Series Hybrid Mining Loader with Zonal Hydraulics

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Abstract
Presently, there is a four-year window to prepare engines for upcoming TIER V regulations through solutions for peak power shaving and downsizing of diesel engines. In particular, Non-road mobile machinery (NRMM) offer a promising and challenging field of application due to their duty cycles, which includes high and short power peaks and extreme working conditions. In this paper, a series hybrid electric powertrain for a mining loader is presented with the goal of reducing the fuel consumption. A full-scale mining loader powertrain prototype was built to exploit the benefits of a series hybrid electric powertrain at low traction requirements with a combination of decentralized e.g. zonal hydraulics. Correspondingly, this paper introduces the structure of the mining loader and initial mathematical model of the system of a Direct Driven hydraulics (DDH). In this research, an experimental test was conducted, and the initial results are presented in this paper.

KEYWORDS: Hybrid mining loader, zonal hydraulics, Direct Driven Hydraulics.

1. Introduction
In recent years, interest in electric and hybrid electric propulsions are continuously growing due to environmental concerns and forced government regulations. Many governments around the globe have set tight CO₂ emission rules /1/, and new exhaust
limits for engine manufacturers have just been implemented, such as Tier IV. The following step of dramatic tightening of exhaust limits, especially in terms of particles, will be enforced in the 2019/2020 Tier V. At present, a four-year window exists to prepare for the upcoming regulations through solutions for the peak power shaving and the downsizing of diesel engines. In particular, non-road mobile machinery (NRMM) is a promising and challenging field of application due to their duty cycles, which includes high and short power peaks and extreme working conditions /2/.

In NRMM powertrains often required linear movement for actuators in addition to the need for kinetic energy (similar to conventional vehicle such as cars). Actuators such as buckets, hoists, and booms usually operate with hydraulic cylinders. The movements and payloads of hydraulic actuators yield additional loads for the ICE, and may demand high power peaks depending on the work cycle. Conventional designs have limitations. For instance, the hydraulic transmission has transferred power in only one direction, thus preventing energy recuperation /3/, and hydrostatic power transmission has traditionally low overall energy efficiency /4/. Previously mentioned, conventional designs of NRMM powertrains do not enable energy recuperation. However, it is available in most NRMM in forms of kinetic and potential energies and normally lost via heat dissipation in brakes and/or hydraulic valves in conventional designs.

Therefore, different hybrid powertrain topologies have been widely studied for the NRMM powertrain, for instance, in heavy forwarders /5/, harvester /6/, excavators /7,8/ and forklifts or reach trucks /9,10/. The design of a hybrid powertrain for non-road mobile machinery and dimensioning of the components in general are complex tasks. In present years, research has been conducted to defining the requirements for vehicular applications /11/. In partial, energy storage has also been widely researched as interest in a development of suitable storage for hybrid and electric vehicle applications /12/. A combination of two types of energy storage such as battery and supercapacitor, is quite typical and can be found in a lot of recent publications/13,14/. These combinations offer a better performance and compensate for the power density limitation off a battery alone. Other energy storage, such as Fuel cells also found their niche in research related to NRMM. In /15/, research has been conducted in the agricultural industry.

Limitation in operation range with conventional batteries, and absence of sufficient recharging infrastructure for fuel cells pushed researchers to develop new technologies such as flow batteries. In /16/, a feasibility study was presented for utilizing flow batteries in heavy vehicles. The authors of /16/ utilized the measured energy demand profiles for various operating conditions of a wheel loader for development of simulation model with
a vanadium redox flow battery. The performance test of an electrified version of the wheel loader is required to be refueled roughly 6 times in order to achieve the same results by utilizing a traditional diesel engine wheel loader.

In /17/, the importance of hydrostatic unit design on the driveline efficiency and machine operating costs has been analyzed via simulation and measurements. In one example with a wheel loader it was shown that the utilized hydrostatic unit system has relevant power loss savings compared to a new state-of-the-art system. These loss differences were explained by authors by the improved design differences of the pump-rotating group.

Industrial tendency for compact electro-hydraulic systems has been continue to grow. These compact units are able to provide powerful, linear movement with valve-controlled or pump-controlled systems. Some studies have been conducted to adapt the concept of electrohydraulic actuators known as zonal hydraulics from an airplane to NRMM. For instance, for the power steering of heavy vehicles /18/ an electrohydraulic actuator was applied. In /19,20/, a new design of electrohydraulic actuators are developed for aircraft applications. In /21/, a Direct Driven Hydraulics (DDH) unit without conventional directional valves was introduced as a hybridization tool. DDH does not require a centralized hydraulic tank and oil pipes all over a machine.

Therefore, in this research, Direct Driven Hydraulics (DDH) is seen as a tool to convert working hydraulics of NRMMs to hybrid and, in the same way, increase overall degree of hybridization of mining loader. The importance of the study arises due to the complexity of the subject, and an implementation of a new design in full-scale non-road mobile machinery.

This paper presents a series hybrid electric powertrain for mining loader. A full-scale hybrid mining loader powertrain prototype was built, and used architecture exploits the benefits of a series hybrid electric powertrain at low traction requirements with a combination of decentralized or zonal hydraulics. This paper introduces the structure of the mining loader and energy consumption estimations based on a mathematical model of the system.

This paper is organized as follows. Section 2 defines hybrid mining loader prototype with components and structure. A detail explanation is provided for main powertrain and working hydraulics. Section 3 illustrates simulation model, which shows simulation results. Section 4 contains discussion of the results with concluding remarks in Section 5.
2. Test setup

Figure 1 illustrates conventional mining loader. The mining loader was equipped originally with hydrostatic transmission. Both axles had own hydraulic motors which were connected parallel in the hydraulic circuit. The hydraulic transmission circuit was equipped with a flow divider which was allowing speed difference between axles and also locking feature which prevented wheel spinning freely when axle is on air e.g. during loading. This type of mining loader characterized by its rigid mechanical connection between axes, which corresponds to wasting energy into internal counterforces, in that sense the loader’s original drive train can be seen advantageous. The main pump was driven by a 90kW constant speed diesel engine, which also corresponds to additional losses in conventional schematics.

Therefore, in order to eliminate losses and decrease energy consumption, series hybrid mining loader was created. In the drivetrain, generator/motor and battery decouple the wheels from the engine operating point in term of mechanical or hydraulic connection. Therefore, the loader engine can be utilized in its high efficiency regions or it can be switched off.

Figure 1: 14 ton serial hybrid mining loader (a) photo, (b) conventional schematics

A novel concept of decentralized e.g. zonal hydraulics for the hybridization of working hydraulics of mining loader was also introduced. This concept based on the Direct Driven Hydraulics (DDH) approach /22,23/. DDH combines the benefits of electrical engineering with hydraulics. In this work, DDH is utilized to achieve high power density, low-noise and high performance in a compact package for lifting bucket of mining loader.

Section 2.1 introduces the structure, working principles and component used in hybrid powertrain. DDH details of tilting cylinder are shown in section 2.2.
2.1. Main powertrain

In the Tubridi research project the mining loader’s original hydraulic transmission was replaced with fully electromechanical transmission. Both axles have own electromechanical drive units and there is no mechanical connection between the axles. Electric power is produced by diesel engine driven generator and buffered with a li-ion battery. The diesel engine has no mechanical connection to the drive train, thus the drive train architecture is series hybrid. In the Figure 2 is shown the system layout of the research electric hybrid mining loader. The main power is supplied through 650 V fixed voltage DC-link which connect all sub-systems together. All subsystems have own fully controllable power electronic device between DC-link and subsystem. The electromechanical drive train is dimensioned so that the four speed rear axle drive unit produces the main traction power and high torque in loading situation. The Front axle drive unit has fixed gear ratio and it’s role is to assist the rear axle drive unit by keeping traction on when rear axle drive unit’s transmission is shifting or when rear axle is on air or when rear wheels are slipping. The electric production and buffering are dimensioned so that full performance can be achieved with only gen-set or with only battery. Both gives about 70kW electric output power to DC-link. Battery is also capable to charge-in all the recharge energy available on downhill drive. When battery is full or otherwise incapable to charge then recharge energy is supplied via the brake chopper to the brake resistor.

![Figure 2: 14 ton serial hybrid mining loader (a) schematics, (b) CAD drawing.](image-url)
Power train subsystems consists of Gen-set, front and rear axle electromechanical drive unit, electromechanical steering system, Low voltage DC-links and High voltage battery system:

- **Gen-set** consist of; VW 75kW 2.0 turbodiesel engine, 85kW Siemens PMSM generator and ABB HES 880 Inverter. The inverter has integrated brake chopper for over voltage protection in 650V DC-link. The brake chopper is connected to 100kW Cressall 4EV2 water cooled resistor unit. When generators and inverters efficiencies are taken into account the gen-set output power to the DC-link is about 70kW.

- **Front axle electromechanical drive unit** consist of; 67kW (max. 150kW@1min) Siemens ASM motor, 1:3 synchronous belt drive reduction gear between axle and the motor and ABB HES 880 Inverter.

- **Rear axle electromechanical drive unit** consist of; 85kW (max. 150kW@1.min) Siemens ASM motor, 1:2 synchronous belt drive reduction gear, 4-speed IEdrives EVT transmission and ABB HES 880 Inverter.

- **High voltage battery system** consists of: nom. 362V li-ion battery based on 98x Kokam 40 Ah cells and Elithion Battery Management System (BMS), ABB HES choke and ABB HES 880 DC/DC-converter.

- **Low voltage DC-links** 96V and 24V are supplied from the high voltage battery voltage via one directional Powerfinn DC-DC converters with galvanic isolation. Both low voltage DC-links has also own battery buffers; 96V battery is Altairnano’s LTO li-ion battery and 24V battery is traditional AGM SLI battery.

The main target in the Tubridi project was to build research platform for new electric functions like DDH and electromechanical steering. The layout shows electromechanical steering system. However, this topic is left out of scope in this paper. Therefore, the next section introduces main topic of this paper working hydraulics realized with DDH approach.

2.2. Working hydraulics

In the EL-Zon research project the mining loader’s original working hydraulics was replaced with direct driven hydraulics (DDH). **Figure 3** illustrates realization of DDH.
The dimensioning constrains and goals for the DDH drives were:

- To achieve the original performance (speed and linear force) for the boom and bucket functions.
- Volumetric dimensions of the original hydraulic cylinders.
- Small enough to be fitted in to the loaders front frame pockets.

DDH unit is supplied from 96 V DC-link and cooling and brake pump power from 24 V DC-link. Both low voltage DC-Links can be supplied with DC/DC-converters up to 3 kW power from 362 V battery side. The needed power levels in DDH unit is around 20-50kW the average power needed during the work cycle is estimated to be below the 3kW charging power. DDH unit consists of motor, gear and pump/motors:

- **Prime mover**: PMSM ME1304 22.3 kW by Motenergy and Inverter is Sevcon Gen 4 with Size 6.

- **Gear** is based on belt Gates Twin Power GT2 8MGT. Gear rations (down from motor): 1.57 to cylinder side pumps and 1.67 to rod side pump.

- **Pump/motors**: 4 units of PG100-016 (displacement of 15.8 cm³/rev) manufactured by HYDAC connected to Cylinder piston side chamber, respectively, to cylinder rod side 2 units of PGI100-022 with displacement of 22.2 cm³/rev.
3. Modelling

In order to develop the simulation model, at first the main components of a mining loader electro-hydraulic circuit of DDH such as pump, electric motor and cylinder are modeled using Matlab SimScape. These components modeling are based on manufacture data obtained for hybridization of the mining loader.

Table 1 contains used parameters in simulation:

Table 1: DDH simulation parameters:

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor</td>
<td>Continuous power</td>
<td>22.32 kW</td>
</tr>
<tr>
<td></td>
<td>Peak power</td>
<td>51.6 kW</td>
</tr>
<tr>
<td></td>
<td>Maximum speed</td>
<td>6500 rpm</td>
</tr>
<tr>
<td>Cylinder</td>
<td>Rod diameter</td>
<td>88.87 mm</td>
</tr>
<tr>
<td></td>
<td>Cylinder diameter</td>
<td>151.6 mm</td>
</tr>
<tr>
<td></td>
<td>Stoke length</td>
<td>850 mm</td>
</tr>
<tr>
<td>Pump/motor 1</td>
<td>Displacement</td>
<td>63.2 cm³/rev</td>
</tr>
<tr>
<td>Pump/motor 2</td>
<td>Displacement</td>
<td>44.4 cm³/rev</td>
</tr>
</tbody>
</table>

3.1. Model

Based on the modelling of each component, a DDH system was established for lifting and lowering, as shown in Figure 4. The speed reference has a rapid acceleration period, constant speed and deceleration period. The ideal motor block behaves according to the reference signal. The torque is transferred between the hydraulic pump and electric motor with ideal mechanical coupling. Pressure is transferred between the cylinder and the pump. The pump delivers an amount of oil to the cylinder to move the tare and the payload with the motor reference speed. The cylinder block Cylinder simulates the moving of the load during lifting and lowering.
Figure 4: DDH for hybrid mining loader

Figure 5 illustrates the dynamic simulation results: speed, cylinder velocity, and cylinder position for a payload of 4000 kg for created tilting cycle of the bucket.

Figure 5: Simulation results of DDH for hybrid mining loader
4. Discussion

Figure 6 presents initial experimental results: pressure and cylinder position with empty bucket of mining loader with created tilting cycle.

Figure 6: Experimental results of DDH for hybrid mining loader: cylinder position and pressure

Figure 7 presents motor speed and torque with empty bucket with created tilting cycle.

Figure 7: Experimental results of DDH for hybrid mining loader: motor speed and torque
DDH as electrohydraulic actuator allows reducing parasitic losses for better fuel efficiency and lower operating costs. The robust, leak free, one-piece housing design delivers system simplicity and lowers both installation and maintenance costs. A challenge is the increasing number of electric components in the limited volume available in the vehicle. On the other side, the main advantages of this architecture are the reduced hydraulic tubing and amount potential leakage points, the elimination of some hydraulic components, simplified machine assembly and bring along redundancy via motor and controller sensors. The second domain of advantages can be found in decreased demand for cooling of hydraulic oil and amount of hydraulic oil itself on board.

DDH enables using hydraulic actuators independently to each other and creating hydraulic power for those actuators only when needed. This zonal hydraulics concept will cut down operation hours of individual circuit depending of the work cycle. Some actuators, for instance, in the boom used only a few times during few tens of seconds during several minute work cycles. This means operating time ratio is very favorable in terms of cooling, need of service and maintenance as well as overall durability of components and hydraulic oil.

5. Conclusion

This paper contributes to a topical subject application of direct driven hydraulics to series-hybrid powertrains to non-road mobile machinery based on example of mining loader.

The main scientific importance of this paper is the design of complete series-hybrid powertrain and implementation of new design principles.

The degree of hybridization of retrofitted series-hybrid powertrain of mining loader was increased by introducing direct driven hydraulics. The increase is significant compared to more classical hybridization concept, with internal combustion engine and generator vs. one large electric motor and set of hydraulic pumps after supported with batteries or supercapacitors. Direct driven hydraulics benefit system by combining benefits of hydraulics and electric system allowing to utilized separate hydraulic circuit on demand based. This will cut down operation hours of individual circuits especially when considering circuits related to NRMM work cycle where some actuators are utilized in very short periods only.

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