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Energy Management of the Hybrid Electric Wheel Loader

Mustafa Karahan
HIDROMEK Research and Development Center

Abstract: In recent years, the design and development of battery or hybrid electric vehicles that work with high efficiency instead of conventional vehicles with internal combustion engines have been very popular, and a lot of vehicle and machine manufacturers are focusing on these kinds of projects and research. In developed countries, electric construction machines are already in use in urban areas. Electric or hybrid vehicles have not only less or zero carbon emission but also less noise emission. In this study, the energy management system of a hybrid electric wheel loader is described. The algorithm of the energy storage system is designed with energy recuperation. In this vehicle, supercapacitors are used to store energy and recuperation. There is no electric battery except 24 V of the local engine batteries. The pros and cons of supercapacitors are mentioned by comparing them to lithium batteries. Power and energy calculations of the supercapacitors are described. This study also provides a valuable approach to fully electric construction machinery. The energy management of a vehicle is quite significant to have better efficiency and less fuel consumption for hybrid electric vehicles. In vehicles with conventional internal combustion engines, some amount of energy is converted to heat energy to slow down or stop the vehicles by the brake system. In this study, some of the energy, called regenerative brake energy, is stored in supercapacitors to use later in the systems.

Keywords: Energy management, Electrification, Hybrid electric construction machinery, Supercapacitors

Introduction

Hybrid Electric Wheel Loader

Hybrid electric driveline is one of the ways to increase the efficiency of vehicles and reduce fuel consumption and carbon emissions. This study is based on a real electrification development project of the wheel loader. The vehicle which is described in this study, the primary energy provider is the generator driven by the engine.

In conventional wheel loaders with internal combustion engines, the energy coming from flywheels of engines is transmitted to drivelines by torque converters, which have 70% efficiency. This means the other 30% is wasted as heat energy and released into the atmosphere. Due to the vehicles' operation conditions, connecting engines to the driveline is not a safe and proper solution. This system does not need a torque converter between the energy source electric motors and the driveline. The electric motors are able to drive the powertrain directly.

The diesel engine drives the generator to provide energy to the system. The separate electric motor drives the implementation and fan pumps. Although the primary energy source is the generator, the supercapacitors store the regenerative brake energy and provide high instantaneous energy demand, which is very common for wheel loader operational conditions. Thus, it is possible to run the diesel engine in a highly efficient range.

Driving separately the electric motors of the powertrain and hydraulic systems improves the overall efficiency. Besides these, avoiding engine speed fluctuation contributes to efficiency. The main focus of this electrification project is increasing energy efficiency and reducing fuel consumption and exhaust gas emissions. The overall layout is shown in Figure 3.

- Selection and peer-review under responsibility of the Organizing Committee of the Conference

Parallel Hybrid Topology

In parallel hybrid vehicles, the engine drives the generator as well as the drive train and hydraulic system. This means the engine is mechanically connected to both the generator and energy consumers. For wheel loader implementations, this solution is a less efficient, however cost-effective solution. Parallel hybrid topology is shown in Figure 1.

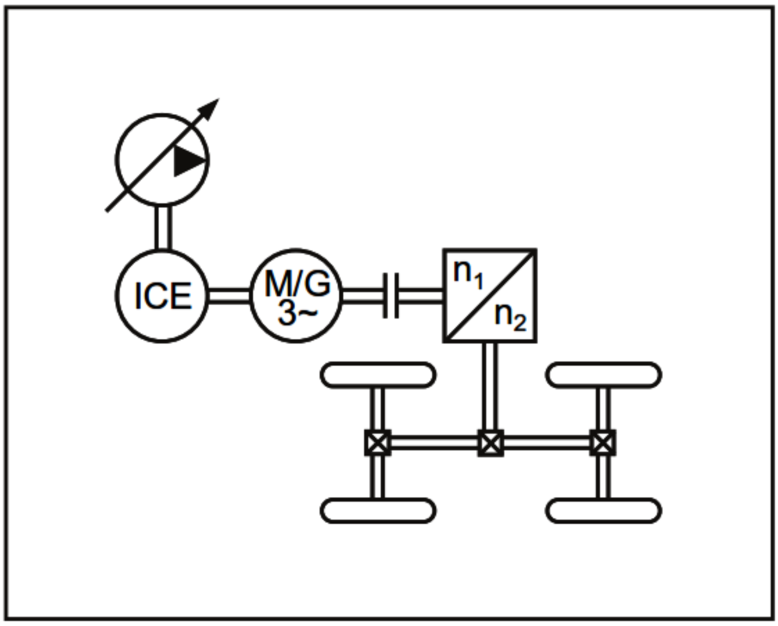

Figure 1. Parallel hybrid topology

Serial Hybrid Topology

There is no direct mechanical connection to the drivetrain, implement, and steering hydraulic pumps. Especially for construction equipment such as wheel loaders, serial hybrid topology brings advantages such as higher efficiency, less fuel consumption, and carbon/noise emissions. Parallel hybrid topology is shown in Figure 2. In this study, a serial hybrid topology has been used to develop the overall vehicle layout.

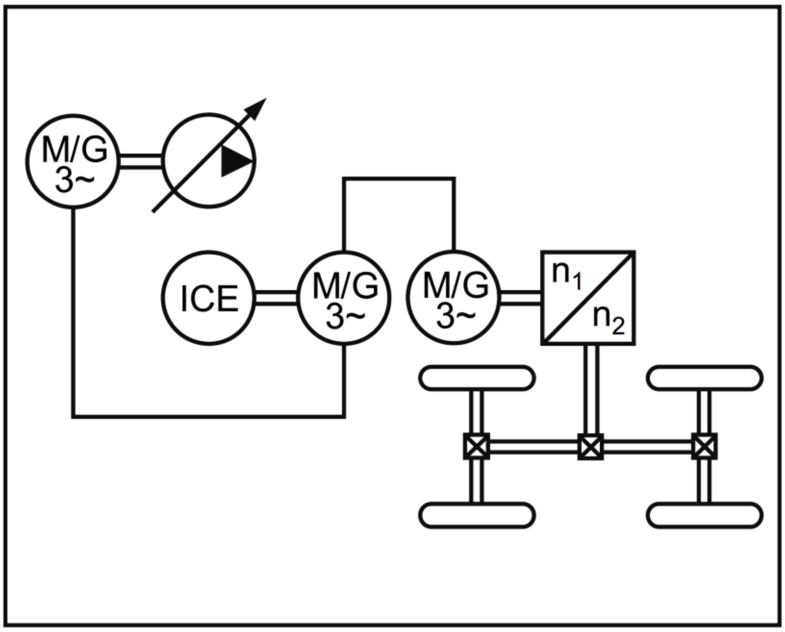

Figure 2. Serial hybrid topology

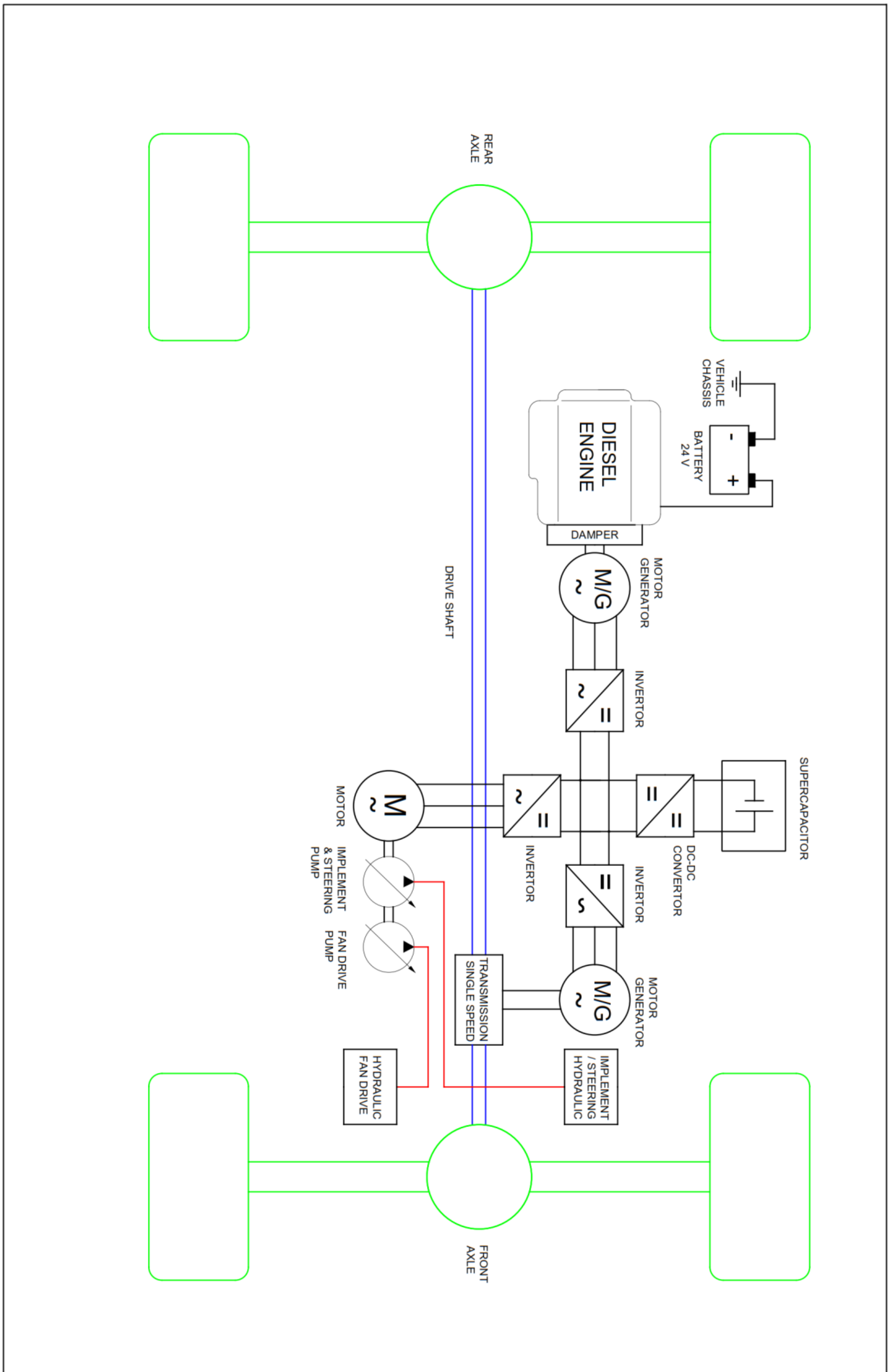

Figure 3. The overall layout of hybrid electric wheel loader

Electronic Brake System

In conventional vehicles, a hydromechanical brake system is used to slow down or stop vehicles. The hydromechanical brake system consists of a mechanical pedal and a hydraulic system. It doesn't have any electronic control equipment. An electronic brake system can manage vehicle brake systems through electronic signals and software. New-generation electric vehicles need this kind of electronic controls to improve efficiency. The electronic brake system provides sufficient and efficient management to the regenerative brake system. Meanwhile, not only in electric vehicles but also in autonomous vehicles, the system plays a crucial role.

The electronic brake system consists of a hydraulic pump providing the hydraulic power, an electronic pedal that detects the brake signals from the operator, an electronic control unit that includes the software according to the algorithm, a proportional electronic dual brake valve, accumulators, and accumulator charge valve which stores some of the hydraulic energy.

Energy Management and System Algorithm

Energy management plays a very significant role in electric vehicles or construction machines to improve efficiency, reduce energy consumption, and increase range or duty period. With recent technologies, energy management is carried out by sophisticated algorithms and software. Only by improving the software of electric vehicles, not changing the hardware or equipment, overall efficiency can be improved highly.

One innovative way of this study is developing an algorithm to run vehicle energy efficiently. The algorithm determines the conditions when regenerative brake energy is obtained and when the supercapacitors are charged. By means of the electronic brake system, regenerative brake energy is managed successfully and efficiently. The regenerative energy is based on running the traction motors as a generator to the obtain energy from the brake system instead of converting the heat energy. The system works through detecting the brake signal. The energy management system detects the charge level of the energy storage package of supercapacitors and decides whether the package needs to be charged or not. For safety reasons and emergency conditions, the system must know the signal status and determine the charging strategy.

Supercapacitors can be charged by the generator to the defined level to meet the vehicle's short-time peak power demands so that the engine can work at a highly efficient torque and speed range. Due to the limited energy storage capacity of the supercapacitors, after they are charged to 100%, the main energy provider generator runs as a motor to meet the engine's parasitic losses and the energy demand of auxiliary equipment such as air conditioning and cabin electricity. Running the primary energy source generator as a motor is considered state-of-the-art. The working algorithm of the energy management system is shown in the Figure 4.

Energy and Power Calculation of Supercapacitors

Supercapacitors are called with their capacitance Farad. In engineering, energy and power units are used for comparison. (1) and (2) formulas describe the calculation of energy and power calculation of supercapacitors.

C	: Capacitance [F]
ESR	: Equivalent series resistance [mΩ]
V	: Voltage [Volt]
E	: Energy [Wh]
$P_{max.}$	: Maximum power [kW]

$$E = 0.5*C*V^2 \quad (1)$$

$$P= V^2/4*ERS \quad (2)$$

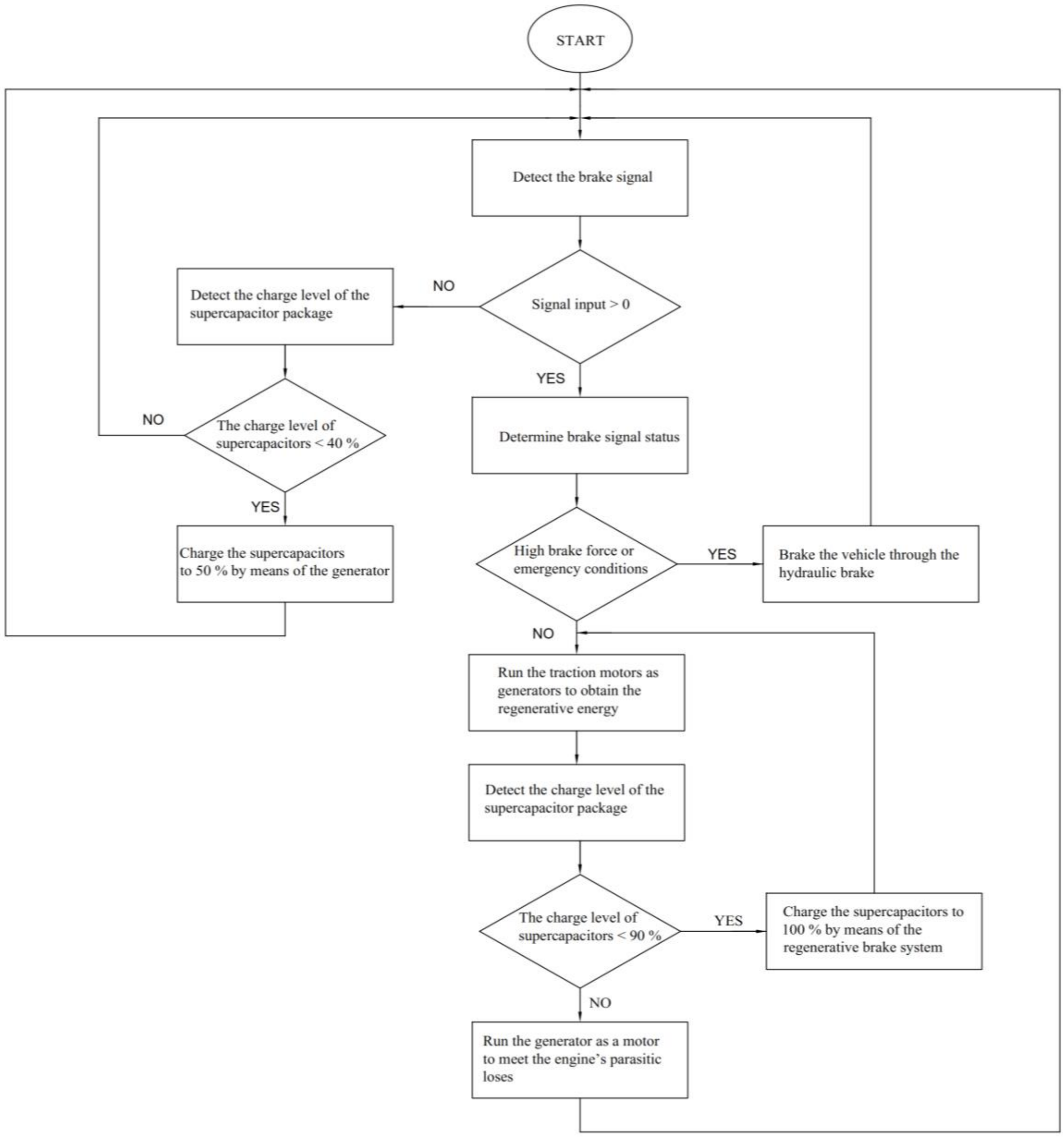

Figure 4. Working algorithm of the energy management system

Table 1. Comparison between supercapacitors and lithium batteries

	Supercapacitors	Lithium Batteries
Operating Temperature, °C	-40 / +70 (85)	-20 / +40
Cycle Life	> 1.000.000	3.000 – 10.000
Calendar Life, Year	5 - 20	3 - 10
Energy Density, Wh/L	1-10	250-650
Power Density, W/L	1.000- 10.000	850-3.000
Efficiency, %	> 98	80-90
Charge Rate, C/x	> 1.500	< 40
Discharge Time	Seconds or Minutes	Hours
Voltage Output	Variable	Constant
Self-Discharge	High	Low

Pros and Cons of Supercapacitors

Supercapacitors have become prominent with their high efficiency, long service life, extensive operating temperature range, short charging time, high instantaneous power, and current capabilities. On the other hand, compared to lithium-ion batteries, their disadvantages are low energy density, changing voltage output, and high self-discharge. The comparison is shown in the Table 1.

Conclusions and Recommendations

Why conventional wheel loaders with internal combustion engines are energy inefficient, and their reasons are explained. The working algorithm of the hybrid electric wheel loader has been created. Supercapacitors have high power density. However, their energy storage amount is relatively low. With several aspects, supercapacitors and batteries are compared. In this study, the working strategy of the regenerative brake system is described, and the charging strategy of the supercapacitors is defined. In which cases, the traction motors run as generators, and the generator runs as a motor are defined.

For on-road and off-road vehicles, it is recommended to use supercapacitors and batteries together. Significantly, the regenerative braking system can cause stresses and thermal runaway on lithium batteries and can reduce their lifetime. Thus, the better approach for the regenerative braking system is using supercapacitors to store the regenerative energy. Supercapacitors are capable of charging and discharging continuously with a high-power rate without thermal runaway.

Scientific Ethics Declaration

The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the author.

Acknowledgements or Notes

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Author Information

Mustafa Karahan
HIDROMEK, Research and Development Center
Ahi Evran OSB mh. Osmanlı cd. No:1
06935 Sincan – Ankara / TURKEY
Contact e-mail: mustafa.karahan@hidromek.com.tr

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