logic circuit. This means that even if the hydraulics are not directly controlled by varying pump displacement, a variable displacement pump with swashplate position transducer is required for ETL control. (Sandvik, 2021)

Torque limiter is necessary for hydraulic applications where the load torque may exceed the motor's torque generating capability. When the load gets high enough (the load torque that the motor has to overcome), the motor will stall as it can no longer produce required torque. In some applications this is resolved by installing bigger motors and inverters but it is an expensive solution and causes the machine getting bigger than necessary. Instead, it is often wise to limit the load torque acting on the motor in the hydraulic pump. When the system pressure rises above a certain threshold, the swashplate angle is reduced to limit pressure. As a result, the torque is reduced but so is flow, meaning the actuator gets slower but the motor will not stop rotating. As mentioned in equation 6, hydraulic torque is directly dependent on pressure. Figure 15 shows how the torque limiter, configured for different cut-off points, works.

Torque may also be limited mechanically. Mechanical torque limiter works by decoupling the load from the hydraulics when the pressure reaches a certain value. This torque value can be adjusted with the adjustment screw that increases or decreases the deadhead cut-off pressure. (Bosch-Rexroth, 2020) Because the pumps that are to be installed in this loader are variable displacement, torque limiting is implemented electronically.

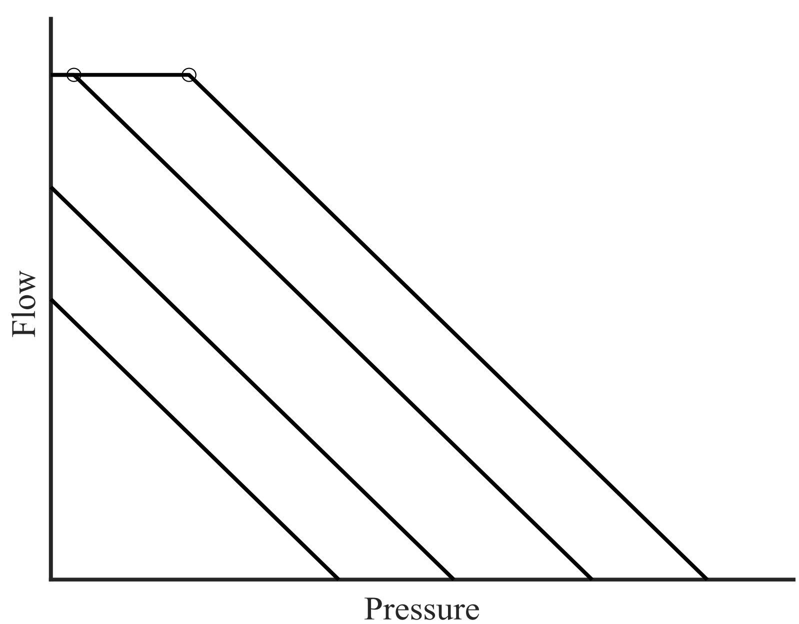


Figure 15 Pressure cut-off curves that characterize torque limiter operation. Circled spots are torque limiter cut-off points (set electronically or mechanically).

# 3 MOTOR CABLES AND EMC

The frequency converter's power electronics usually work more reliably when the cables are short. Malfunctions due to cable length are caused by internal capacitance of cabling that causes power transients (sudden irregularities in AC waveform). In addition to malfunctions in the converter, the transients can cause abrupt thermal stress to motor insulations and bearing stress. (Danfoss, 2019, p. 200)

## 3.1 Electromagnetic compatibility

In addition to conducted electrical disturbance, cabling also causes radiated electromagnetic emission. Radiated emission can be suppressed by shielded cables but it is important that the shielding has no breaks throughout the cable's length. The cabling should be made so that the power cables are separated by adequate distance from control cables. The control cables should also be of twisted pair type to cancel electromagnetic radiation among the cables inside the shielding insulator. The better the shielding material is, the lower the transfer impedance is.

EMC can be guaranteed by using shielded motor cables or by ensuring that EMI of cabling stays within a low enough range. The latter may be accomplished by using common-mode filters with unshielded cables, most likely reducing the cost of cabling. Unshielded cables may be as much as three times more inexpensive than shielded cables. However, EMC behaviour of cabling can change on any modification of the electrical configuration and EMI (electromagnetic interference) needs to be eliminated again using another EMI shielding filter. EU EMC directive states that the transfer impedance of cabling must be less than 100 mΩ/m. (ABB, 2013)

More specifically, the transients are caused by common mode voltage in frequency converters because of asymmetrical voltage pulses of PWM to the three legs (characterized by the 3-phase nature of the frequency converter). The components that cause common mode voltage in the inverter are created by the diode rectifier and the PWM (one component in switching frequency and its harmonics and broadband frequency component because of sharp PWM pulses). (Landkildehus, et al., 2006)

Electrical converters sold in the EU must have a certain immunity to EMI but it is the system designer's responsibility to design the electrical circuit so that these EMI ratings are not exceeded in order to protect the electronics and motor bearings.

## 3.2 Protection of motor insulations and bearings

Bearings and insulation are the weakest links in electrical machines and precautions need to be taken to protect them. The converter output to the motor is not pure sinusoidal AC voltage, instead it is high frequency pulsating voltage that produces a reasonable approximation of a sine wave when filtered by the transient inductance of the machine. Because of the pulsating waveform, fast voltage rises in the output signal of the frequency converter can cause motor's insulation breakdown if the system is not properly designed. In addition, unfiltered harmonic distortion heats the motor windings and magnetic circuit resulting in lower efficiency of the motor and higher thermal stress than in DOL operation.

Insulation stress is caused by thermal, contamination, mechanical, vibration, dielectric, carrier frequency and winding phenomena. High thermal stress is caused when insulator temperature frequently exceeds its rated temperature. Contamination is caused when motor is operating in dirty environments, where it may be subject to contaminants such as oil, salt or dirt. Contaminants create conductive paths across the windings, causing short circuits. Mechanical stress occurs in DOL applications when motor is started and powerful magnetic fields propagate the motor pulling stator coils and high inrush currents rapidly heat stator conductors, expanding them. As a result, the coils tear the adhesive varnish that keep them in the stator core. This strain damages the coils' insulators and may, finally, cause shorting to ground, which in turn creates more paths for contaminants to enter stator core resulting in even more insulation damage. Mechanical damage, however, is reduced with modern VFD technology as the converter supplies the motor with a limited current compare to DOL drive. Vibration stress happens due to resonance. Motors, like any physical objects, have particular resonant frequencies, but traction motors are normally designed so that this frequency is well above line frequency (resonant frequency is altered by adding mass, changing supports and increasing mounting base lengths). In VFD applications, the likelihood of hitting the motor's resonant frequency is increased. Avoiding the resonant frequency can be achieved by programming a frequency offset in the converter that skips a certain frequency band that includes the resonant frequency. Forementioned phenomena affect the dielectric strength of the motor. This will change the properties of motor's rated voltage and if enough damage has been caused by motor stress, the motor will no longer withstand its nameplate voltage and will result in major failure. (ABB, 1997)

Bearing damage is caused by a phenomenon called EDM (electrical discharge machining). While the greasing between the bearing balls is supposed to act as insulator, breakdowns can be caused by high voltages resulting in sparks between balls and the running track, damaging the bearing itself. EDM can be avoided to some extent by ensuring that grease is pure and plentiful, avoiding excessive axial and radial loading of motor, proper alignment of the load and protecting the bearing from excessive vibration. EDM can also be reduced electronically using HF-CM (high-frequency common mode) filters. (Danfoss, 2010)

## 3.3 Motor cable length

Motor lead length is related to two adverse phenomena to the drive. These are reflected wave (also known as standing wave) phenomenon and voltage overshoot. The likelihood of both decrease when conductors are shorter because motor cable length is directly proportional to conductor impedance (as a result of increased inductance and capacitance).

When the cable impedance mismatches that of the motor's characteristics, the voltage will experience ringing in the point of contact (between cables and motor terminals). This is called voltage overshoot or voltage surge. The bigger the difference between the impedances, the higher the ringing amplitude, and higher switching frequency leads to more times this overshoot occurs in the motor.

Impedance of the conductors stores energy during rise times of voltage pulses. The higher the inductance in conductors, the higher the energy stored in them, and the longer it takes to charge the internal capacitance of the motor. As the amount of stored energy is higher, the higher are the voltage overshoots once the motor is started to its correct potential. Voltage overshoot can be as much as twice the DC link voltage of the frequency converter and its magnitude is dependent on switch-on times of transistors and cable types. (Yaskawa Electric America Inc., 2016)

Motor's surge impedance decreases when motor size is increased. According to IEC (International Electrotechnical Commission), the d$u$/d$t$ ratio's rise time is defined as the period between 10% and 90% of the voltage peak value ($u_{\mathrm{peak}}$), whereas NEMA (National Electrical Manufacturers Association) define it as the period between 10% and 90% between the final DC link voltage ($u_{\mathrm{DC}}$). d$u$/d$t$ according to IEC is

$$du/dt = \frac{0.8u_{\mathrm{peak}}}{t_{\mathrm{r}}} \tag{16}$$

where $u_{\mathrm{peak}}$ is the maximum or peak voltage and $t_{\mathrm{r}}$ is rise time between 10% and 90% of peak voltage (figure 16).

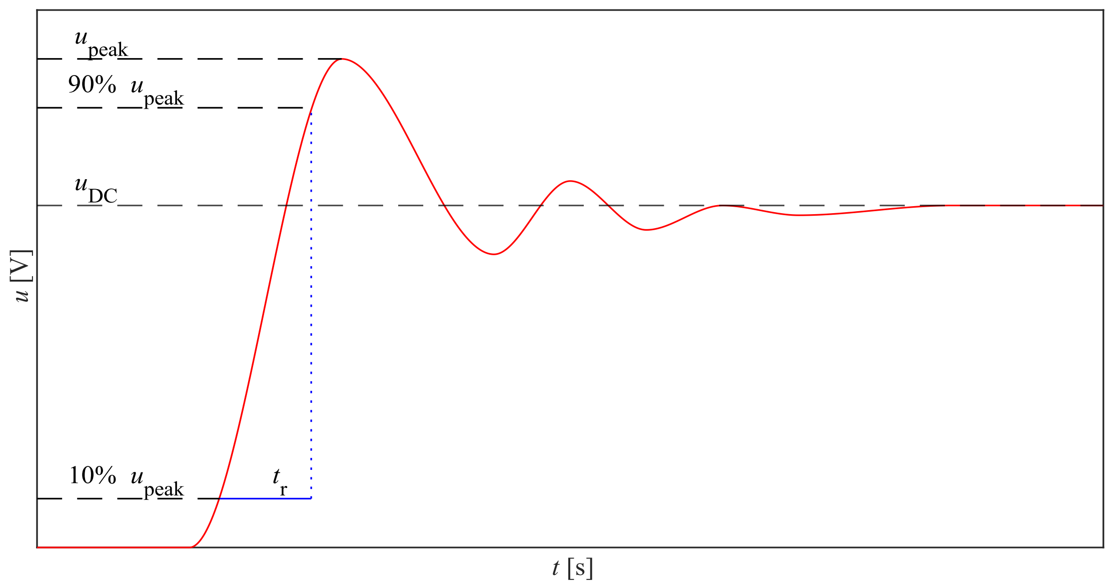


Figure 16 d$u$/d$t$ rise time ($t_{\mathrm{r}}$) according to IEC.

To understand how to avoid reflected waves, critical length of conductors must be calculated. The velocity of the progressive wave can be calculated with

$$v = \frac{C}{\sqrt{\mu_{\mathrm{r}}\varepsilon_{\mathrm{r}}}} = \frac{1}{\sqrt{lc}} \tag{17}$$

where $C$ is the speed of light ($0.3 \cdot 10^9$ m/s), $\mu_r$ is the relative permeability of cable material, $\varepsilon_r$ is the relative permittivity of insulation material, $l$ is inductance per unit length and $c$ is capacitance per unit length.

The critical length of conductor can be calculated with

$$l_{\mathrm{cr}} = \frac{t_{\mathrm{r}} v}{2} \tag{17}$$

where $t_r$ is the rise time of voltage in the conductor.

Progressive wave's velocity in motor leads is usually roughly 150 m/µs and $t_r$ is 100 ns for an IGBT. This means that the critical length for motor cabling is 7.5 meters. (Pyrhönen, et al., 2008, p. 453) Design process should take this critical length into account and attempt not to exceed it as to not allow full reflected waves to take place. On the other hand, reflected waves' effect can be countered with output load reactors should the critical length be exceeded. They are three phase series inductors connected to the load side of the converter and they work by opposing the fast change in current coming out of the converter, reducing d$U$/d$t$ and peak voltage at motor terminals. (Eaton, 2020) Fortunately, motor power cables in this loader are no more than few meters at best, hence the critical length will not be reached.

# 4 BATTERY BALANCING

The two batteries in the battery pack must be balanced to allow for steady power at all times, higher longevity and to avoid early degradation. Battery cells also inherently have imbalances even if they are from the same manufacturer and from the same batch, and therefore balancing the individual batteries within a common battery pack is crucial to keep the voltage as constant as possible.

## 4.1 Characteristics of $LiFePo_4$ batteries

Traditionally, lithium-ion (Li-ion) batteries are used in automotive industries. A subtype of Li-ion battery, $LiFePO_4$ is attractive due to its excellent thermal stability and chemical characteristics resulting in increased safety and their price is relatively low per cell. (Wang, et al., 2010). $LiFePO_4$ batteries are also free of cobalt, which is a scarce and expensive element used in many other battery technologies (Li, et al., 2020).

## 4.2 $LiFePO_4$ health measurement

For some battery chemistries, such as lead acid, measuring the voltage gives a rough, but fairly good estimation on battery health. This measurement for lithium and nickel based batteries is however impractical due to their flat voltage vs. capacity curves (figure 17).

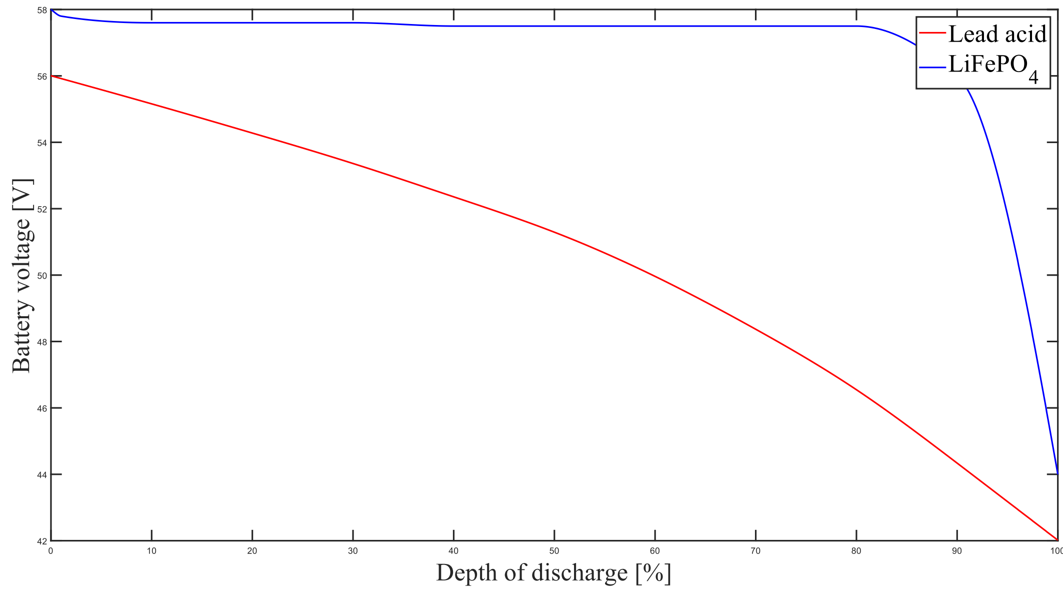


Figure 17 Lead acid and $LiFePO_4$ batteries' voltage vs. depth of discharge curves.

Extremely low voltage fluctuation of $LiFePO_4$ cells during discharge (and charge for that matter) makes it impossible to determine battery charge by looking at the voltage alone. Battery SoC can however be metered by reading other parameters of the battery. SoC measurement circuit must at least monitor the temperature of the battery pack, instantaneous discharge current, remaining state of charge (measured using current integration, or in other words, coulomb counting) and average current (for example over 20 ms) in addition to the voltage. These parameters are used with known models of battery discharge profiles hard-coded into the measurement circuit. Unfortunately, battery aging causes phenomena that makes reliable battery capacity estimation even more complicated. Over time, battery's internal chemistry causes the battery to wear out which reduces its discharge ability over a fixed voltage (change in impedance). There exist algorithms that measure the impedance to update the battery model and give accurate readings even when the battery is aging.

Batteries also self-discharge over time, meaning that the battery loses charge even if it is not connected to any electrical circuit. If battery meter is installed on to the vehicle, self-discharge when battery is not connected to it never gets reported and the reading will be off. Therefore, placing the meter on the individual battery packs is essential for correct SoC measurements. (Fundaro, 2007)

## 4.3 $LiFePo_4$ balancing

The imbalances of battery cells are due to internal impedance, minor fluctuations of cell capacities (impact of both increase as the cells age), impact of the peripheral circuit and thermal difference. (Li, et al., 2013)

There are two types of battery balancing: passive and active battery balancing. Passive method is also called *resistor bleeding balancing* and as the name implies, excess battery charge is dissipated in a resistor, effectively wasting energy. It is a straightforward method of keeping the batteries healthy but it is not an attractive option when energy efficiency and long runtime are of utmost importance. Active battery balancing instead uses capacitors to maintain equilibrium among the battery cells with significantly lower losses, effectively coupling the batteries into a single entity. (Texas Instruments, 2009)

Yet another method of balancing out multiple batteries is to measure the SoC of all batteries within the battery pack and using the one with the highest SoC value. Once the SoC of this battery decreases over a certain threshold compared to other batteries, the battery with the highest SoC will be selected again. In the loader application, this method seems like the most practical routine because the SoCs must be measured anyway and does not therefore result in need to install additional balancing circuits.

Battery faults can be identified with proper battery monitoring and control. The battery faults can be internal or external. Internal faults include overcharge, overdischarge, short circuiting, overheating and thermal runaway. These faults are often indicated by abrupt drop in voltage or SoC, temperature rise and physical deformation. While overcharging only happens when the battery is being charged, all the other phenomena may occur during operation (discharge cycles).

As the battery management systems are becoming increasingly more complex, the battery failures are becoming more complex to identify. More sophisticated algorithms are required to protect the machinery and operators from hazards created by powerful batteries.

BMS safety monitoring methods can be model-based or non-model based. Model-based methods incorporate a model of the specific battery within its algorithms and compares the battery's state to the mathematical model within boundary conditions. Model-based monitoring methods usually consume less computation time but because they use less sensor data, they might be more inaccurate than non-model based methods. (Tran & Fowler, 2020)

# 5 CONCLUSIONS

Several aspects of hydraulic system dimensioning were assessed and concrete workflow was established. Before all else, the pump's requirements are judged by actuators' parameters and actuation periods, resulting in hydraulic fluid flow rates that the pump must be capable of supplying. At this point, it is important to take special functionality into account. For this application, it is important that the pump's torque can be limited. This means that choosing a variable-displacement pump is necessary (preferably with electronic swashplate control). Based on flow rates and pressures, Danfoss Series 45 pump with 100 $cm^3$ maximum displacement was selected.

To power the pump, a high-efficiency motor needs to be selected so that the pump can operate the cylinders within the required actuation periods. Motor types were discussed and looking at different AC motors of this size range, it was evident that most motors suitable for this application are PMSMs, based on studying manufacturers' catalogues and meetings with suppliers. The main parameter to keep track of is the torque producing capability of the motor and the current that is needed to produce the torque. The torque must naturally be enough to turn the pump without stalling. One of the motors that were compared, does not produce enough peak torque to turn the Series 45 pump at full displacement and pressure. However by studying the duty of a similarly sized loader, this amount of torque is never really required. But to be on the safe size, torque limiter can be used in the pump to never let the load go so high that the motor is caused to stall. Another key parameter in motor selection is compatibility with the energy source. Since the speeds and torque requirements that the motor experiences are highly variable as a function of time, it was necessary to check that the motor thermal loadability stays within reason. The data used to calculate this was again from the diesel loader of similar size class, and as a result of this calculation, the somewhat small Danfoss EM-PMI280-T180 motor was suitable for this type of duty.

Once the motor was selected, the next step was to choose a frequency converter to supply the motor. This task is made effortless because most of the time, certain frequency converters are recommended to be used with specific motors. However for the sake of completeness, the parameters needed for the frequency converter were presented if the designer decides to use another frequency converter. Because of the varying loads, control method description is of utmost importance. Some types of control were brought up, and their pros and cons were assessed in order to pick the one that is best for this application.

Cooling of the electric parts of the hydraulic system was briefly discussed in order to clarify what types of cooling are used in specific electronic components. Analyzing the hydraulic oil cooling was not a part of this thesis. The electric motor and the frequency converter selected for this application are liquid-cooled, therefore a liquid-cooler and cooling lines need to be designed to avoid overheating of the electronics.

Some aspects of electromagnetic compatibility were studied to explain how the electronics may fail if the system is not properly designed. It turns out that a modern frequency converter takes care of numerous failure mechanisms, whereas some can be avoided with wise installation, such as proper alignment of the motor and pump, as well as using short shielded cables.

Because the control system's operation is based on battery SoC, its measurement was discussed. The same chapter also brings up different methods of battery balancing, but the most straight-forward method of setting batteries as primary based on the available SoC was chosen.

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