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OPTIMIZING THE HYDRAULIC POWER SYSTEM OF ARTICULATED STEERING

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OPTIMIZING THE HYDRAULIC POWER SYSTEM OF ARTICULATED STEERING

This thesis deals with the energy consumption and features of the articulated steering hydraulic system of a mining loader. The purpose was to study the current hydraulic system and its improvement solutions. The system compared with the current one is a direct drive hydraulics, which is new technology.

Sandvik LH307B mining loader was used as the research platform. The study was made in three steps. In the first step, measurements were made with a load sensing hydraulics system, which is the original system of the machine. In the second step, intelligent control for the hydraulic pump was added to the load sensing hydraulic system, and measurements were made. In the third step, a layout of the direct drive hydraulic components had to be designed to the machine and installed according to plan. As many times with new technology, the system start-up encountered challenges, which had to be solved before starting the tests.

The theory part of the thesis dealt with the properties and requirements of articulated steering hydraulics in mine loading and hauling machines. The analysis examined the efficiency and properties of the hydraulic systems, which affect the choice of the system.

The load sensing system with the intelligent pump control gains significant energy saving without losing its features. With the direct drive hydraulic system there is a possibility to achieve an energy efficient solution. The system is operational, but there are still unresolved issues in the system after this study.

Keywords: Hydraulics, hydraulic systems, hydraulic machines, energy consumption

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Jani Heinonen

OPTIMIZING THE HYDRAULIC POWER SYSTEM OF ARTICULATED STEERING

Lopputyössä tutkitaan kaivoslastauskoneen runko-ohjauksen hydrauliikkajärjestelmän energiankulutusta ja toiminnallisuutta. Tavoitteena on tarkastella koneen nykyistä järjestelmää ja sen paranneltua versiota ja verrata nykyjärjestelmää uuden teknologian hydrauliikkajärjestelmään.

Tutkimusalustana on käytetty Sandvik LH307B maanalaista kaivos lastauskonetta. Tutkimus koostuu kolmesta vaiheesta. Ensimmäisessä vaiheessa on mitattu lähtöarvot koneen alkuperäisestä kuormantuntevasta hydrauliikkajärjestelmästä. Toisessa vaiheessa kuormantuntevaan hydrauliikkajärjestelmään on lisätty älykäs pumpun ohjaus, josta on tehty tarvittavat mittaukset. Kolmannessa vaiheessa oli suunniteltava layout suorakäyttöhydrauliikan komponenteille ja asentaa ne suunnitellusti. Kuten useasti uutta teknologiaa sisältävän järjestelmän ylös ajossa, oli ratkaistava muutama ongelma ennen testien aloitusta. Lopulta kun suorakäyttöhydrauliikkajärjestelmän sai käyttökuntoon, oli mahdollista tehdä tarvittavat testit ja mittaukset.

Lopputyön teoriaosassa käsitellään kaivoslastaus ja kuljetuskoneiden runko-ohjaushydrauliikkajärjestelmiä ja niitä koskevia ominaisuuksia ja vaatimuksia. Analyysissä tarkastellaan hydrauliikkajärjestelmien ominaisuuksia ja energiatehokkuutta, jotka vaikuttavat tulevaisuuden hydrauliikkajärjestelmien valintaan.

Älykkäällä pumpunohjauksella kuormantuntevassa hydrauliikkajärjestelmässä saavutetaan merkittävä energiansäästö menettämättä järjestelmän muita ominaisuuksia. Suorakäyttöhydrauliikkajärjestelmällä on mahdollista toteuttaa energiatehokas ratkaisu. Järjestelmä saatiin toimintakuntoon, mutta siinä on vielä asioita, joita ei saatu ratkaistua tässä tutkimuksessa.

Avainsanat: Hydrauliikka, hydraulijärjestelmät, hydrauliset koneet, energiankulutus

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ABBREVIATIONS

A	Ampere
BEV	Battery electric vehicle
CAN	Controller area network
DDH	Direct drive hydraulic
HV	High voltage
km/h	Kilometers per hour
LHD	Load, haul, dump machine
LOHA	Load and haul product area
LS	Load sensing hydraulic
PMSM	Permanent-magnet synchronous motor
RPM	Revolutions per minute
V	Voltage
VCM	Vehicle control management
W	Watt

NOTATION

A	Area
ω	Angular velocity
Δp	Pressure difference
η	Efficiency
P	Power
p	Pressure
r	Radius
V_k	Revolution volume
n	Rotation speed
T	Torque
v	Velocity
q_v	Volume flow from cylinder
η_v	Volumetric efficiency

1 INTRODUCTION

This thesis has been made for the Turku factory of Sandvik Mining and Construction Oy. The Sandvik group conducts operations in four business areas with responsibility for research and development. The business area Sandvik Mining and Rock Solutions is a global leading supplier of equipment and tools, parts, service and technical solutions for the mining and constructions industries. (Sandvik, 2021.)

Sandvik Mining and Rock Solutions has a technology center of loading and hauling product area (LOHA) in the Turku factory. LOHA's production is divided into Turku factory in Finland, Jiading factory in China, Johannesburg factory in South Africa and Camarillo factory in the USA. The development of BEV machines is divided between Finland and the USA technology centers.

The mining industry's interest in electric drives has increased significantly. Ventilation has caused high costs for the mines. Electrification of mobile machinery reduces emissions, which reduces the need for ventilation. In some countries, legislation directs the mining industry to use low-emission solutions. Green values are also used to improve the image of the mining companies.

Mining machine manufacturers are working to respond to the mining companies' drive for lower-emission mines. Electrification of mining machines is in the center of development at the moment. The development of hybrid and battery drives requires energy-efficient solutions in order to achieve the required productivity.

Battery technology is constantly improving, which increases machines' operating time, but also the efficiency of energy using systems needs to be improved. High-efficiency systems produce less heat, which reduces the need for cooling and saves energy.

Electrification in vehicles creates opportunities for the development of hydraulic systems. Direct drive hydraulics require advanced power electronics control. Nowadays inverters suitable for mining conditions are also available, which allows the use of new technology for hydraulic power units.

Universities have done research work on direct drive hydraulics for LHD machine. Aalto university has a test bench, which is based on the articulated steering geometry of Sandvik LH307 mining loader. The components of direct drive hydraulics are almost the same on the test bench as on the test mining loader. In this thesis, the university research work was implemented to real mining loaders.

It was appropriate to start from the articulated steering when applying direct drive hydraulics to the machines. Every LOHA's product has articulated steering, so new technology is applicable to all machines. Articulated steering hydraulics is implemented with two cylinders placed almost symmetrically compared to each other, so that the flows are almost the same in both directions. It would be possible to implement the system almost without a valve but given the requirements of the standard EN ISO 5010:2019, the directional control valves must be in the system. The back-up system of the power unit must also be available. When the articulated steering is idle, the valves prevent the move of the articulation due to external forces.

This thesis examines the energy consumption of a mining loader's articulated steering hydraulic system. I study the current load sensing hydraulic systems, one with constant velocity control of the pump and the other with intelligent velocity control of the pump. The system these are compared to is a direct drive hydraulic system, which is of new technology.

The results of this thesis can be utilized in future projects, when selecting hydraulic systems to LHD machines.

2 ARTICULATED STEERING

In LHD machines, the commonly used steering method is the articulated steering. Every machine produced by Sandvik LOHA has articulated steering. The mine loaders have a joystick control for articulated steering and the operator sits sideways with respect to the direction of travel. The mine dump trucks have a steering wheel and the operator sits facing the direction of travel, with a few exceptions.

In many mining methods, a mining loader drives almost as much to both driving directions. When the bucket is filled, forward visibility is limited, so the backward drive is a safer direction. After dumping the bucket, often the direction of travel is forward. Mining tunnels are often very narrow, so there is no room for changing the driving direction of the machine. Since the tunnel turns are very steep, the steering movements must be fast and controlled. The loader's transportation distances are usually short, so work cycles are fast.

The driving cycle of a mine dump truck is different from the driving cycle of a mining loader. The dumper's driving cycle is mainly driven forward. The dumper's transportation distances are usually long, so work cycles are long lasting.

The articulated steering hydraulics of mine loading machines has been studied before. In 2005, Jarno Viitaniemi made a master's thesis for Sandvik Turku factory, which dealt with the research and development of automatic loading machine's articulated steering hydraulics (Viitaniemi 2006). In 2012, Mikko Halme made a master's thesis for Sandvik Turku factory, which dealt with the development of articulated steering in machines (Halme 2012).

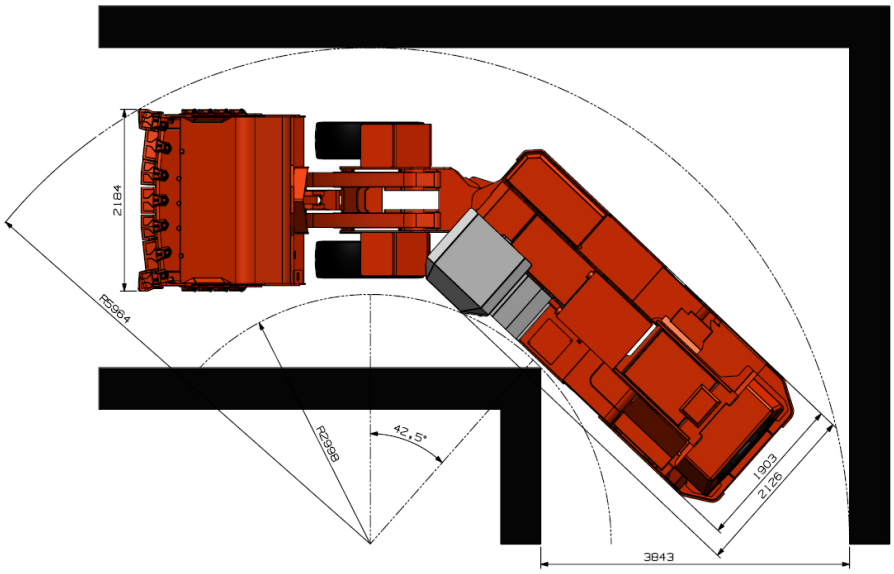

Figure 2.1 Articulated steering (Sandvik product 2021).

Figure 2.1 shows how wide a tunnel can be operated with the machine.

There are many requirements on the articulated steering of LHD machines. These requirements are clarified in the following chapters.

2.1 Standard

LHD machines observe standard EN ISO 5010:2019 of the requirements of articulated steering. The standard includes the requirement in which the machine has to pass a test track (figure 2.2). The dimensions of the steering test course are determined by the dimensions of the machine to be tested. The maximum speed of the machine also affects the dimensions of the test track. Machines with a maximum speed exceeding 20 km/h must have a secondary steering system. The maximum force required to rotate the steering wheel is defined in the standard (ISO 5010:2019). In addition to these, the standard has several requirements for LHD machines.

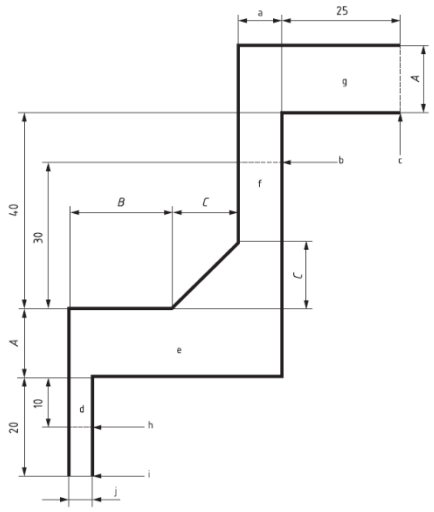

Figure 2.2 Steering test course (ISO 5010:2019).

2.2 Manual operations

The manual operator's requirements for articulated steering are more complicated. Partially the requirements are based on opinions and previous customs. The steering feel of an operator consists of the steering's response to speed, the discomfort that the operator feels and the individual differences in the ways of steering (Halme 2011, 71). The steering feel should be well adjustable, there should be enough velocity in the steering, and the start and stop of the motion have to be smooth enough.

2.3 Automation operations

The requirements for machinery operated by automation are different from the requirements for manually operated machinery. The automation LHD that machines use will increase in the future, so it should be taken into account. A machine with an automation system can drive at a greater speed in narrow mine tunnels than a manually operated machine. Due to higher speed, articulated steering should be faster, more controlled, and have good repeatability. The most important automation system requirements for hydraulic valve features are linearity, delays and dynamics (Viitaniemi 2006, 79).

3 ENERGY EFFICIENCY OF HYDRAULIC SYSTEM

Energy efficient LHD machines have been the aim of machine manufacturers' design for a long time. The power train is LHD machines' largest energy consumer, which is the focus of many studies nowadays. The hydraulic functions of LHD machines which use significant amounts of energy include the bucket, boom, articulated steering, brakes, cooling system and cable reeling system.

Hydraulics systems' advantage compared to other transmission power systems is good power to weight ratio of components. The power transfer takes place along hoses and tubes, which enables the free placement of the components. Development in digital electronics has enabled the integration of control systems to hydraulic components. In the field of hydraulics, development creates opportunities to improve existing systems and develop new systems with better controllability and energy economic properties (Hydraulitekniikka 2008, 1.)

3.1 Load sensing hydraulics (LS)

The LS system is a generally open system with a liquid tank. From the tank, the liquid is sucked into the system and it returns to the tank from the actuators. (Figure 3.1) The system pump is one direction, so the actuators' motion directions are controlled by valves (Hydraulitekniikka 2008, 4-5).

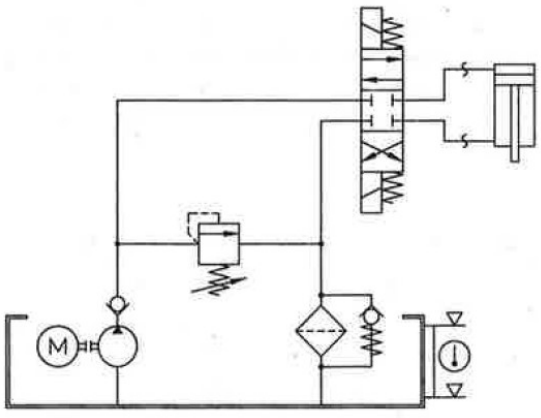

Figure 3.1 Open hydraulic system (Hydraulitekniikka 2008, 5).

In the load sensing system, only the amount of flow and pressure needed to perform the work is used. LS system is a very energy efficient system, which produces only a little waste heat. With LS system, a highly accurate hydraulic operation control is achieved (Parker 1999, chapter 3, 17.)

The load of system determines the pump pressure. The system recognizes the amount of the load and adjusts the power by load. In variable displacement pump systems, the pump pressure is controlled by LS signal (Ajoneuvo- ja työkonehydrauliikat 1992, 79.) The pump will always try to maintain a constant pressure drop across the flow control orifice, which is equal to the pump differential pressure control setting. In multiple valve system, the maximum load determines the pump pressure. The maximum flow to the actuators is determined by the influence of the valve spool and compensator. The directional control valve regulates pump displacement via a load pressure signal, providing a constant Δp between the pump outlet and the load sensing signal (Parker 1999, chapter 3,18).

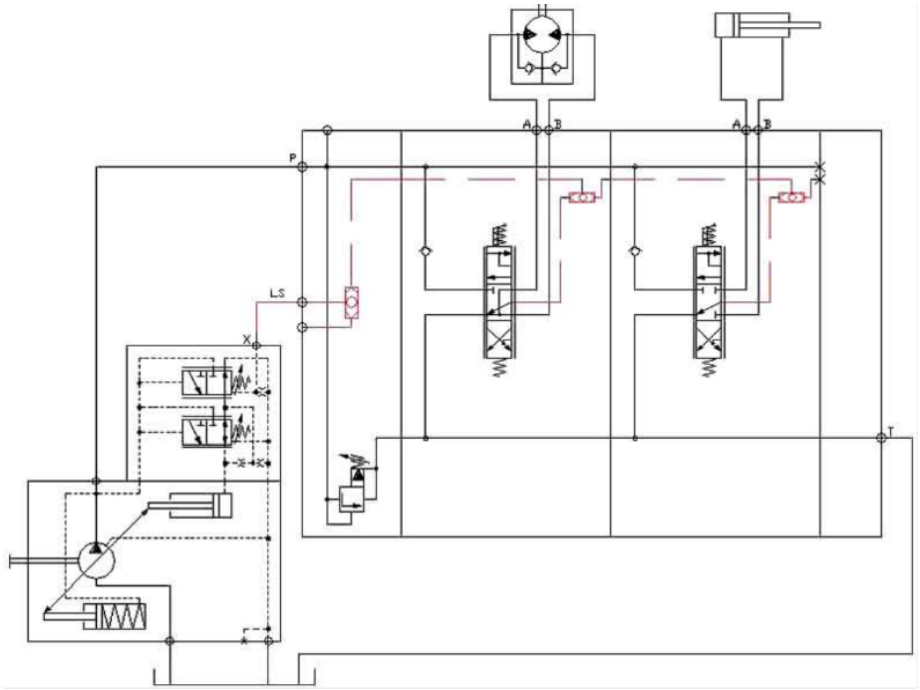

Figure 3.2 LS hydraulic system (Hydraulic supermarket 2021).

3.2 Direct driven hydraulics (DDH)

Direct driven hydraulics is a new technology that is believed to be the future solution for hydraulic systems. System development aims at good energy efficiency. Advanced inverter technology enables the use of a pump-driven system.

The DDH is a closed hydraulic system with a small liquid tank. The closed hydraulic systems use two-direction pumps, whereby the liquid returning from the actuator is returned to the suction line of the pump. The operating direction of the pump determines the operating direction of the actuator and the rotation speed volume the motion speed. A separate small feed pump is required to compensate for system leakage and cooling. (Hydraulitekniikka 2008, 5)

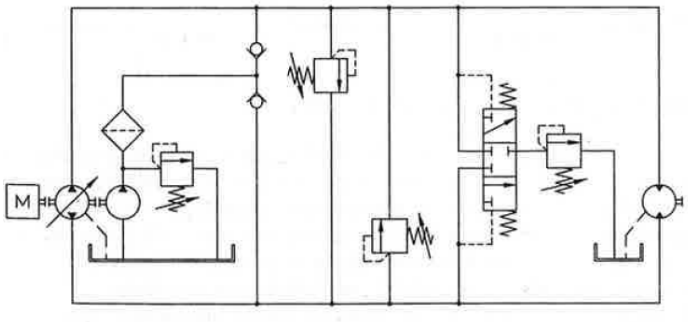

Figure 3.3 Closed hydraulic system (Hydraulitekniikka 2008, 5).

In direct drive hydraulic systems, energy recovery from actuators is possible by controlling the actuator. In the regeneration situation, the flow returns through the pump of the system, whereby the pump acts as a motor by means of its recovery of the hydraulic power back to its drive motor (Tikkanen 2012, 12.)

4 THE STRUCTURE OF HYDRAULIC SYSTEM

In designing the hydraulic systems of LHD machines, the problem is often the lack of space, so hydraulic lines are designed with minimum size. The cramped hydraulic lines cause considerable pressure drops in the system.

The technology project during which the LH307B machine was manufactured is only six years old, so the hydraulic systems selected for it are still up to date. Load sensing hydraulic system has been selected for the articulated steering system. This thesis examines a LS hydraulic system with an intelligent pump control. The comparison system is a direct drive hydraulic system.

The power unit used with the hydraulic pump is Parker PMSM motor, which is controlled by an Inmotion inverter. The articulated steering cylinders 100/50x450mm x 2pcs are Sandvik's own design.

The LS system valve has a spool and compensator, which restrict the system's flow rate to 74 l/min, which is reached with the velocity of 1700 RPM of the pump. This is calculated with formula (1).

$$q_{v,tod} = n * V_k * \eta_v \qquad (1)$$

In the LS system with intelligent pump control, the pump is stopped when it is not needed. The pump starts immediately when the joystick is turned, and the pump rounds rise linearly as the joystick request increases. The joystick was scaled to respond to pump rounds 500-1700 RPM.

Aalto university has a test bench which is based on the articulated steering geometry of Sandvik LH307 mining loader. The components of direct drive hydraulics are almost the same in the test bench as in the test mining loader. The energy efficiency of components has been studied in the test bench. In this study the university research work was implemented to real mining loaders.

5 RESEARCH PLATFORM: LH307B MINING LOADER

For my thesis work, I was allowed to use the Sandvik LH307B serial number L607B663 mining loader. (figure 3.1) The LH307B is a battery-powered underground loader with a quick-charging feature. The tramming capacity is 6,7 tons and total weight 23 tons. The driveline is implemented with a 115-kW inverter-controlled electromechanical solution. The hydraulic functions of the machine are divided into three different sections with their own power unit. Bucket hydraulics is operated by two 41 kW inverter-controlled power units, one of which also used the articulated steering. For brake hydraulics there is an 18-kW inverter-controlled power unit. This unit is a technology prototype.

Figure 5.1 Test machine.

5.1 Initiation of the study

The purpose of the thesis is to study the operation of steering hydraulics, so it had to be separated from the other systems. The control of the inverter of the hydraulic power unit was disconnected from the machine control system and its diagnostics was disabled. It would have been possible to do the study with the machine's own control system, but the possibility to make changes to it was limited. It is more flexible to do the electronic control by separating the controller because in that case the controller algorithms are

more manageable, and changes are easier. The controller is connected to the machine's CAN bus, so that the required safety features can be implemented.

5.1.1 Control system

Parker IQAN-MC43 master module was selected as the controller and Parker IQAN-MD4-7-T1E2 touchscreen as the interface. The program was made in collaboration with Parker Hannifin Finland. The controller programming was made with IQAN design 6 software, which I was also able to modify myself.

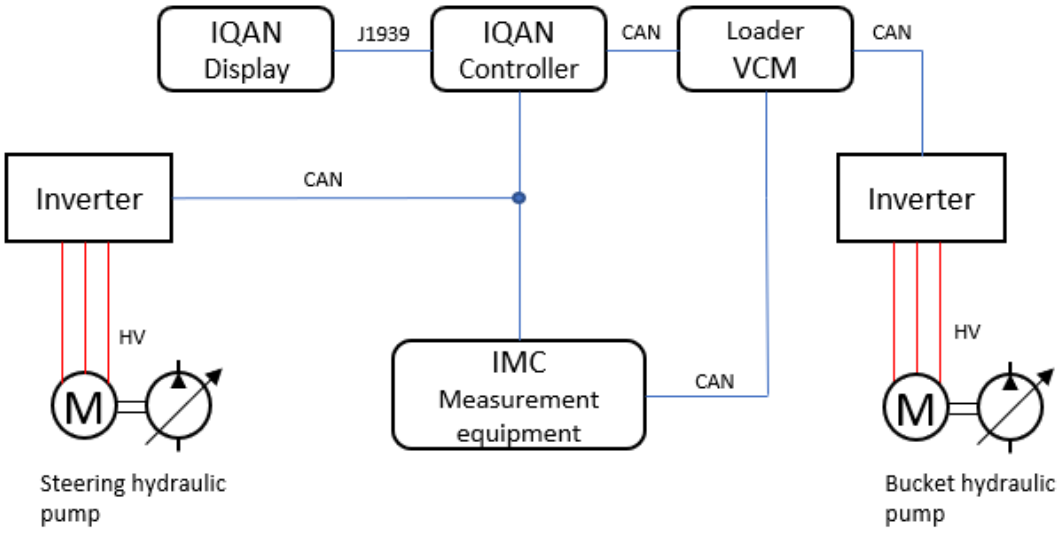

Figure 5.2 Control system.

Figure 5.2 shows that the study has used control system architecture where the articulated steering system is separated from the vehicle control management system.

5.1.2 Hydraulics

Figure 5.3 shows that the steering hydraulics had to be separated from the bucket hydraulics, which reduced the bucket and boom velocity by half. The velocity reduction is significant but does not affect this study because bucket motion times are enough in this case.

The steering valve had an integrated pilot pressure regulation, so a separate valve had to be installed to regulate the pilot pressure to the bucket valve and the greasing system.

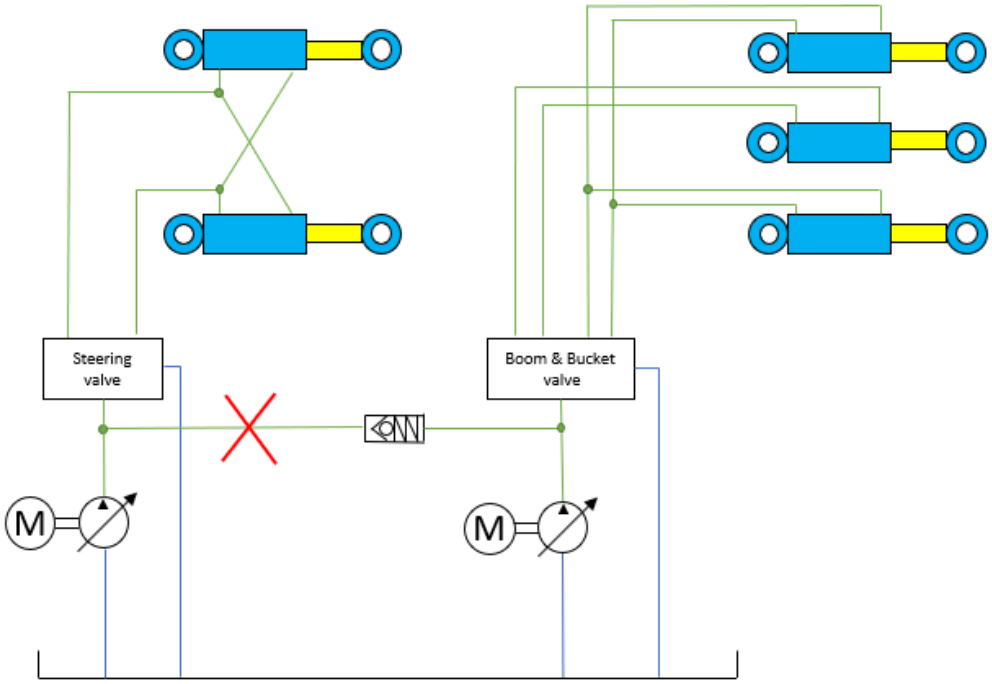

Figure 5.3 The separation of steering hydraulics.

5.2 Measurement equipment

IMC 7008-N and IMC Cronos PL-2 (picture 5.4) universal data acquisition devices were used for the study. The devices include the same amplifiers and connections but are different generation devices. One device includes 8 analog inputs, 16 digital inputs, 4 counter inputs, 8 digital outputs and 2 CAN nodes. The devices were connected to each other with a synchronization cable, whereby the data from both devices had the same time stamp. The real time measurement devices work without PC saving data to CF memory cards.

The IMC 7008 N amplifier channels were enough to measure the load sensing hydraulic system. The new technology demanded closer examination, so a number of sensors needed to be added. Due to the addition of sensors, the channels of the data acquisition device also ran out, so it was necessary to add another data acquisition device.

Because of K- type temperature sensors, IMC SC16 amplifier which is connected to data acquisition device via CAN bus was added.

IMC Studio software 5.0 was used to configure the measurement device. Measurement could be seen in the PC real time. Communication between the device and the PC worked in ethernet network either wirelessly or with cable connection.

The devices were enclosed in a waterproof case and mounted on the loader roof. The supply voltage for the measuring equipment came from the 24 V system of the machine. To avoid electrical disturbances, the measuring devices were grounded to the same potential with the machine control system.

Figure 5.4 Measurement devices.

Trafag NAH type sensors with 4-20 mA transmit current were used for measuring the pressure. The sensors were selected based on the highest pressure level of the object to reach the best accuracy. Sensors with the pressure areas of 0-60 bar, 0-200 bar, 0-400bar were used for the measuring. Parker SCFT-015 turbine flow sensor with the flow area of 0-15l/min was used for the oil flow measure. The sensor output of Parker flow sensor is 4-20mA transmit current. Hydac ETS 4144-A-000 sensors and K-type thermo-couple sensors were used for measuring the temperature. The CAN1 node of measure device IMC7008-N was connected to the 250kbits CAN bus of the machine. A lot of useful measurement data was obtained from the machine bus to support the study. The device's CAN2 node was connected to the inverter's 250kbits CAN bus which is used for

articulated steering. The CAN 1 node of the device IMC Cronos PL2 was connected to IMC SC16.

Dewesoft Sirius i amplifier and Dewesoft DS current clamp equipment were used in the measurement verification of the inverter.

5.3 Data analysis and processing

IMC Famos professional 7.2 software was used for analyzing data. It is a diverse and graphical data analysis software.

The volume flow measurement of an LS system with a variable displacement hydraulic pump had to be made with separate flow sensors or calculated from the cylinder movement. In the original installation, part of the hydraulic lines was steel tube, so flow sensor installation would have been very difficult. The machine's own sensors include an articulate angle sensor, on the basis of which the calculation of the cylinder position was made. The position of cylinder was calculated by the formula (2). (Tekniikan kaavasto 2000, 18)

$$c^2 = a^2 + b^2 - ab\cos\gamma \quad (2)$$

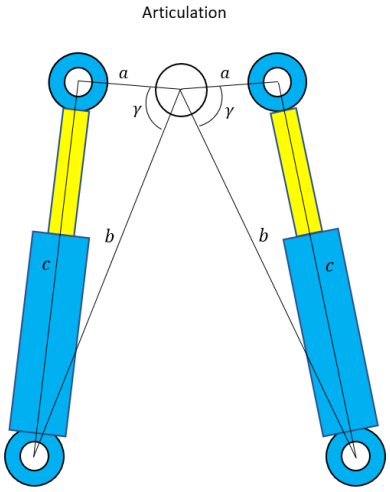

Figure 5.5 Cylinders position.

Cylinder position

Cylinders were not symmetric in relation to the articulation, so calculations had to be made from both cylinders. The cylinder's speed is the derivative of its position.

The cylinder area was calculated using the formula (3).

$$A = \pi r^2 \qquad (3)$$

Cylinder's flow rate was calculated using formula (4). Cylinders are slightly asymmetrical in relation to the articulated point, so the movement of both cylinders was calculated.

$$q_v = \frac{A * v}{\eta_V} \qquad (4)$$

The speed of rotation was changed to angular speed using formula (5). The inverter transmits the motor rotational speed and torque, from which the power was calculated using formula (6).

$$\omega = 2 * \pi * n \qquad (5)$$

$$P = T * \omega \qquad (6)$$

Hydraulics power was calculated using formula (7)

$$P = q_V * p \qquad (7)$$

6 WORK CYCLE SIMULATION

To compare different solutions of articulated steering hydraulics there was a need to create a repeatable test track that simulates the realistic work cycle of a mining loader. The available space of the test area set limits to the size of the simulation track. The simple execution saved time when building the test track. Less torque was needed to turn the machine when it was loaded, since the rear part of the loaded machine was lighter (Halme 2012, 10). All tests were driven with an empty bucket.

6.1 The first cycle

The first cycle simulated a typical loader work cycle. The test track was designed to the dimensions of the LH307B machine. The things affecting the test track design were the repeatable driving cycle, simple execution, and available space in the factory area. The test track surface was even and asphalted.

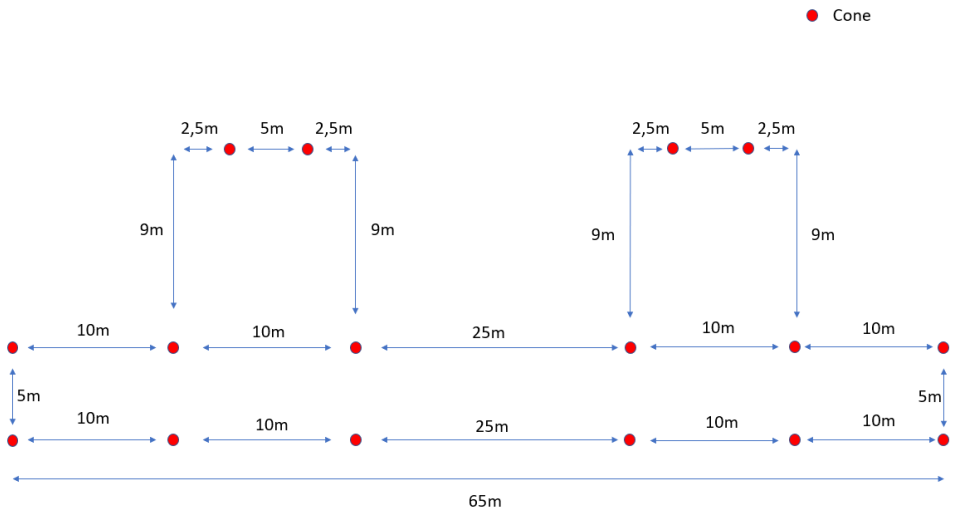

Figure 6.1 The track dimensions of the first cycle

One driving cycle included two turns to the right and two turns to the left while driving forward, two turns to the right and two turns to the left while driving backward. The maximum speed of the machine during the driving cycle was 6 km/h. The driving time of one cycle was about 120 seconds.

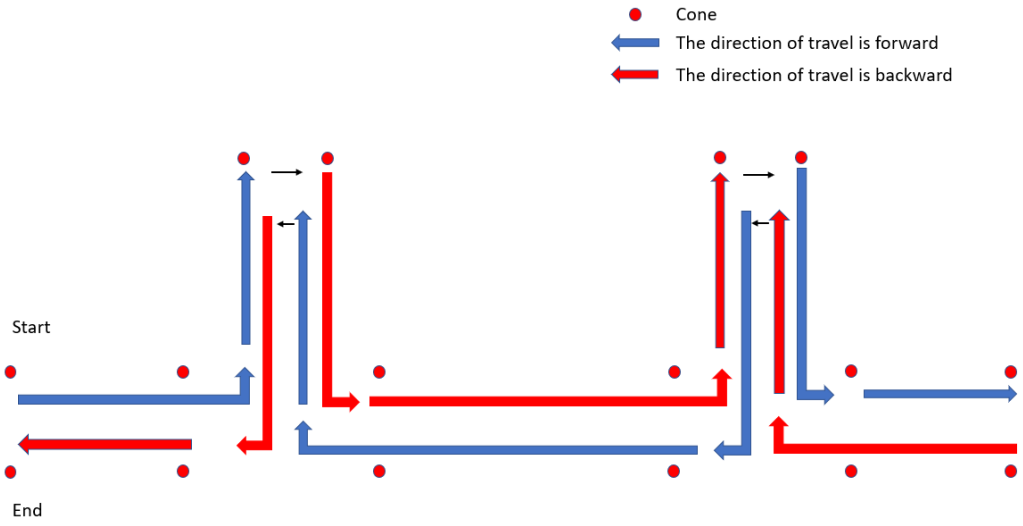

Figure 6.2 The first cycle drive model

6.2 The second cycle

The second cycle was continuous driving without changes in the direction simulating a dump truck's driving cycle in a mine. The track was made on the test-driving track of the Turku factory and followed its lines. On the surface of the test track there was a few meters of height difference and it was asphalted. The maximum speed of the machine during the driving cycle was 12 km/h. The length of the track was about 245 meters.

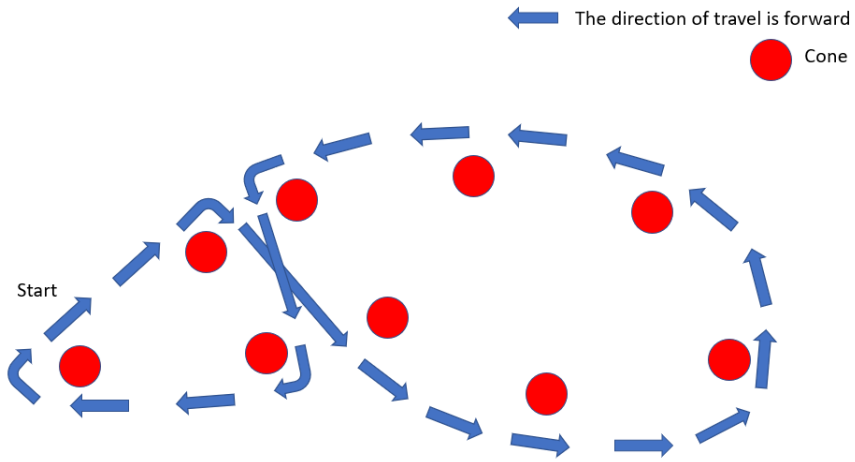

Figure 6.3 The second cycle drive model

7 ENERGY CONSUMPTION ANALYSIS OF HYDRAULICS SYSTEM

This thesis examines the energy consumption of the mining loader's articulated steering hydraulic system. The energy consumption is the focus of this study, but also other requirements have been taken into account. In this study the delay time of the hydraulics system is under review, which is very important to the operation of the machine.

7.1 Load sensing hydraulics

The load sensing (LS) hydraulics system already had good efficiency, but it was improved by adding an intelligent power unit control to the system. In the baseline, the hydraulic power unit of the articulated steering was rotated constantly 1700 RPM. In the second step, the power unit was rotated only when articulated steering was used.

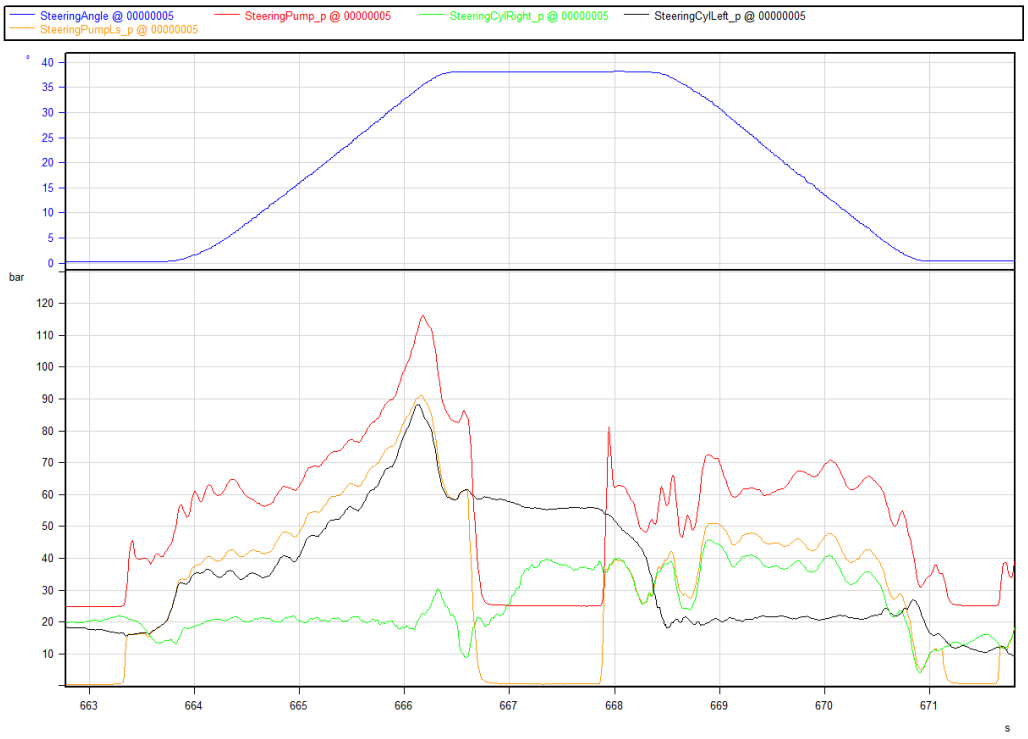

Figure 7.1 The turn and back turn of steering

Figure 7.1 shows the counterforce of power line and tires to hydraulics system when turning the machine. The force needed to turn the machine straight was less, since there was external force that tried to turn the frame straight. As a result, the valve spool properties caused the cylinder to have 20 bar counterpressure. The cylinder counterpressure aimed to stiffen the system against external forces. The constantly changing direction of external forces brought challenges to the control.

7.1.1 Standstill torque

When testing the pump's intelligent control, there was a problem which reduced the energy save. When the pump was stopped, the inverter requested a torque.

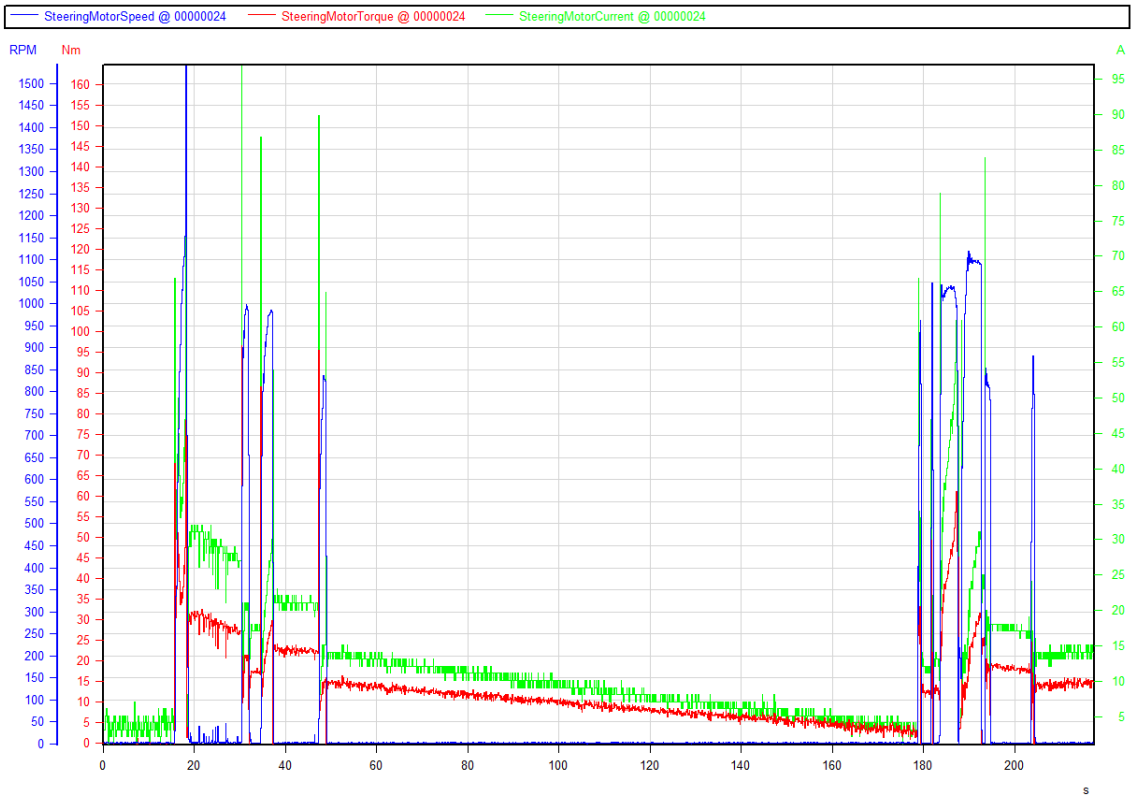

Figure 7.2 Standstill torque

Figure 7.2 shows the inverter's aim to hold the standstill torque between 50 and 180 seconds (red curve). The used energy in the standstill function could not be defined when the inverter output voltage was not available. This was caused by an inverter's feature, which is indispensable in some applications but is not required when the direction valve is used. No solution was found in the inverter manual, so I sent an email to the Inmotion

representative. I got a recommendation to just disable the inverter, which means no power consumption since there is no request to either be still (no brake) or to keep torque (Jörgen Rickan 4.9.2020). This disablement raised a question whether it would cause a delay to the system.

7.1.2 LS system delay

Figure 7.3 shows the delay of the constant speed system and the variable speed system. It also shows that there is no delay in steering when the pump has been stopped.

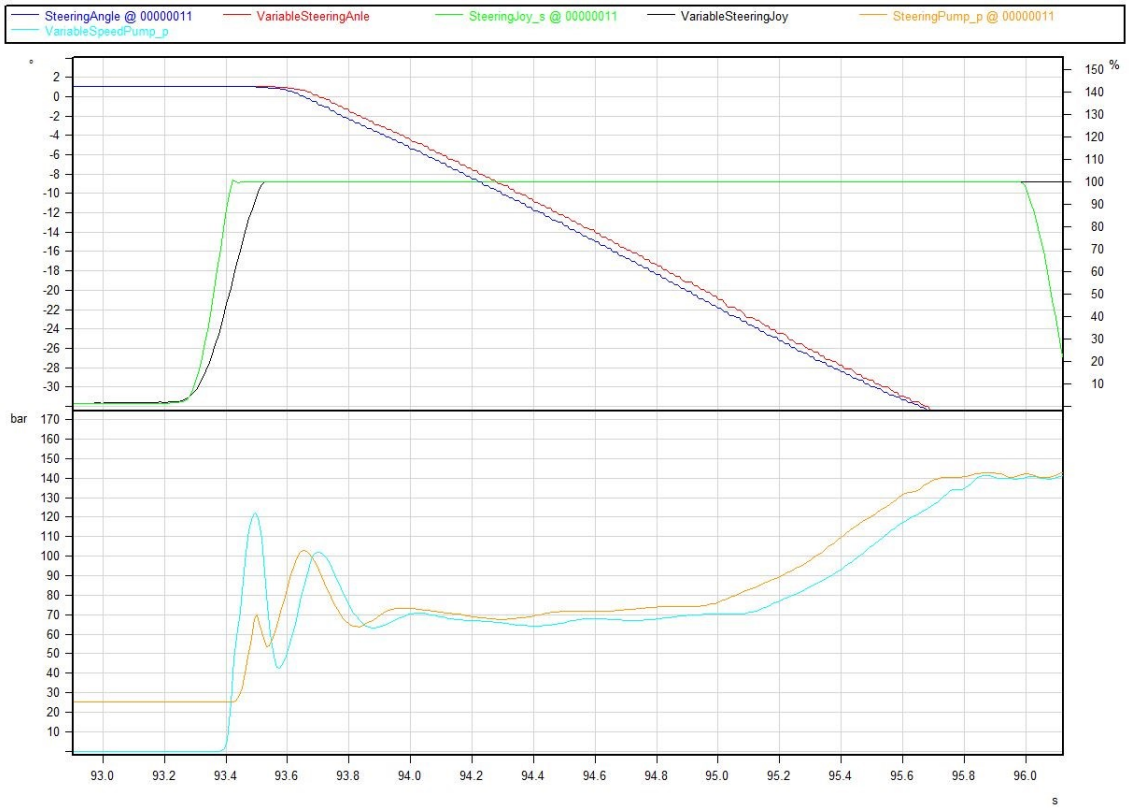

Figure 7.3 LS system delay

Figure 7.3 has the turns made manually using the joystick, so they are not identical, but they start at the same time. The graph shows that the inverter disablement does not cause delay. The time difference was not noticeable when driving the machine. The valve delay is greater than the inverter's, so it does not cause a problem.

7.2 Direct drive hydraulics

At the start-up phase of DDH system, pump cavitation formed a problem. Figure 7.8 shows that when the system flow is 60 l/min, the pressure of the pump suction port drops to zero (green curve) and the pump has a strong cavitation sound. Also, at the start of the pump, the suction pressure drops to zero.

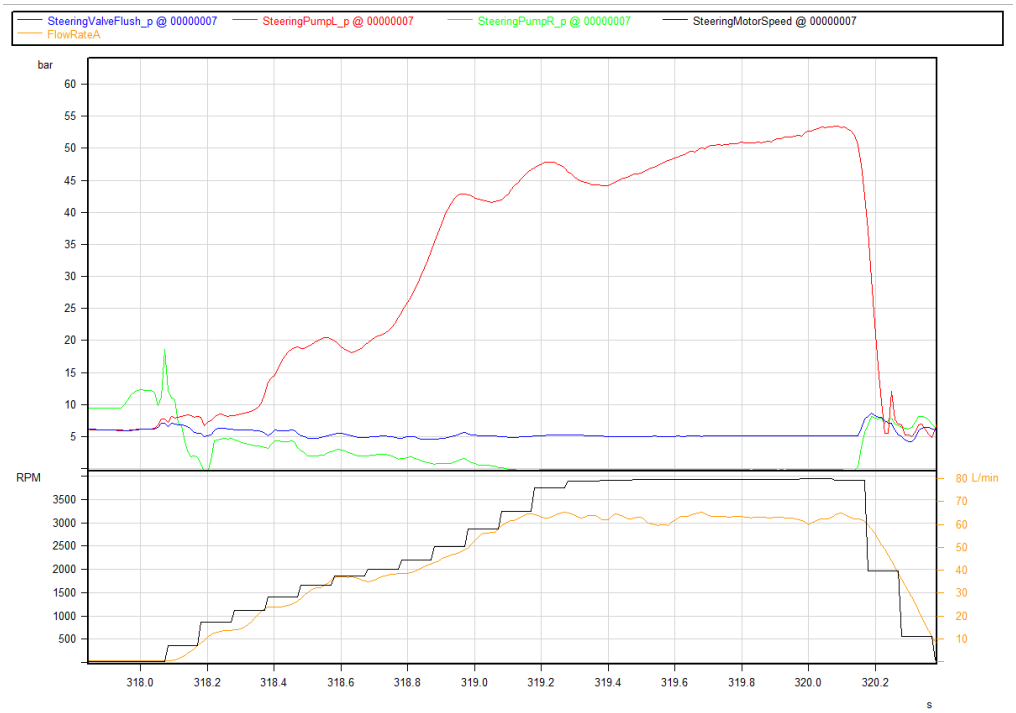

Figure 7.4 DDH pump cavitation

Since the target flow system was 74 l/min, changes had to be made to the system. The options were to enlarge the pump line size, raise charge pressure, reduce oil viscosity or change the component layout. The enlargement of line size would have been a sensible change, but it would have demanded a considerable amount of installation in the machine that was not possible in the study schedule. The solution was to raise charge pressure, which was not easy to put in practice. The maximum pressure of the charging pump is 5 bar, which it not possible to raise, and the purchase of a new pump would have taken too much time. In the limits of the schedule, it was possible to take charge pressure from the bucket pump. The bucket pump pressure is connected to the pressure reducer and direction valve, which control charging supply.

This implementation is not sensible in the actual application, but the arrangement enabled the study. In addition, charge pressure is connected with a separate hose to the pump ports, and the ports have 0.35 bar check valves. Due to the test results, charge pressure was raised to about 10 bar.

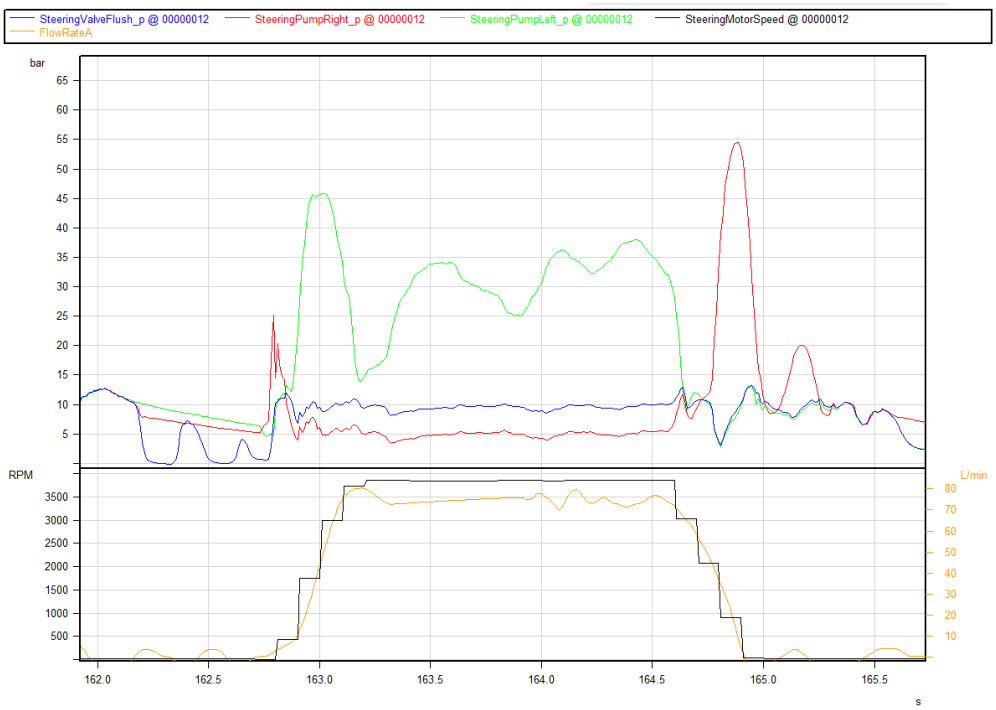

Figure 7.5 DDH fixed flush pressure

Figure 7.5 shows that when the charge pressure (blue curve) has been raised to about 10 bar, the suction pressure (red curve) remains at a sufficient level.

Electric motor acceleration defines what sort of initial speed is achieved in the articulated steering of DDH system.

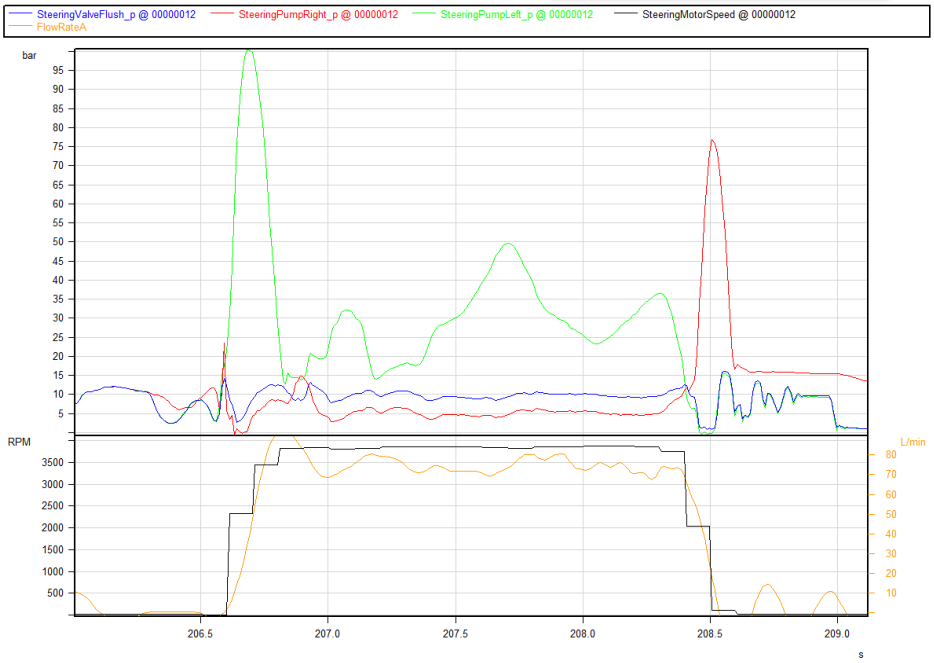

Figure 7.6 DDH fast acceleration

Figure 7.6 shows that if the pump velocity is raised too fast, the pump cavitates in the acceleration (red curve) and causes high pressure peak in the system pressure port (green curve). Also, the too fast stop of the motor causes under pressure to the system (green curve). The ramp for motor acceleration must be set in order to avoid cavitation.

7.2.1 DDH efficiency

In the DDH system, the speed of the actuator is adjusted by pump velocity, so the system has no component which controls the flow.

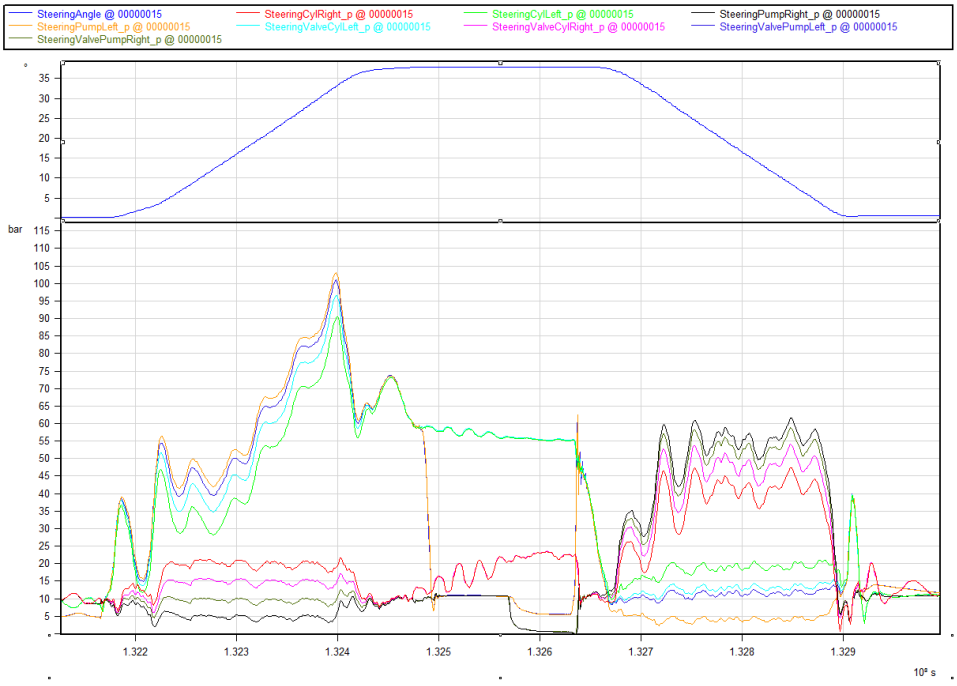

Figure 7.7 DDH The turn and back turn of steering

Figure 7.7 shows that DDH system's total pressure drop from the pump to the cylinder is 14 bar. The total pressure drop is divided as follows: from pump to valve 2,4 bar, valve 4,6 bar, from valve to cylinder 7 bar. The hydraulic line from valve to cylinder should be reviewed due to the high pressure drops.

7.2.2 DDH flushing

In a closed hydraulics system, the flushing function removes heat and impurities from the system. System flushing is connected to the valve block and pump case. The flow rate of the flushing system is adjusted with orifices.

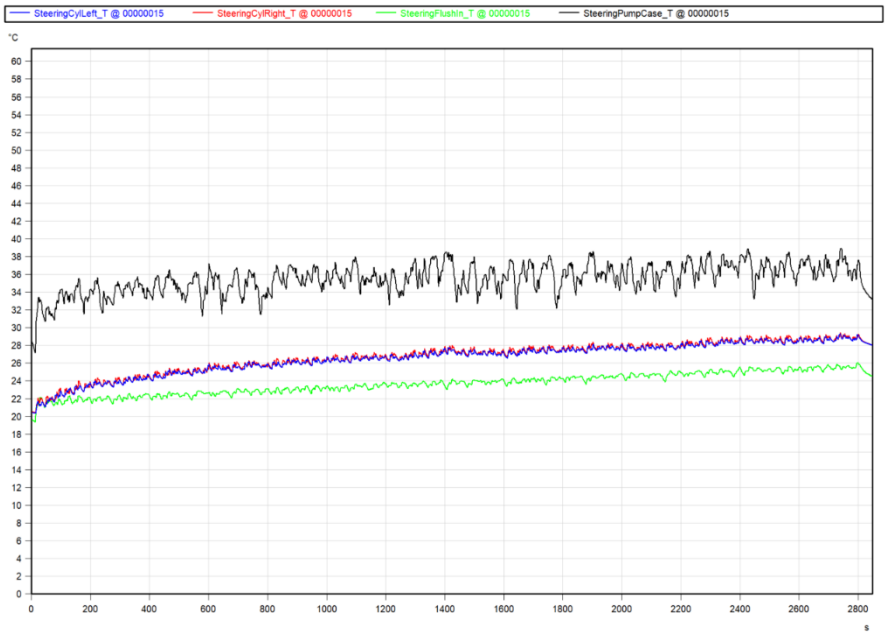

Figure 7.8 DDH system temperature

Figure 7.8 shows the system cooling operation. The system temperatures (blue and red curves) stabilize in relation to flushing oil temperature (green curve). The pump has internal leaks and oil frictional resistance, which generate heat (black curve).

7.2.3 Secondary steering system

The requirement of secondary steering system comes from the standard, so the secondary pump was connected parallel to the hydraulics power unit.

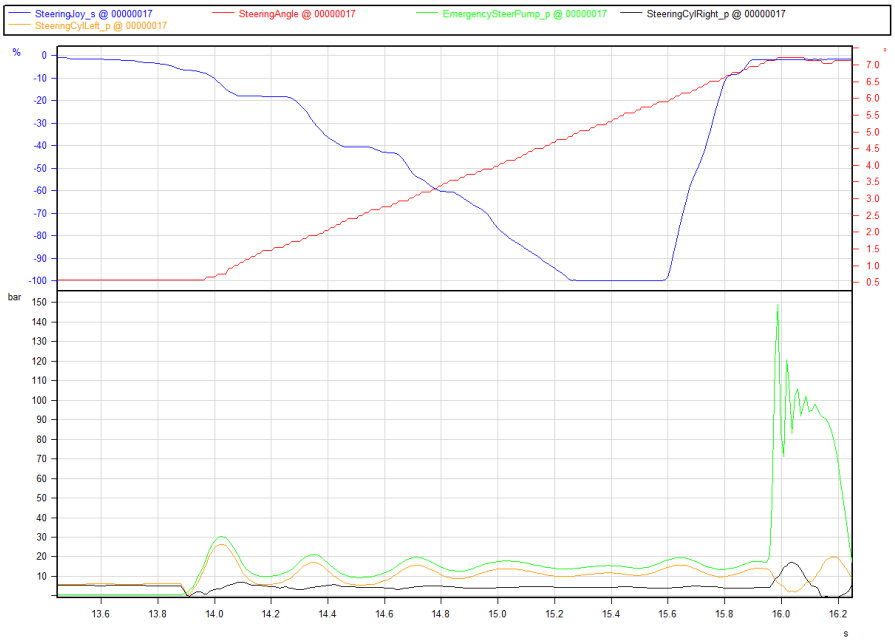

Figure 7.9 Secondary steering system

Figure 7.9 shows the secondary steering pump in action. The articulated steering turns at a rate of 3,4 °/s. Wider testing of the system was not possible since 24-volt system's voltage dropped when using the pump.

7.3 Comparation driving

When comparing energy consumption, the machine drove cycle 1 fifteen times. Since the cycles were driven by the operator, individual cycles may have human differences, so several repetitions provided a more accurate average.

7.3.1 Cycle 1

Driving cycle 1 is shown on page 26 of section 6.1. First cycle

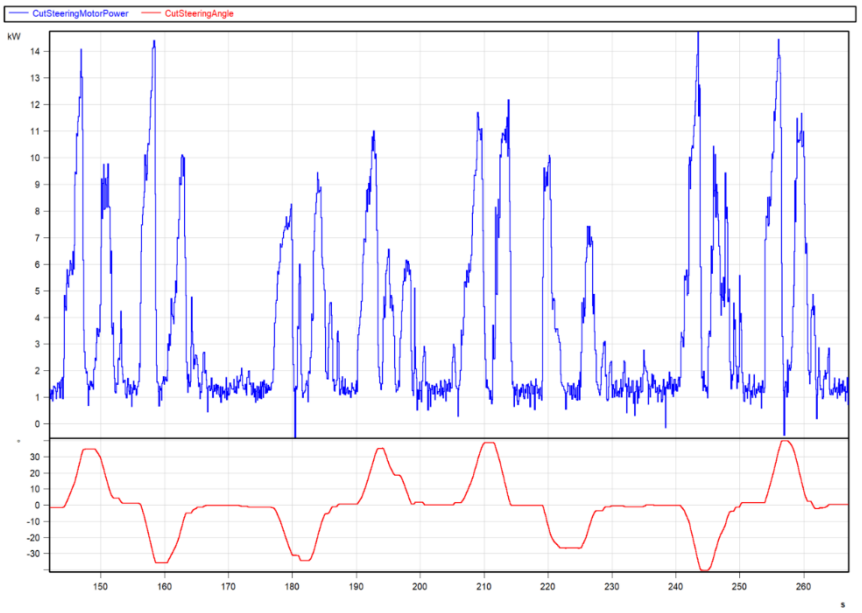

Figure 7.10 LS system with pump constant speed. Cycle1.

Figure 7.10 shows that when the articulated steering is unused, the pump still uses over 1 kW of power.

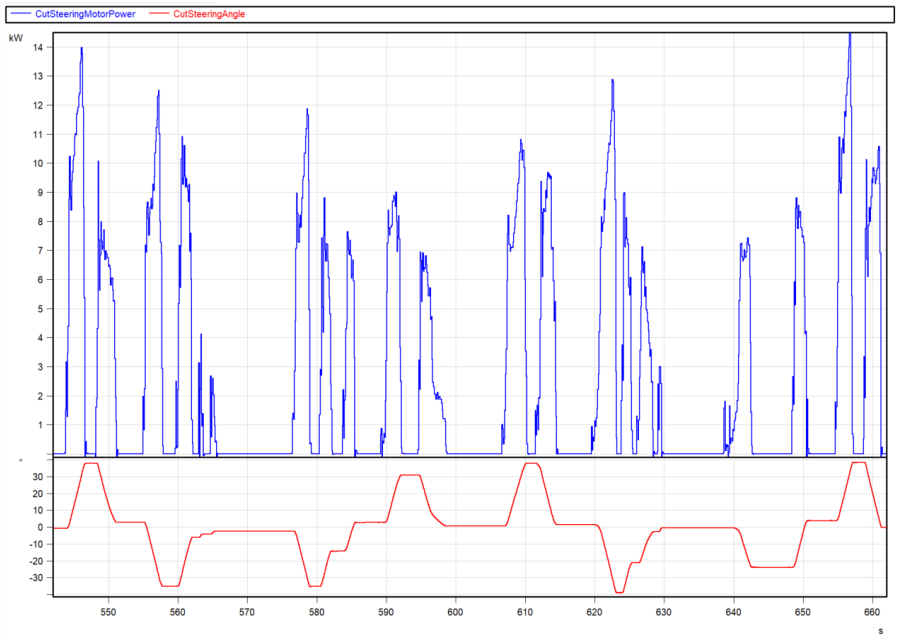

Figure 7.11 LS system with pump variable speed. Cycle1.

Figure 7.11 shows that when the pump is used only when necessary, there is no useless energy consumption.

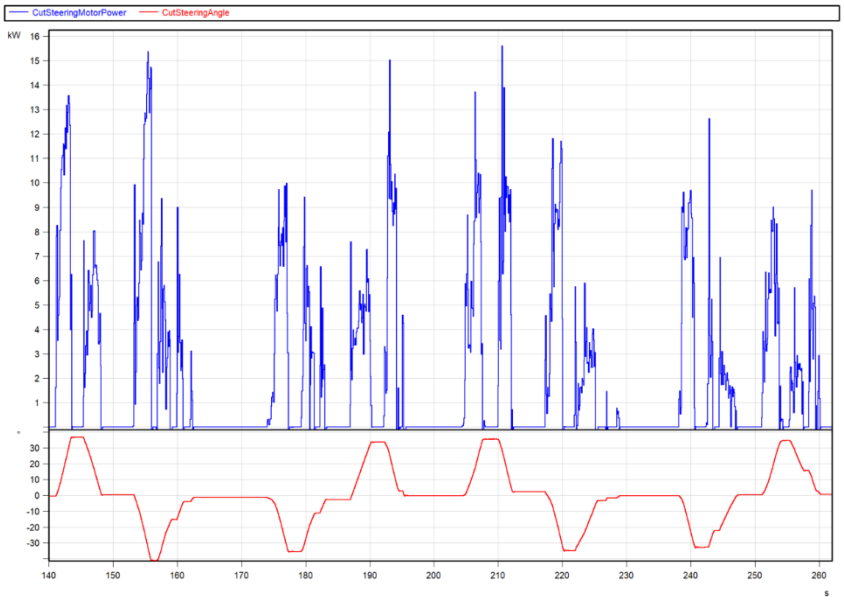

Figure 7.12 DDH system. Cycle1.

Figure 7.12 shows that DDH system power peaks are even higher than in the LS system.

Figures 7.9-7.11 show one driving cycle. Cycle1 has steep turns as a result of which the articulated steering has to turn close to capacity. The power needed to turn significantly increases, as the turning angle increases near the limits. Driving one cycle takes about 130 seconds.

7.3.2 Cycle 2

Driving cycle 2 is shown on page 28 of section 6.2. Second cycle

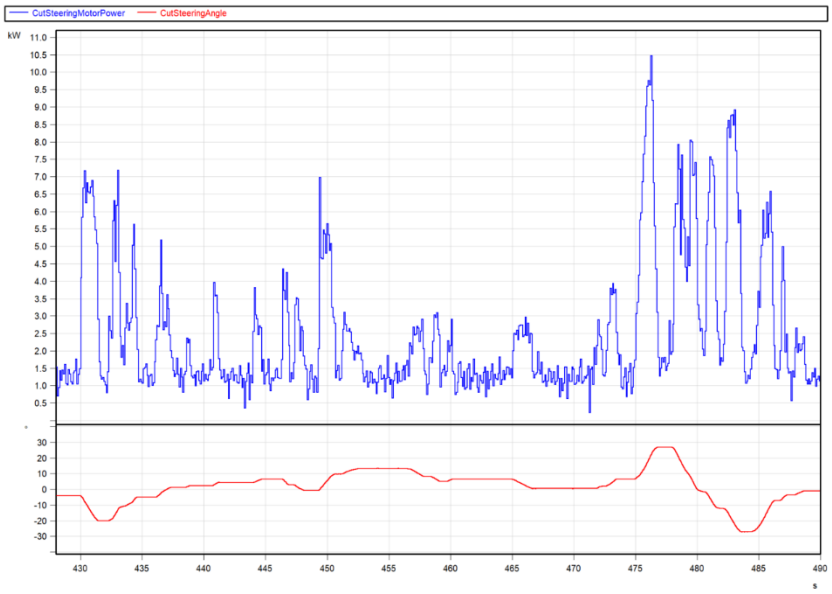

Figure 7.13 LS system with pump constant speed. Cycle2.

Figure 7.13 shows that standby power consumption is high in relation to the power needed when the steering is low.

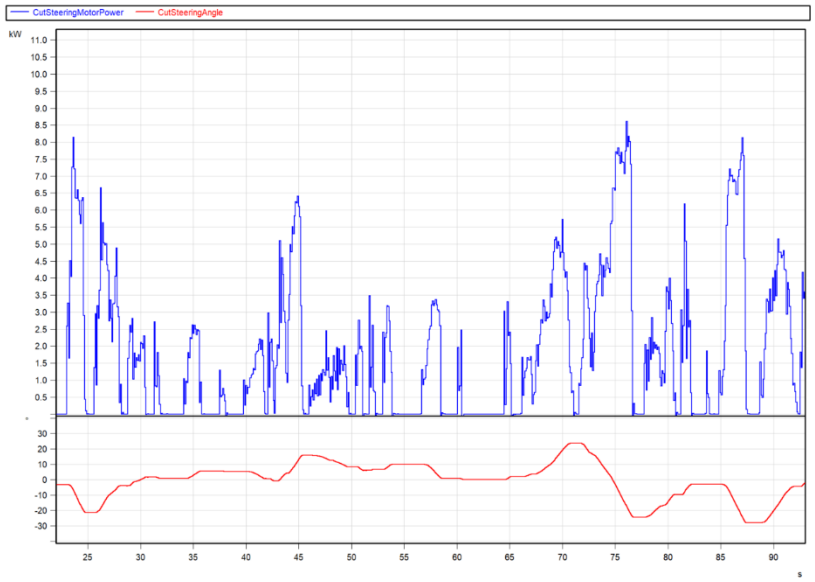

Figure 7.14 LS system with pump variable speed. Cycle2.

Figure 7.14 shows that the cycle has continuous steering, so the pump is not stopped for long periods of time.

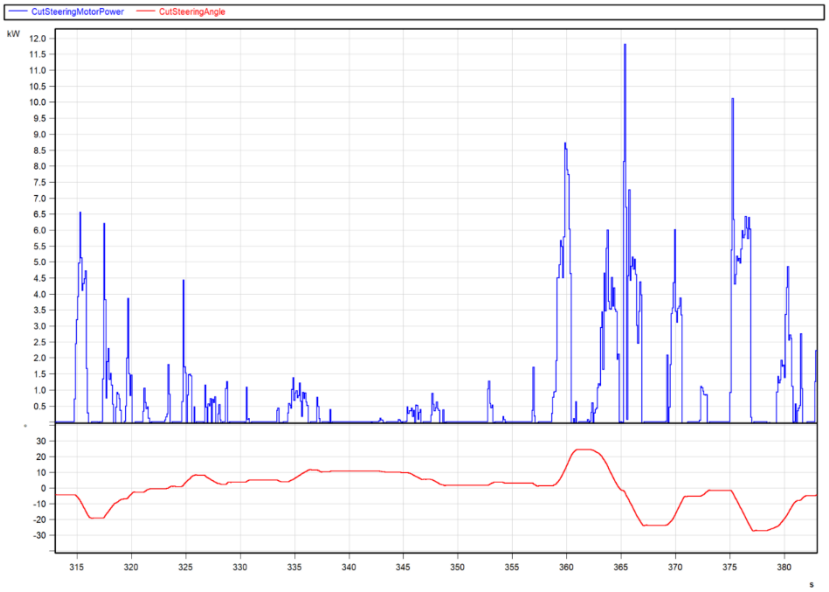

Figure 7.15 DDH system. Cycle2.

Figure 7.15 shows that in DDH system small turns use very little power. Power peaks are higher than in other systems.

Figures 7.13 – 7.15 show one driving cycle. In cycle 2 all turns are not steep, so the used power is lower and cycle driving time is shorter than in cycle 1. Driving one cycle takes about 69 seconds.

7.4 Systems comparison

When calculating the average power, the regenerated power has not been taken into account, because it is insignificant in the articulated steering system. The charging system power is the hydraulic power, which is only part of the real power of the function. The average power has been calculated from the torque and rotation speed given by the inverter, so the result has not taken into account the efficiency of the inverter and PMSM motor.

In cycle 1 with steep turns, the intelligent pump control has achieved 32% energy saving compared to continuous pump use. DDH system saves energy up to 50% compared to the continuously powered LS system. Since the DDH system and the LS system with intelligent pump control are controlled by stopping the pump, the DDH system with smaller pressure drop achieves energy saving. DDH system energy consumption is 25% lower than that of LS system with the intelligent pump control.

In cycle 2 without direction exchanges and smaller turns, the intelligent pump control has achieved 36% energy saving compared to continuous pump use. Cycles where there are no steep turns are well suited to the DDH system because its energy consumption is significantly lower than that of the LS system. DDH system saves energy up to 60% compared to the continuously powered LS system. DDH system energy consumption is 42% lower than LS system with the intelligent pump control.

8 CONCLUSIONS

The thesis was intended to compare the hydraulic systems in the mine loading machine's articulated steering. The underground mine loading machine LH307B, which was studied, allowed the actual comparison of the systems.

Measurements were made at the beginning of the study of the machine's original system, which gave the initial data for the study. The energy efficiency of the original load sensing hydraulics system was improved by intelligent pump control. In the original system, the pump was used at constant velocity. As the result of the tests, stopping the pump did not cause significant delay in the articulated steering. There was no noticeable change in the operator's driving feel when the pump was stopped. In the articulated steering hydraulic system with the intelligent pump control, 32% saving of average power consumption was achieved. It is still possible to improve the efficiency of the load sensing system by reducing the flow resistance in the hydraulic lines. In the LS system, it is reasonable to stop the pump when it is not needed, but its work depends on the features of the inverters.

The direct drive hydraulic components were installed in the machine as planned. In the system testing phase, pump cavitation became a problem. The solution, in which the cavitation problem had to be solved by using a bucket pump to produce flushing pressure, is not eligible for production, so unresolved issues still remain in the system. However, the system was in such a condition that the tests were possible.

The DDH system achieved up to 50-60% of energy saving for continuously powered LS system. Since the DDH system and the LS system with intelligent pump control are controlled by stopping the pump, the DDH system with smaller pressure drop achieves energy saving. The DDH system achieves 25-42% energy saving compared to the LS system with intelligent pump control. The benefits will be reduced, but how much depends on the implementation of the system charge.

The DDH system achieved the corresponding driving feel to the LS system. The steering speed could be adjusted to the pump rotation speed, which made it easy to find a good steering feel.

With the DDH system it is possible to recover energy, but that was not studied in this thesis. On the basis of this study, DDH system design should take into account the lay-out of the components in the machine and the hydraulics lines size. Based on this, it could be concluded that it is justified to continue the research of DDH system.

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