

Self-Learning Control Strategy for Electrified Off-Highway Machines to Optimize Energy Efficiency

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ABSTRACT

The electrification of off-highway machines are increasing significantly. Advanced functionalities, beneficial energy efficiency and effectiveness are only a few advantages of electric propulsion systems. To control these complex systems in varying environments intelligent algorithms at system level are needed. This paper addresses the topic of machine learning algorithms applied to off-highway machines and presents a methodology based on artificial neural networks to identify and recognize recurrent load cycles and work tasks. To gain efficiency and effectiveness benefits the recognized pattern settings are applied to the electric propulsion system to adjust relevant parameters online. A dynamic adaption of the DC-link voltage based on the operating points of the machine processes is identified as such a parameter.

CITATION: Pohlandt, C. and Geimer, M., "Self-Learning Control Strategy for Electrified Off-Highway Machines to Optimize Energy Efficiency," *SAE Int. J. Commer. Veh.* 8(2):2015, doi:10.4271/2015-01-2831.

INTRODUCTION

The electrification of conventional powertrains in off-highway machines are increasing significantly. Due to stricter environmental responsibilities and a high demand for efficient and effective propulsion systems for complex and wide range machines, electric components are utilized.

A propulsion system for off-highway machines addressed in this paper is designed to provide power to fulfill a work process and to move the machine. This kind of propulsion architecture is representative for agricultural machines like tractors and combines, for construction equipment like wheel loaders and excavators but also for commercial vehicle like garbage trucks and forklifts.

Conventional propulsion systems like mechanic or hydraulic powertrains are operated at their limits. Besides measures to increase efficiency benefits, the gain of effectiveness needed to be taken into account for the defined off-highway machines. Electric propulsion systems fulfill these requirements and are excellent efficient and effective propulsion systems. Compared to conventional drivetrains electric propulsion systems add advantages like higher efficiency and better controllability to the drivetrain. Due to the increased dynamic of electric machines advanced functionalities raises accuracy, quality and desired work process results. Electric propulsion systems offer the implementation of high controllable, high efficient and effective smart operating strategies.

This paper will make a contribution towards a generic smart self-learning strategy to raise the work productivity of the machines and to increase the efficiency at the same time.

Section I will introduce the propulsion system considered in the paper and point out the specific demands of off-highway machines. Section II introduces considerations regarding efficiency and effectiveness of electric propulsion systems. Appropriate measures to optimize the system are discussed and individual aspects of minimizing power losses are demonstrated. Section III addresses these optimization considerations and infers a control strategy at the system level. Section IV explains the implemented learning algorithm based on artificial neural network to be adapted to control the propulsion system. A multi-layer perceptron network is trained by predefined load cycle classes of desired work processes to predict upcoming events and to take efficiency measures at system level. Section V presents the results and advantages of load cycle prediction using artificial neural networks as a smart operating strategy. A conclusion is summarized in section VI.

SYSTEM OVERVIEW

The powertrain topology of an off-highway machine referred to in this paper is a serial-hybrid powertrain with two main energy pathways, see figure 1. One is powering the main work functionalities of the machine, whereas the other one is powering the driveline. A diesel engine and a Li-Ion battery pack are providing the required energy. The electric system topology is build up as a DC-link voltage

bus with an adjustable voltage level. The diesel engine is attached to a generator/inverter system and operates as an integrated range extender module including a controller. The battery pack is supervised by a top level battery management system monitoring all safety critical and in-use parameter. A DC/DC converter connected between battery pack and the DC-link voltage bus ensures a controlled and defined DC voltage level. Furthermore two inverter-fed electric machines are powering the driveline and the work functionalities.

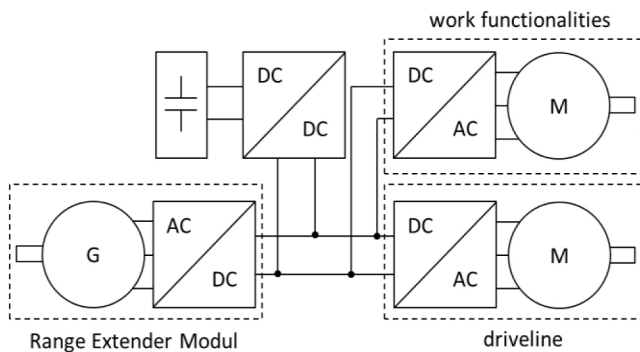


Figure 1. System layout of the electric components with the main power pathways for work functionalities and driveline.

The converters and the inverter can be operated bidirectional so that the system can handle multiple operating strategies. The energy can be recuperated using the electric machine in the driveline and in the work functionalities. This energy can be directed to the battery pack. Also the range extender module can be used to load the battery. Furthermore short time excess energy can be regenerated directly through the driveline and the work functionalities without buffering in the battery pack. To gain efficiency benefits on the range extender module the operating strategy of the diesel engine can be shifted towards a single point operation at the lowest fuel consumption area. Also the losses of the electric machines and their inverters can be reduced by shifting the points of operation towards areas of high efficiency and adjusting relevant parameter at the system level. Therefore the total system losses of the serial-hybrid powertrain are relevant and have to be taken into account. The system boundary according to Fig. 1 divides the powerflow into two main pathways, one for the work functionalities and the other one for the driveline. The boundaries for consideration of effects are the mechanical output power at the shaft of the electric machines. Additional components like gearboxes or the tire-ground interaction are considered as they effect the mechanical output power.

EFFICIENCY CONSIDERATIONS

Conventional powertrains for the mentioned off-highway machines are operated at their limit. To increase the effectiveness of the work process, for example the farmed acres per hour or the handled tons per hour, advanced powertrain topologies are needed. To optimize the efficiency and the effectiveness at the same time intelligent machine learning algorithms are needed. Electric propulsion systems meet these requirements and guarantee a precise high controllable propulsion system.

The overall system efficiency depends on the power losses of single hardware components like the inverter or the electric machines. These system losses are depending on the current operating point of the machine. Single power losses are summed up to the system losses, meaning individual power losses at component level do not indicate best efficiency operating areas to the entire powertrain. To optimize the total system efficiency decreased single component losses can be accepted with respect to the system losses.

Adding a DC/DC converter to the powertrain instead of coupling the battery pack directly to the DC-link adds significant benefits to the system. Especially for high performance applications like heavy off-highway machines with a high demand on torque and speed at extended load cycle time series the adjustment of the DC-link voltage increases the system efficiency [1]. Furthermore the effectiveness of the work process is increased by pre-powering up the DC-link voltage level to provide high dynamic and beneficial response characteristics to the work functionalities.

Therefore the performance of the whole machine has to be taken into account to gain an accurate and acceptable work process. Since the driving function is a part of the work process the desired intention of the machine are the work functionalities. Shifting power from the driveline to the work functions may increase the effectiveness of the work process.

A conventional DC/AC converter provides a lower output voltage than the applied voltage of the battery pack and thus at the DC-link. The DC-link voltage depends directly on the state of charge of the battery pack. Adding a DC/DC converter to the drivetrain would detach the battery voltage level from the DC/AC converter input voltage and consequently from the input voltage of the electric motor. Moreover the DC-link voltage is available as additional degree of freedom in the propulsion system. The DC-link voltage can buffer remaining energy a certain time. Thus a DC-link voltage drop caused by high dynamic load shifts can be avoided while high power at the motor is needed. But also the DC-link voltage level absorbs remaining energy during recuperation or regeneration. Therefore the voltage level needs to be reduced prior to the change of power request. The adaptation of the DC-link voltage enables advanced control algorithms on system level concerning smart energy management algorithms.

To provide equivalent power at the electric machines an increased DC-link voltage level requires reduced currents and thus the copper losses in the machine windings are reduced. Rising up the DC-link voltage level above the battery voltage level reduces the overall system losses due to decreased electric machine losses and decreased inverter losses [2] [3].

In general electric powertrains offer the capability to optimize the system regarding to energy efficiency and work process effectiveness by adjusting well-chosen system parameters. The DC-link voltage is such a parameter. Since the load cycles varies under dynamic load conditions, the optimal setting are depending on the operating point of the machine and have to be adjusted by an online algorithm.