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Design and verification of the methodology for determining the hybrid drive architecture for groups of mobile working machines

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ABSTRACT

In their quest for better economic and environmental parameters, manufacturers of mobile work machines are pioneering new machine propulsion principles, including hybrid drives. The potential of these hybrid drives to significantly reduce fuel consumption and exhaust emissions and to meet the stringent environmental requirements of EU legislative activities is a promising development. Current experience confirms that the above-mentioned approach in the drive concept is also relevant in this machine group. The paper delved into the possibilities of implementing hybrid drives in the construction of mobile work machines, the specification of their selection criteria, the appropriate drive architecture, and the creation of a comprehensive methodology for the design of the type of hybrid drive for a specific group and type of mobile work machine.

Keywords: hybrid drive, hybridization factor, excavator, duty cycle.

INTRODUCTION

Users of mobile work machines (hereinafter referred to as MPS) are increasingly demanding a reduction in operating costs and a negative environmental impact. The urgency of this demand is underscored by the prepared legislation and already valid regulations and standards, which prioritize the reduction of greenhouse gas emissions generated during the operation of machines. These facts are enshrined in the documents of the IPCC [1] and UNEP [2], whose mission is to provide scientific, technical and socio-economic information from the perspective of adverse climate change. For mobile work machines, the priority is to solve these problems, mainly by reducing fuel consumption.

With their inherent adaptability, hybrid drives are considered a relevant solution regarding the advantages and disadvantages of available drive methods for reducing fuel consumption and emissions in mobile work machines. The high-performance demands and variability of work cycles in mobile machines create specific requirements for selecting and arranging hybrid drive systems. The thesis thoroughly analyzed various possibilities for implementing hybrid drives and set criteria for their selection based on work cycles and the needs of individual types of machines.

Hybrid drives are innovative solutions that combine an internal combustion engine and an electric drive, allowing for more efficient energy use during operation, as discussed in [3]. Within the framework of mobile work machines, three basic concepts of hybrid drives are used: series, parallel, and combined hybrid, as presented by Procházka et al. [4]. Each of these concepts offers unique advantages depending on the working conditions and requirements of the specific machine.

The main advantage of hybrid drives is the ability to recover energy during breaking or load reduction, which can be stored in the energy storage and used for work cycles requiring higher power, as presented in [5]. This technology contributes to reducing fuel consumption and emissions while improving the overall efficiency of the working machine. In addition, Li and Zhao [6] mentioned that electric motors minimize noise, vibration and other environmental impacts, which are especially beneficial when working in urbanized areas.

He and Jiang [7] presented that the disadvantages of hybrid drives are higher initial acquisition costs and more complex maintenance than traditional drives. However, according to Lin et al. [8], the return on investment is influenced by the type of machine as well as the intensity of its time and power use.

According to Conway et al. [9], hybrid drives are expected to play a key role in the transition to fully electric systems in the future, contributing to long-term sustainability and improving the environmental footprint of mobile work machines.

According to the wiring method, hybrid drives can be divided into series, parallel, and series-parallel arrangements. Serial drives use an internal combustion engine to drive a generator that generates electricity for the traction of electric motors, as presented in [10, 11]. The parallel arrangement allows the machine to be directly driven by an internal combustion engine, an electric motor, or a combination of both [11]. Series-parallel drives combine the advantages of the two previous arrangements, enabling to change the driving mode efficiently depending on the operating conditions. According to the level of hybridization, they are divided into full hybrid, mild-hybrid and minimal hybrid drives. Complete hybrid systems allow full electric mode without using an internal combustion engine, while mild-hybrid powertrains support electric motors, especially when starting and accelerating. At least hybrid drives mainly use the electric motor for the start-stop function. On the basis of the mentioned introduction, the authors established the following scientific hypotheses:

1. The hybrid drive architecture for mobile working machines can (significantly) improve fuel efficiency.
2. A combined analysis of operational characteristics and environmental factors presents a more effective way of determining the hybrid drive architecture.
3. Mobile working machines with optimized hybrid drive architecture have lower total lifetime operating costs than conventional drive systems.
4. Hybrid drive architecture can improve environmental suitability

The methodology in this paper was designed to improve energy efficiency, reduce costs, and minimize environmental impact. The key steps in the method are:

1. Duty cycle analysis includes operational phases, such as material handling, transport, etc. The selected phases were analyzed based on their performance requirements, duration, and power demands during this analysis.
2. Determination of performance requirements – This methodology included energy recovery capability (such as load or breaking reduction) and maximum and medium power requirements (such as the average power of the entire cycle).
3. Calculation of hybridization factor – it was presented by the ratio of the electric motor's power to the total power, i.e. electric motor and internal combustion engine
4. Selection of drive layout – The selection is based on an analytical hierarchical process for evaluating technical and economic factors that ensure the efficiency of hybrid architecture.
5. Verification of hybrid drive configuration – For this step, a specific example is used, and the effectiveness of this demonstration is realized by designing and simulating the drive system, including calculating the hybridization factor, which is based on the duty cycle analysis.

SPECIFICATION OF THE SELECTION CRITERIA FOR HYBRID DRIVE MODULES

The criteria for selecting hybrid drives are defined based on the duty cycle of a particular machine type. The analysis includes identifying performance requirements and the type and frequency of operating conditions. The selection of suitable hybrid drive modules for mobile work machines is based on the presented comprehensive methodology, which considers various factors affecting the efficiency and performance of hybrid systems. Steps such as duty cycle analysis, determination of performance requirements, and identification of appropriate levels of hybridization are included in this methodology. The steps of the method include:

1. Duty cycle analysis – each type of mobile work machine has a specific duty cycle that affects the power requirement and energy intensity. For example, an excavator's work cycle involves digging, moving, material handling, and more [10, 11]. These phases are analyzed regarding

performance requirements, considering the duration and performance required for each activity.
2. Determination of performance requirements – Figure 1 shows the specific power requirements for each drive type based on a duty cycle analysis. This includes maximum and medium power requirements, peak load, and energy recovery capability. Performance requirements are critical for choosing the appropriate type of electric motor, internal combustion engine, and battery.
3. Choosing the drive's level of hybridization – determining the level of hybridization is essential to choosing the right one. The hybridization factor (*Hf*) is used to quantify the level of hybridization, which is defined as the ratio between the electric motor's power and the propulsion system's total power [12].

$$H_f = \frac{P_{em}}{P_{em} + P_{ice}} \ [\text{-}] \quad (1)$$

where: P_{em} – electric motor power [W], P_{ice} – is the power of the internal combustion engine [W].

The H_f value ranges from 0 (pure combustion engine) to 1 (pure electric drive). An entire hybrid drive (H_f = 0.5–0.7) is usually recommended for mobile work machines, ensuring sufficient electrical power to handle peak loads [12].

From a typical work cycle, the value of the hybridization factor H_f can only be obtained and interpreted through its complementary value of the motorization factor M_f:

$$M_f = \frac{P_{ice}}{P_{ice}+P_{em}} = \frac{P_{avg}}{P_{max}} \ [\text{-}] \quad (2)$$

$$1H_f = 1 - M_f \ [\text{-}] \quad (3)$$

where: P_{em} – electric motor power [W], P_{ice} – the power of the internal combustion engine [W], P_{avg} average power during one cycle [W], P_{max} – maximum power during one cycle [W]

Medium power is the charging power that, with a constant power supply, would deliver as much energy as is consumed in a single cycle. This means that the energy in the batteries before and after the duty cycle would be the same, even after the maximum power is taken, i.e. the power higher than the mean power. This power value is the first approximation to determining the parameters of a hybrid combustion engine [10, 11]. To determine the mean power, it was necessary to decide on the amount of energy supplied. This energy is represented by the area under the curve of the power consumed during the cycle. The mean power value is then obtained as a ratio of the total energy supplied to the total cycle time [12]. The maximum power consumption represents the sum of the electric motor's power and the internal combustion engine [12].

Choice of drive layout

The layout of a hybrid drive (series, parallel or series-parallel) is determined based on the duty cycle and its performance requirements. On the basis of these requirements for the arrangement of the drive for the case of an excavator, value analysis is based on the analytical hierarchical process developed by Saaty et al. [13]. The graphical output of the analysis based on technical and economic parameters is shown in Figure 2

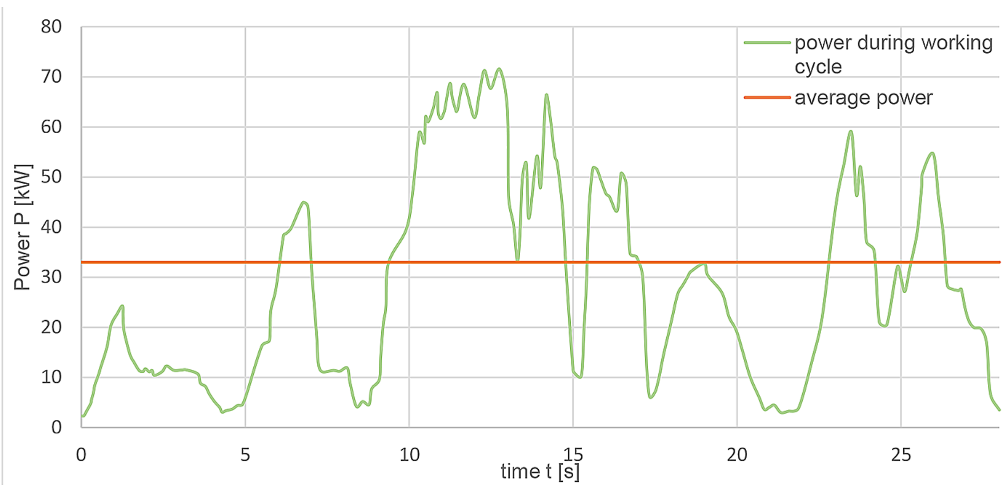

Figure 1. Power flow during excavator duty cycle

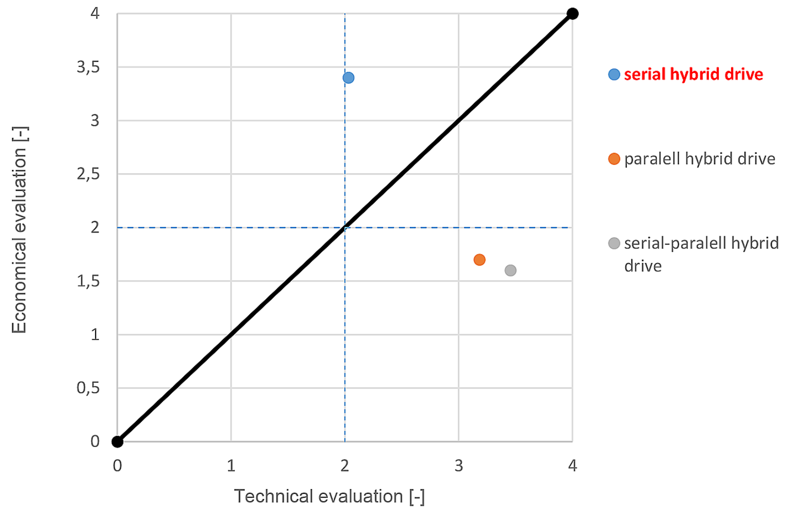

Figure 2. Graphical evaluation of the value analysis

EVALUATION AND VERIFICATION OF HYBRID DRIVE CONFIGURATIONS

The methodology for selecting hybrid drives systematically optimizes the energy efficiency and performance of mobile work machines, reducing operating costs and overall environmental burden.

Figure 3 shows an alternative drive for the UDS 132H excavator to verify the design methodology of the hybrid drive. On the basis of this methodology, the machine's serial drive system was realistically designed, as shown in Figure 4. In this particular case of the excavator drive design, the level of hybridization reached $H_f = 0.607$, based on the steps of

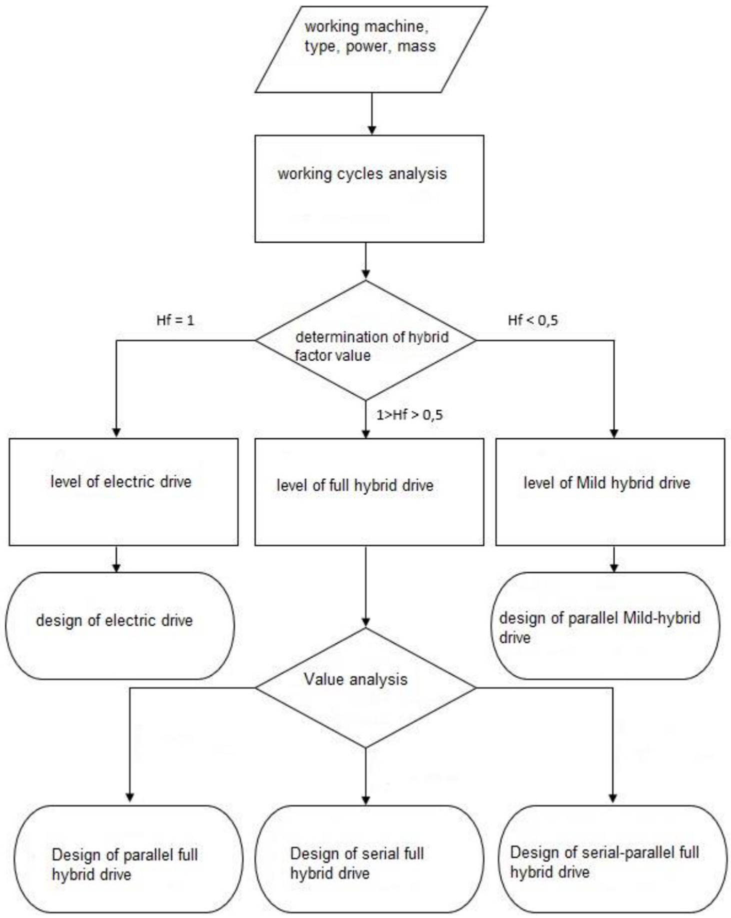

Figure 3. MPS hybrid drive design methodology

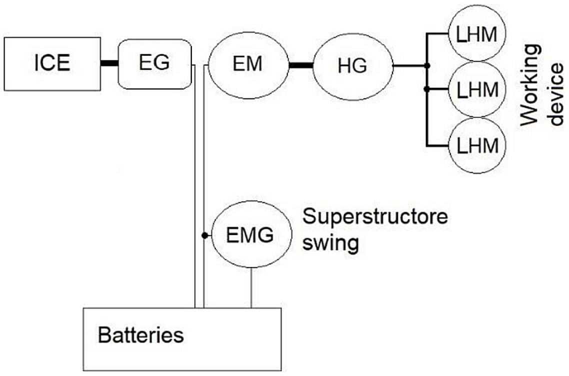

Figure 4. Block diagram of the layout of the UDS 132H hybrid drive . ICE – internal combustion engine, EG – electric generator, EM – electric motor, HG – hydraulic generator, LHM – linear hydraulic motor, EMG – electric motor-generator

the proposed methodology. This machine-specific drive architecture thus ensures optimal drive power use during its typical duty cycle [12, 13].

On the basis of the power course of the UDS 132H excavator drives, it is possible to create a cycle for charging and discharging the batteries, Figure 5. The increment to the battery capacity during the cycle is non-zero. The power consumption during the cycle did not require a larger power capacity than was obtained in previous power consumption drops. Therefore, the generator's power can be sufficient. The final energy gain with each cycle allows the batteries to be recharged and then operated without using the internal combustion engine.

The course confirms these facts over 12 cycles (Fig. 6). This is the most minor period in which the charging and discharging of batteries can be presented. The course is divided into three intervals.

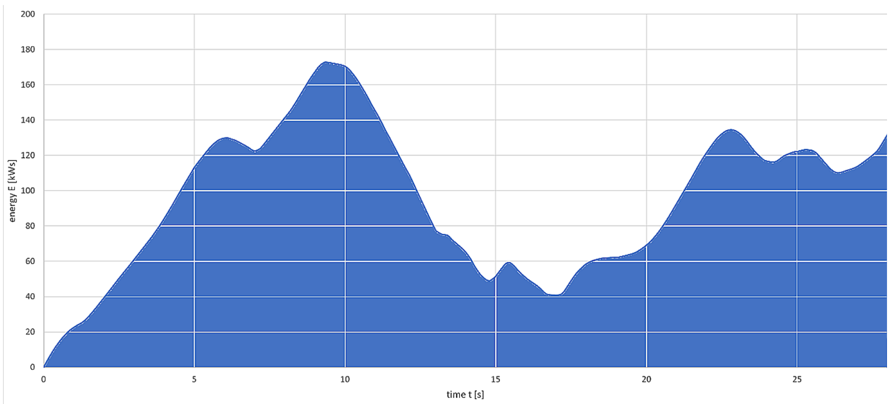

Figure 5. Charging and discharging batteries during the duty cycle

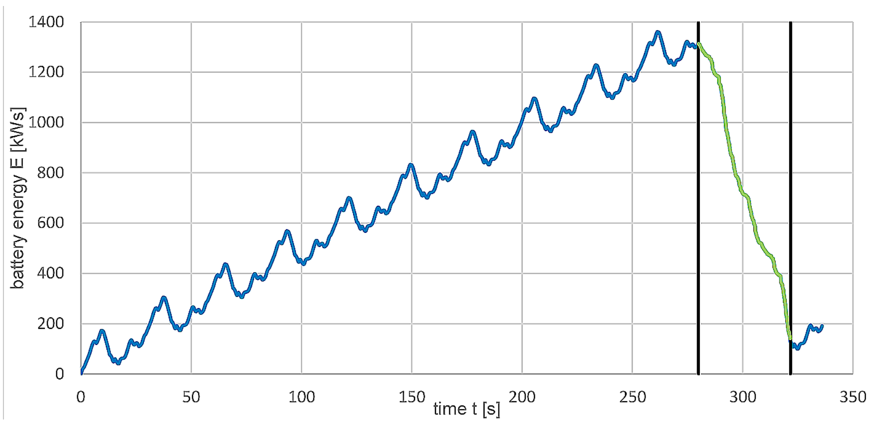

Figure 6. The course of energy accumulation in batteries during 12 work cycles

Table 1. Comparison of fuel consumption and emission generation of the UDS 132 excavator

Parameters	Type of drive					
	Original drive		Full hybrid drive		Mild hybrid drive	
Rotation speed n	2200	min^{-1}	1890	min^{-1}	2200	min^{-1}
Power of ICE P_{ice}	71.5	kW	37.5	kW	53.5	kW
Consumption S_m	230,00	g/kwh	225	g/kwh	230	g/kwh
Diesel density ρ	860	kg/m^3	860	kg/m^3	860	kg/m^3
Consumption S_p	19.122*	l/hour	9.811*	l/hour	14.308*	l/hour
Fuel reduction	–		cca 48%		cca 25%	
Working time t_r	1 600	h/year	1 334	h/year	1 600	h/year
Production of CO_2 V_e	0.0000248	t/l	0,0000248	t/l	0.0000248	t/l
Emissions E_t	0.759	t/year	0,325	t/year	0.568	t/year
Reduction of emissions			cca 57%		cca 25%	

The first consists of the course of energy increment over 10 operating cycles. The second interval shows the discharge course during the duration of 1.6 operating cycles in emission-free mode. The third interval represents recharging by the generator after detecting a decrease in energy to a low level. The calculation found substantial fuel savings and thus a corresponding reduction in emissions: fuel savings of about 48%, corresponding to a reduction of about 57% of the produced $CO_{2,}$ while considering the possibility of operating the drive in the emission-free mode (Table 1).

CONCLUSIONS

On the basis of the findings above, hybrid drives, including mobile work machines, reduce fuel consumption and emissions. A key factor for successful implementation is correctly determining the level of hybridization and drive layout, which must consider the specific requirements of a particular type of machine. This thesis provides a comprehensive overview of the field of hybrid drives and a proposed methodology that can serve as a basis for further research and development of efficient drive systems for different groups of mobile work machines. The importance of the work also lies in its scientific contribution, which can be summarized in the following points:

- Determination of previously unmentioned evaluation criteria for hybrid drives of mobile work machines and their application in the selection of drive for a specific group of machines,
- Creation of a methodology for the design of an optimal hybrid drive for mobile working machines, including the application of a suitable type of drive to selected machines,
- implementation of the requirements of EU legislation aimed at reducing greenhouse gas emissions generated during the operation of mobile work machines.

Thus, the work represents a significant contribution to developing environmentally friendly and efficient solutions in mobile work machines, offering theoretical foundations and practical tools for further implementation. The results of this research can be used in the development and innovation of MPS structures to reduce fuel consumption and greenhouse gas emissions. This benefit can also be defined as follows:

- objectification of the possibilities of using hybrid drives in the MPS group.
- contribution to the innovation of MPS drives meeting the requirements for sustainable development.

Thus, the methodology can suit developers, designers, and students designing hybrid drives and modules for mobile work machines. The knowledge gained provides the basis for analyzing conventional drive modules and possibly replacing them with hybrid modules. The proposed knowledge and methodology can also be used in educational processes, including study programs dealing with this issue. It can be employed in academic activities and compiling teaching texts and professional publications.

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