Final report

1.1 Project details

Project title	EMoCrane
Project identification (program abbrev. and file)	EMoCrane – Energieffektive mobile kraner. Journalnr.: 64012-0233
Name of the programme which has funded the project	EUDP 12-II
Project managing company/institution (name and address)	Banke Accessory Drives ApS Nordborgvej 81, 6430 Nordborg
Project partners	Syddansk Universitet Danfoss Power Solutions
CVR (central business register)	DK32773974
Date for submission	20170630

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1.2 Short description of project objective and results

EN:

The project has demonstrated that all considered objectives, within the overall scope of efficiency improvements of mobile cranes, can and will, individually or combined, lead to substantial efficiency improvements.

The industrial participants have partly already brought project results to the market giving additional turnover and customer awareness, partly plans marked introduction and production scale-up in 2018-19.

SDU furthermore also use the project results as part of teaching activities within power electronics.

The project results do not only result in reduced energy consumption, but also enables a shift towards renewable sources, noise and heat reductions, and air pollution reduction both globally and locally around the crane vehicle.

DK:

Projektet har demonstreret at alle de opstillede målsætninger om mere energieffektive mobile kraner kan og vil blive opfyldt, både enkeltstående og i kombination, hvorved væsentlige effektivitetsforbedringer opnås.

De industrielle deltagere har dels allerede bragt produkter, som resultat af projektet, på markedet, dels planlægges introduktion og produktions-skalering i 2018-19

Endvidere bruger SDU projektresultaterne som led i undervisningen indenfor power electronics.

Resultaterne vil, ud over et reduceret energiforbrug, også muliggøre et skift til fornyelige energikilder, reduktion af støj og varme og endelig en reduktion i luftforurening, både i global sammenhæng, og lokalt omkring køretøjet.

1.3 Executive summary

Many of the technologies and principles developed and demonstrated within the project will directly give improvements in crane efficiency and as such create additional business for the industrial partners.

Furthermore, the project has also demonstrated additional efficiency improvement potentials, both from combining the individual developments, and from taking the results from the PhD project to an industrial level.

The project partners feel confident this has the potential to create even further commercial business and research results.

1.4 Project objectives

General:

The project is divide into 3 main objectives, 1) energy optimization of electronic converters, 2) energy harvesting in hydraulic valves for cranes, and 3) modular battery based energy source for truck mounted cranes including how to feed harvested energy to said batteries.

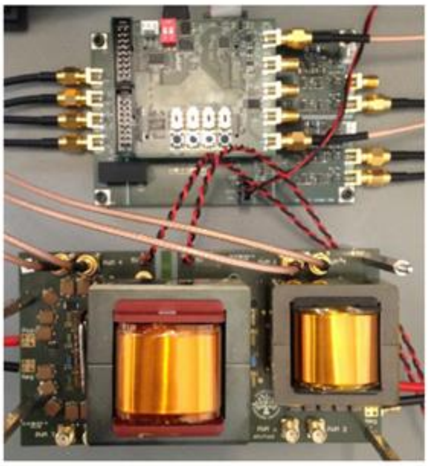
All 3 main objectives have been implemented during the project period and individually demonstrated, whereas a compilation/merge of the 3 objectives is to be done.

Despite this, the project has created openings for specific product developments and commercialisations which has been utilized with very positive results.

Detailed objectives description:

Digital control of DC-DC converters for energy efficient battery chargers.

Traditionally dc-dc converters for battery chargers have been controlled using analog techniques due to the high bandwidth requirement of the control loop, which is needed in order to minimize the overall dc-dc converter size and cost. However, since the control circuitry of an analog controller suffers from aging, component tolerance and temperature drift, the interest in digital control of dc-dc converters has increased. One of the challenges with digital controllers for dc-dc converters is the high bandwidth needed to ensure a fast response during load changes. The bandwidth in a digital controlled system is reduced by measurement, sampling and calculation delays. Increasing the bandwidth of the dc-dc converter can result in smaller input and output filters and thereby have the potential to decrease the overall dc-dc converter size and cost. Furthermore, to obtain efficient switching and minimizing converter loses in e.g. Zero Voltage Switching converter, precise timing is required. Digital control of dc-dc converters have the potential to increase the overall performance and create a dc-dc converter for battery chargers with increased efficiency, robustness and flexibility compared to an analog controlled system.



Energy efficient valve for truck mounted cranes.

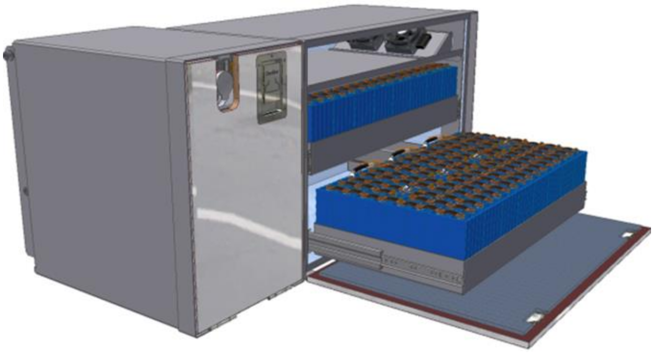
Current mass market hydraulic valves in truck mounted cranes use a single spool for flow control and a hydraulically controlled secondary spool for compensation. This arrangement leads to loss of energy as the compensation spool requires a constant pressure drop independent of load. In this project, we have adapted a new design for use with truck mounted cranes. The two spool valve enables independent control of flow in and out of the cylinders on the crane arm, making it possible to have minimal pressure drop across the spools and thus reducing energy loss.

In order to use this valve with truck mounted cranes it is necessary to design a manual override system for safe operation in case of pressure loss.

Battery based energy source.

Truck mounted cranes currently use the traditional, in most cases diesel, chassis thermal engine to create the power needed to operate the hydraulics of the crane. This has several limitations, the root energy source is fossil fuel, noise level is high due to continuous engine operation, energy harvesting from the crane is limited, in many cases impossible, and emissions of CO_2 and potentially harmful products from engine exhaust cannot be avoided.

In this project we have demonstrated that these limitations can be substantially overcome by adapting a battery based power source for crane operation.



1.5 Project results and dissemination of results

A demonstrator for a full electric battery powered 20 tm truck mounted crane has been developed and field tested with good results.

This demonstrator also comprises a fully electronic solution for recharging the battery from vehicle, using the existing propulsion diesel engine and when available also small scale surplus kinetic energy.

During these field trials, analysis of measurement data led to the assumption that implementing some form of electronic torque control of the hydraulic pump might expand the application field and lead to further energy and noise optimizations.

Such electronic torque control was developed and field tested on a bigger truck mounted crane (30 tm) where the results confirm above mentioned assumptions.

To enlarge the re-charging option another solution with a direct driven generator was developed and demonstrated on 2 different vehicles, however of logistical reasons not demonstrated on crane trucks but on refuse trucks, but this has no influence on the results. All developments and demonstrations have been made in the project period including the normal modifications and adjustments, known in most product development projects.

All demonstrations have gone through further product development and are all now introduced to the marked as new products, both for crane and refuse truck application, and have been positively received by the customers.

Estimated sales in 2018 is 4 mill DKK with an export share of approx. 80%, and expanding staff with one additional FTE

Above mentioned direct driven generator solution is an effective way of harvesting surplus mechanical energy. The valve has been designed and tested on a crane. The two-spool design has been shown to not only allow lower pressure drops in the normal operation, but in addition it has been demonstrated that it is possible to take advantage of pressure intensification in the cylinder to recirculate oil from the low-pressure side to the high-pressure side (regeneration). Side-by-side comparison with a traditional hydraulic valve shows an energy saving of 17% in a representative work cycle.

In addition to saving energy by reducing loss, it is also possible to reclaim (harvest) energy when gravity induced pressure is used to push oil flow into a hydraulic driven generator. Calculations based on the representative cycle indicate that 2% energy can be reclaimed using this method.

To make the valve feasible on truck mounted cranes a manual override has also been designed. This has been shared with a potential customer and judged acceptable as a safety feature.

Exploiting the full potential of changing to electric energy domain opens a discussion of efficiency electric power conversions. A battery charger has been chosen as object for this discussion on PhD level.

The PhD project has demonstrated that it is possible to use digital control of dc-dc converter for energy efficient control of battery chargers. A FPGA based digital controller platform for control of dc-dc converters has been developed during the project period. The platform has been used for testing new digital control strategies, but can also serve as base for future battery charger prototypes, since the platform is created in a modular way, which support easy, update or replacement of modules. The digital controller platform supports different types of converter topologies, including Zero Voltage Switching of isolated full bridge converters, different switching frequency and control strategies. Additionally, an accurate switch cycle simulation model, which includes dc-dc converter parameters variations, such as output filter inductor variations has been developed during the project. The simulation model were used during the project period for testing and validation of new control strategies. The PhD project has demonstrated that digital control of dc-dc converters can achieve high bandwidth comparable to analog control of dc-dc converters. Furthermore, the project has shown theoretically and experimentally, the advantages of using digital control for controlling current loop stability in dc-dc converter over a large operating range by use of adaptive slope compensation. Additionally, the project has demonstrated that use of current prediction in a dc-dc converter can, depending of dc-dc converter topology, increase the duty cycle range compared to analog control. A large duty cycle range is important in order to utilize the converter operating range, increase transient response and minimize output filter components. In isolated full bridge dc-dc converters used for battery chargers, capacitors in series with the primary transformer winding or an air-gab in the transformer is typically used in order to prevent transformer saturation in digital controlled converters. Adding capacitors will increase cost and size of the converter and adding an air-gab will lower the efficiency of the converter. The project has demonstrated it is possible, when using a digital controller, to avoid the capacitor and transformer air-gab, by using a mathematically model of the transformer magnetizing and only measuring the primary transformer current. Furthermore, it is planned to demonstrate secondary side digital control of isolated full bridge buck dc-dc converters by only sensing the primary transformer current. Using one current sensor compared to two, that are normally used, will lower cost and potential increase the efficiency of the converter, since adding an additional current sensor can interfere with crucial layout of the converter in order to archive high-energy efficient converters.

Conventional crane system

Subsystem: Diesel engine
Efficiency: ~ 35%

Pump – Valve – Cylinder/motor
~ 70%

Total efficiency: ~ 25%

EFFICIENCY	Conventional	EMoCrane	EMoCrane new converter
Thermal engine	0,35		
Charger		0,88	0,99
Battery		0,997	0,997
Inverter		0,98	0,99
Motor		0,9	0,9
Pump-valve-cylinder/motor	0,7	0,85	0,85
Total efficiency from tap/grid to work	**0,25**	**0,66**	**0,75**

EMocrane system

Subsystem: Battery – Inverter/el-motor
Efficiency: ~ 89%

Pump – Valve – Cylinder/motor
~ 85%

Total efficiency: ~ 75%

SDU Banke ACCESSORY DRIVES ENGINEERING TOMORROW

1.6 Utilization of project results

Knowledge from the PhD project has been adopted in projects and teaching activities on both bachelor and master level including a control course where control of dc-dc converter is a main course activity. The results from the PhD project has been presented on international conferences such as the European Conference on Power Electronics and Applications (EPE) and IEEE Southern Power Electronics Conference (SPEC) during the project period.

Articles related to the PhD project:

- Predictive Digital Peak Current Mode Controller with Inductor Inductance Estimation for DC-DC Converter.
- Adaptive Digital Current Mode Controller for DC-DC Converters.
- Flexible experimental FPGA based platform: For testing and verifying digital controlled DC-DC converters.
- Predictive Digital Peak Current Mode Controller for DC-DC Converters Capable of Operating Over the Full 0-100% Duty Cycle Range.
- Digital Peak Current Mode Control with Adaptive Slope Compensation for DC-DC Converters.
- Estimating and Balancing Transformer Magnetizing Current in an Isolated Full Bridge Buck converter (under review)
- Digital Control of ultra-high efficient Isolated Full Bridge Buck Converter (Planned)

The valve has been delivered to a possible customer for testing and expectation is that it will go into production some time in 2019, a lower specified version not suitable for cranes has been released this year. 4 patents have been published for technologies developed in this project, and all are part of the product offered.

The demonstrated conversion to battery based energy source of cranes has already created commercial results, which has initialed an updated business plan showing continued growth within the crane segment 2018 and forward.

All aspects of this project have demonstrated to give CO_2 reductions seen from several aspects.

Improved efficiency; -of electric conversion, -of hydraulic valves, -of power chain from source to torque.

Energy savings; -from above mentioned efficiency improvements, -from re-using pressure in return oil in hydraulic valve, -from eliminating idling loss since the electric solution runs idle-free.

Energy harvesting; -since the battery is a large-scale reservoir that will never limit the storage available for recuperated energy.

Energy source conversion; -since the batteries can, and in many cases already will be, charged from renewable sources like wind turbines and photovoltaics.
As an example; a battery powered crane will save approximately 8 l diesel pr. day, and 20 kg CO_2, just from being battery powered.

1.7 Project conclusion and perspective

We expect the technologies demonstrated to spread more generally to many energy demanding heavy duty mobile applications, examples could be sweepers, implement carriers, concrete mixers, mobile reefers etc.
Also, more specialized applications like forestry machines and mining machines are expected to move towards efficient, electrical and battery powered technologies.
Furthermore, on component level, we also expect the demonstrated technologies and principles to lead to even more energy efficient electronic and mechanical products.

Annex

- List of patents.
- Article from "DTL Magasinet" September 2015.
- PhD project: Hardware and experimental setup
- SDU presentation from meeting 20170627
- DPS presentation from meeting 20170627
- BAD presentation from meeting 20170627