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IMPROVING ENERGY EFFICIENCY OF AN ELECTRIC MINI EXCAVATOR

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Abstract: *Construction takes place increasingly in a city environment, which puts limits to noise and gas emissions produced by construction machinery. In city environment work is also often done indoors, where local emission are not allowed. These requirements forces to use zero emission machinery, for example fully electric machinery. This study aims to improve the energy efficiency of a battery powered electric mini excavator.*
A start & stop logic system was developed to achieve this. The benefits of this system was measured using a test cycle. The cycle was done using the old and the new configuration and the improvement in the operation time proved to be at least 50 % longer than old one.

Key words: mobile machinery, start & stop system

1. INTRODUCTION

Construction takes place increasingly in a city environment, which sets limits to noise and gas emissions produced by construction machinery. In city environment work is often done indoors, where emission are not allowed. Emissions will be strictly regulated by authorities also for heavy machinery. These requirements forces to use zero emission machinery for example fully electric machinery. Following new regulations as early as possible, a company shows out as an environment caring ‘green’ company, which is generally good for business.[1] Furthermore markets are going to be ready for fully electric machinery, which can be seen for example from commercial production of electric busses. [2]
Research in electric power construction machinery has become more active in recent years mainly due to increased emission regulations. Research has been mostly focused on hybrid technologies due to concern of low battery capacities and possibility of conversions from existing diesel powered excavators. Both series and parallel hybrid types have been investigated [3]. Most common type of excavator hybridization is implementing the chassis swing with an electric motor and energy recovery with capacitors or batteries [3]. There have been available a few fully electric powered excavators of varying sizes, though they have had external power supply [2][4][5]. Fully electric or hybrid excavator with separate electric motors for hybrid actuators enables recovering of kinetic and potential energy, which leads to better energy efficiency [6]. However, with battery powered large electric vehicles such as busses having started to prove themselves, there has been increasing interest in full electric battery powered excavators. There also exists a patent from 1999 for a battery powered electric mini excavator with an automatic power control system based on measuring excess hydraulic flow rate [7]. In 2011 Takeuchi released a prototype battery powered electric excavator [8].
High price of large lithium batteries is one of the key factors that slows down generalization of fully electrified mobile machinery [9]. The battery can be as

expensive as a traditional excavator itself, therefore minimizing the battery size and cost without decreasing operating time is important. The price of the batteries will probably decrease significantly in five or ten years, but before that, minimum sized batteries must be used, in order to keep the price of an electric excavator somehow comparable to traditional excavator.

In this study, the main task is to develop a motor control which will use the motor only when needed. This system will be implemented into a mini excavator that was converted to battery electric power from a conventional diesel excavator. The excavator is powered by 10 kW electric motor with power source of a 96 V and 60 Ah lithium-titanium battery. The main benefit of this study is to improve the energy efficiency of the excavator. In this case it means that the operational time of the excavator is extended. With better energy efficiency smaller and cheaper batteries can be used.

The key for saving power in our excavator is to create intelligent controlling system for the electric motor. Several possible solutions on how to implement a start and stop-like control system were considered ranging from measuring changes in pressure during actuator movement, to detection of movement of the control levers. A pressure accumulator was considered to reduce motor start delay. Due to the type of the control valves being open centered, measuring pressure changes proved to be impossible because when the motor and pump are not running there is no pressure in the hydraulic system. The open center valves cannot tolerate high pressure in the center position either. Thus a simpler mechanical system was designed using limit switches. The intelligent controlling system gives also a possibility to collect information for new research and revenue generation models. The benefits of this system will be measured using a test cycle, which imitates an actual work cycle as closely as possible while being easily repeatable. The cycle will be done using the old and the new configuration and the improvement in the operation time should be at least 50 %.

2. METHODS

The excavator is based on JCB 8008 CTS micro excavator. All mechanical functions are powered by hydraulic system. Bucket, beam and dozer extension and retraction operations are driven by several hydraulic pistons. Chassis and tread rotation functions are powered by hydraulic motors. The hydraulic system has 2-section fixed displacement gear pump that is driven by the electric motor. Simplified hydraulic schematic is shown in Fig 1. The power for the electric motor is supplied by DC-AC converter from the lithium-titanium battery pack. The motor is controlled by a ready-made control unit at the back of the excavator.

2.1 The start-and-stop mechanism

The start-and-stop system is implemented with a microcontroller based control. Variables for the microcontroller comes from a cable operated limit switch, which is activated when one or more of the working loop valves of the excavator is opened or closed. The valves are operated by control levers, which by lever linkages move the valve control rods vertically. The working principle of the switch mechanism is described in Fig 2. When one of the main valve control levers is moved, the pivoting lever mechanism pulls a cable, which operates the limit switch. Fork plates in the pivoting levers are connected to the valve control rods and they allow some bending to compensate angular changes. When the limit switch indicates that at least one of the valves is open, the controller starts the motor.

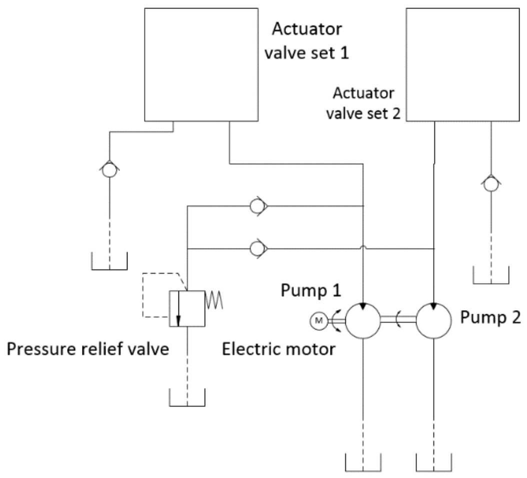

Fig 1. Simplified hydraulic schematics

The controller is set to turn the motor off when none of the valves are open in a brief period of a time. Speed control for the motor is manual because the motor speed is often used to set sensitivity and speed of the analogue controls, which is dependent on the preferences of the operator. Automatically adjusting the motor speed in analogue valve control may result in unwanted or unexpected behavior. In the preliminary basic layout, the pressure accumulator is omitted due to increased cost and complexity of the system. As the electric motor has a sufficiently short start time, it is questionable if a pressure accumulator is needed.

2.2 Measurements

To determine how much energy is saved using this new control logic system, a test cycle was developed. There were two main points when planning the test cycle. First of all, the test cycle has to be simple enough to carry out and easy to repeat multiple times. Secondly, the test cycle has to be similar to a common work cycle when excavator is used at construction site. This means beam movements, driving forwards, turning the cabin and idling. The work cycle was created by thinking a regular work period and operating the excavator manually. The test cycle consisted in total of nine steps:

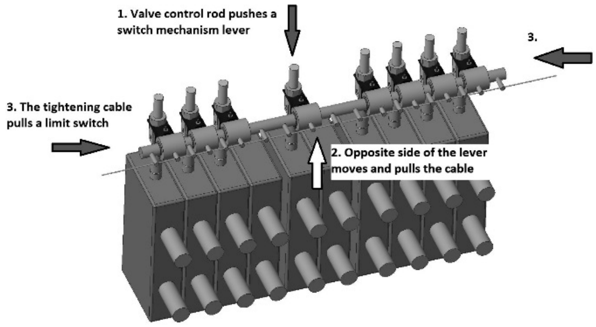

Fig 2. Concept model and operating principle of the switch mechanism

1. Driving forwards 22 meters
2. Idling for 5 minutes
3. Lifting and moving the weight twenty times
4. Idling for 5 minutes
5. Lifting and moving the weight twenty times
6. Idling for 5 minutes
7. Lifting and moving the weight twenty times
8. Idling for 5 minutes
9. Driving forwards 22 meters

In steps 3, 5 and 7, mass of the weight used was 90±5 kg. The weight was lifted from ground level to 1 m upwards. After lifting, beam of the excavator was turned 90 degrees. Then the weight was lowered down to ground level. Performing this step takes time approximately 5 minutes.
Changes made to the excavator influence only to idling. Therefore, idling was measured with original system and full test was done with new system. All measurements were done outside on even ground paved with asphalt. Temperature outside was approximately +5 °C and asphalt was slippery but this did not affect the measurements. The energy consumption was logged by the microcontroller.

3. RESULTS

In this study an electrified excavator was upgraded by adding start and stop feature to it. The conversions made to excavator only affects to idling period. Therefore, modified excavator was able to perform as well as the excavator before conversion. Table 1 shows battery voltage, stage of charge (SOC), discharge and calculated energy consumption for each measurement of the test cycle done by excavator with new system. Battery charge consumption of idle use for 5 minutes was measured separately and the result was 0.7 Ah/5 min. Saved energy highly depends on how much idling there is in working cycle. Our estimate is that at least 50 percent is idling when working with excavator. Especially, when working indoors where more time is used on planning where and how to use excavator or waiting for dumper to carry excavated material away. In test cycle showed in measurements paragraph, idling takes approximately half of the time used. The charge consumption of original system was calculated by replacing zero consumptions of idling cycles by measured idling consumption of 0.7 Ah/5min. Thereby with similar cycle the original system would have consumed charge of 8.8 Ah and the charge saving is now 32 % with the new system. The energy saving is the same at 32 % when calculated with average voltage during the cycle.

Table 1. Energy consumption during the test cycle.

Step	**Voltage, (V)**	**SOC, (%)**	**Discharge, (Ah)**	**Energy used, (kWh)**
At start	96.4	83.0	-	-
1	96.1	82.2	0.5	0.05
2	96.1	82.2	0.0	0.0
3	95.0	78.4	2.0	0.19
4	95.0	78.4	0.0	0.0
5	94.2	75.5	1.6	0.15
6	94.2	75.5	0.0	0.0
7	93.0	70.8	1.4	0.15
8	93.0	70.8	0.0	0.0
9	92.5	74.8	0.5	0,05
In total			6.0	0.58

4. CONCLUSION

New system saves a lot of energy with relatively low costs. An objective for this study was to degrease energy consumption by 50 percent. The objective was not achieved as it was shown in results. However, the results highly depend on how much idling is assumed to be in working cycle. In the end, by decreasing energy consumption it is possible to use smaller capacity battery. With 26 % charge usage saving it is possible to use 40 Ah battery instead of current 60 Ah battery without decrease in operating time. The difference in cost is remarkable.

For future studies there is possibility to upgrade system to be even more intelligent. For example the motor control could be improved so that motor speed changes depending on how much hydraulic power is needed. Also more sophisticated hydraulic system with pressure accumulators should be considered.

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