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ENERGETIC BALANCE OF UNMANNED GROUND VEHICLE HYBRID POWER TRANSMISSION

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Abstract

Article presents the energetic balance of small-unmanned vehicle hybrid power transmission. The vehicle equipped with series hybrid transmission consisted of electric engines connected to the battery pack and small Diesel power generator. In mentioned construction, battery is used as energy buffer and combustion engine is used more as emergency power supply, and is turned on when battery is depleted. In other condition, power generator can be turned off, without reducing power of transmission parameters, except its range. Investigation was divided on two stages. At first stage generator, charging unit and battery were placed outside the vehicle. One piston power generator was feed by Diesel fuel. Fuel consumption of power generator was recorded from AVL fuel balance and energy parameters were recorded by power line analyser of BMR Company. Generator was connected to the direct current power plant. 70 Ah and 48 DC Lithium-polymer battery was charged from the power plant. After charging cycle, small water resistor was used to discharge the battery. Power parameters of discharged battery were measured. This enable to measure balance form tank to the battery. Second stage of the energetic balance determination was to measure internal resistances of vehicle power transmission from current inverter/converter connected to the engine and through the transmission up to the wheels of the vehicle. Power loss of energy at different speed of vehicle wheels without ground contact was measured in respect of power consumption. The series hybrid transmission is consider less efficient than parallel but because of specific configuration of power transmission, it was possible to reach higher efficiency.

Keywords: *balance, unmanned vehicle, hybrid transmission, test stand*

1. Introduction

Because of usability of unmanned ground vehicles, a military of civil use of those vehicles is more often used [1, 2]. Especially, their use in military conflict region can have impact on safety of soldiers attending in this conflict. Unmanned vehicles can patrol area, measure contamination level of the environment, deliver supplies, operate as a movable fire stand or help to evacuate wounded soldiers [3]. To comply its tasks, it is necessary to ensure quiet relocation and long range or long operating time in conflict area without support. Those requirements can be met by vehicles equipped with series hybrid drive, power transmission system with electric engines enable to quiet operate in endangered area [4, 5]. High efficiency of those engines cause slight thermal trace, improve undetectability by enemy forces. Equipped with power generator, enable to load battery and increase range and operation time without need of fast come back to the base [6].

It is necessary to undertake a study to assign energy balance from tank and vehicle's wheels from efficiency point of view, according Tank-to-wheel balance.

2. Laboratory testing of a hybrid vehicle

The main goal of laboratory tests of hybrid power transmission system of unmanned ground vehicle was to determine energy balance of this system after integration and install on a vehicle

hull. Tests were held on stands of combustion engines laboratory of Military University of Technology. Tested object was six wheeled unmanned vehicle equipped with series hybrid power transmission with power generator, lithium-polymer battery and six electric engines situated together with transmission in rocker arms of a vehicle. Range of the tests included:
– measurements of lithium $LiFePO_4$ battery charged from on-board power generator,
– measurements of electric engines efficiency of vehicle,
– measurements of power transmission efficiency.

Based on efficiency of particular elements of power transmission system and calorific value, fuel consumption, energetic balance of unmanned vehicle was calculated and determined.

2.1. Test stands

During tests, four stands were used. First, one was designed for measuring charging of $LiFePO_4$ battery. Second one was prepared for discharging process measurements and third one for measuring efficiency of electric engines. On the last test stand, efficiency of the power transmission of unmanned vehicle was measured.

Battery charging test stand

A stand for measuring charging characteristics of battery by power generator, powered by compressed ignition engine, enables to determine efficiency of designed assembly. This stand consists of four main elements (Fig. 1):
1. power generator with Diesel engine,
2. current-voltage parameters acquisition system,
3. constant current power station,
4. battery,
5. fuel consumption measurement device.

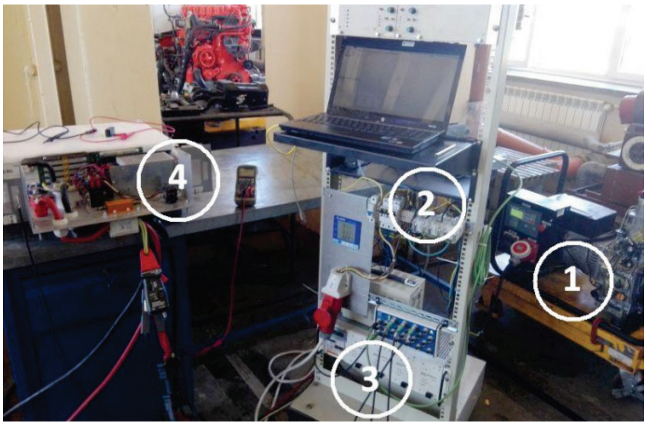

Fig. 1. Charging test stand: 1 – power generator 2 – current-voltage parameters acquisition system 3 – constant-current power station, 4 – battery

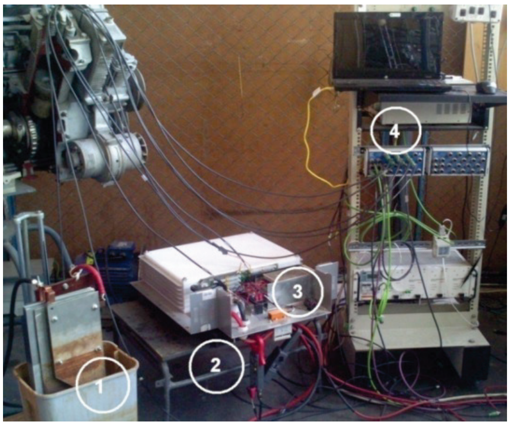

Fig. 2. Battery discharging test stand: 1 – water resistor, 2 – current clamps, 3 – battery with voltage sensors, 4 – acquisition computer

A charging system works on two modes, at the beginning, charging process is realized by constant current (CC mode), further charging is realized by constant voltage mode (CV mode) (Fig. 3a). After activation of power station and charging process beginning of the battery, 50 A of current was set, from the beginning of charging process where voltage of the battery was about 40.5 V to 49.5 V. This mode was CC mode. Power generated from power generator was about 2500 W at the beginning of this mode, up to 2700 W at the end of CC mode in time of 50 min. This power increase was caused by holding constant current and in meantime, voltage was increasing. When constant current mode was over, battery voltage reach 49.5 V, constant voltage mode was started and current was decreasing together with power from power generator, up to zero. Difference between power of power generator and power of charging process come from power station efficiency was equal to 92%. Charging process was end after 93 minutes of work and power of charging station reach zero Amperes of charging current and standby mode was activated.

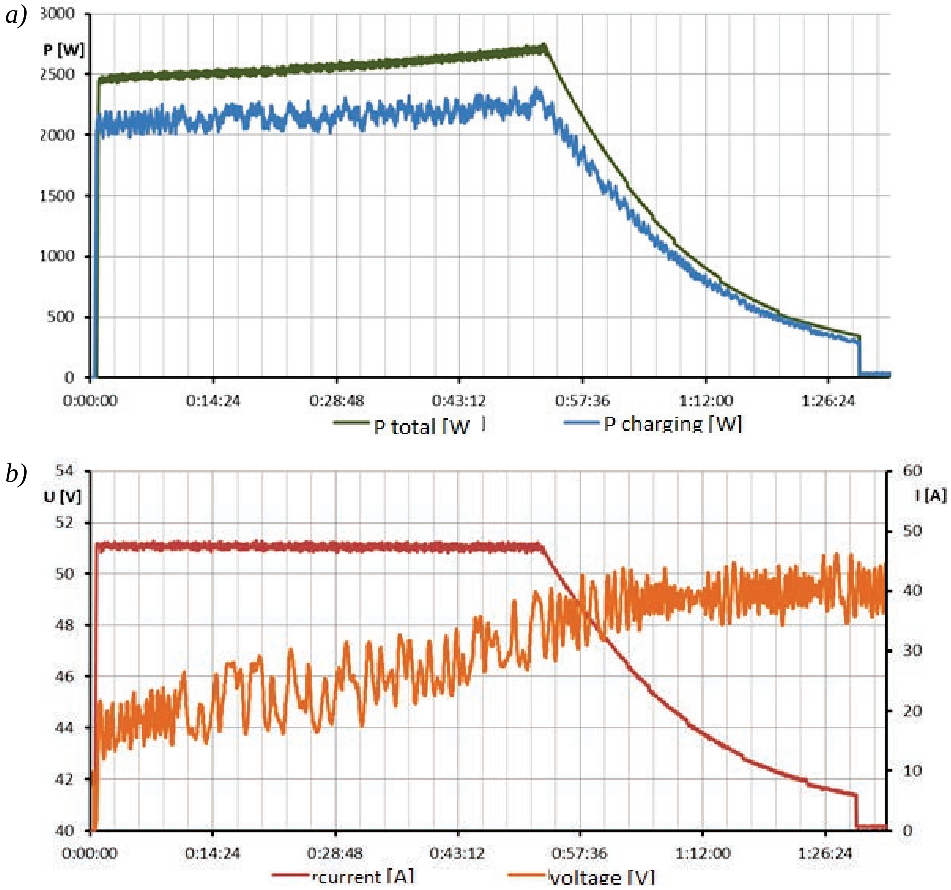

Fig. 3. Battery charging process: a) power of generator (green line), power of battery charging (blue line) b) battery charging voltage (orange), battery charging current (red line)

Fuel consumption at the beginning equals 0.51 kg/h (Fig. 4) because power generator works without any load. Under load (CC mode) fuel consumption reach 0.91 kg/h and last to the end of CC mode. On the end phase of CV mode, fuel consumption again reach 0.51 kg/h of consumption, the level from the beginning of charging process. Total amount of used fuel needed for one full loading of battery cycle was 1150 g.

Battery discharging test stand

Test stand for measuring discharging parameters of battery enable to set discharging characteristics under different load (Fig. 5). This stand consists of four main elements:

1. water resistor,
2. curerent and voltage sensors,
3. battery,
4. computer with acquisition software and hardware.

For battery load, water resistor was build. This type of resistor enable fast and simple operation of resistor, by submerse metal plates of resistor in wear. Discharging current could be increased by increasing number of metal plates or water additives. Battery was equipped with voltage sensors.

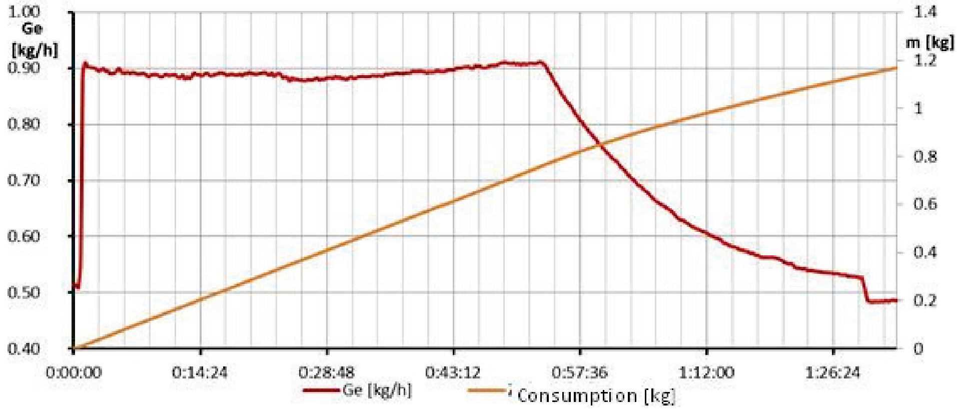

Fig. 4. Power generator: a) momentary fuel consumption (red), b) total fuel consumption (orange)

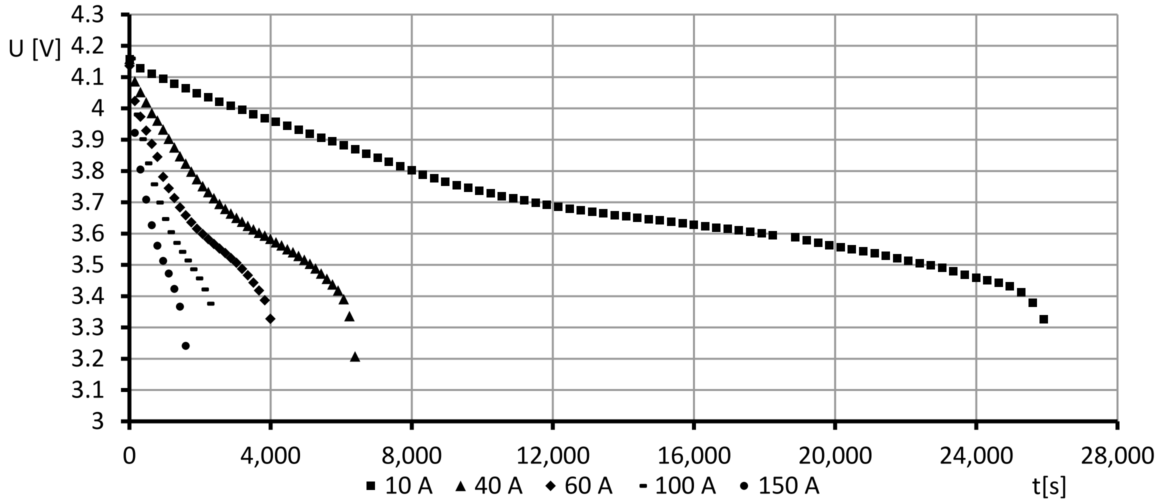

Fig. 5. Voltage changes on single battery cell during discharging process in function of time for different discharging currents

Battery discharging of current 10 A (Fig. 5) from cell voltage 4.18 V (100% S.O.C.) up to 3.33 V – discharged, last more than 7 hours. Discharging of current 40 A decreased time up to 1 hour and 46 minutes. During 150 A discharging, battery was depleted after 27 minutes. Discharging was carried on to reach minimum voltage per cell – 3.3 V. Then safety switch inside battery disconnect the battery to prevent deep discharging and help to elongate battery life.

Engine test stand

To determine characteristics of electric engines, dynamometer test stand was build. On this stand, changes of the engine torque were measured if function of engine speed (Fig. 6).

Test stand was equipped with sensors:

1. voltage sensors;
2. current sensors;
3. engine rotation speed sensor;
4. force sensor on a dynamometer stand (torque on an engine).

Investigated engine (2) was mounted on a dyno stand and connected through the clutch with engine of the dyno stand (6) (Fig. 6). Engine mounted on the stand worked as a dynamometer. On his housing, force meter was mounted (3), and force was measured. Examined engine was connected to the inverter (5) and inverter was connected to the power supply (battery). Current and voltage sensors were connected to the acquisition card (4) and computer (1). Speed of the engine was measured by DGS 66 speed encoder.

Fig. 6. Dyno test stand: 1 – acquisition equipment, 2 – electric engine, 3 – force sensor, 4 – acquisition hardware 5 – current inverter, 6 – electric engine of the dyno stand

During engines characteristics determination, their speed was decreased from maximum to zero by increasing torque of the dynamometer engine. This caused increasing of the examined engine power by inverter. Inverter was programmed to keep speed set by operator. Because dynamometer engine has higher power and higher torque, this speed was adapted to the examined engine maximum parameters. From current and voltage measurements, power consumed by the engine was calculated (Fig. 7) and torque (Fig. 8). Six characteristics were calculated of measured engines.

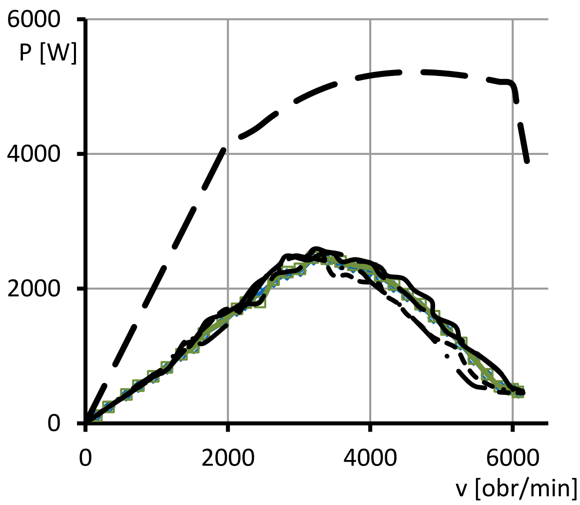

Fig. 7. Power characteristic of PMS100 engines

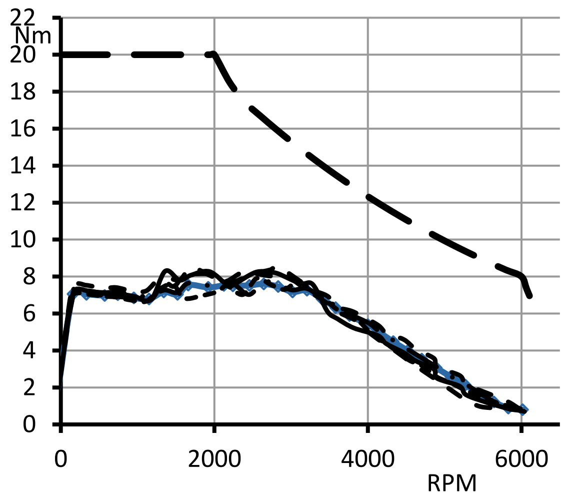

Fig. 8. Torque characteristics of PMS100 engines

3. Internal resistance stand

Measurements of internal resistance of the power transmission was made after lifting vehicle by warehouse truck to loose contact between wheels and ground (Fig. 9). Speed was increased in stages to the maximum and then decreased to the wheels stop. Rotation velocity of the wheels was set by voltmeters indication, placed next to the controller. Voltage values changes from 0 V (0 km/h) to 5 V (34 km/h) for speed equal 2, 4 and 5 V, measurement time was elongated.

Because engine speed was set separately for left and right side of the vehicle, signals of actual rotation speed are displaced (Fig. 10). Momentary speed differences of individual wheels were small and do not exceed 1 km/h. Higher was difference between left and right side of the vehicle (2 km/h). This difference was caused by controller accuracy.

Fig. 9. Vehicle lifted and prepared for measurements

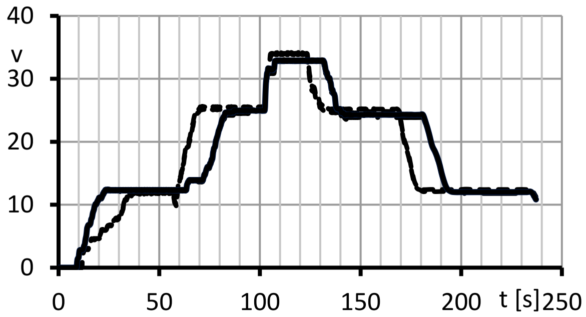

Fig. 10. Changes in speed of the wheels during test

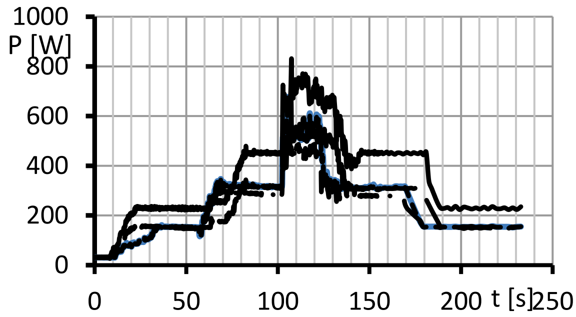

Fig. 11. Changes of the power during test

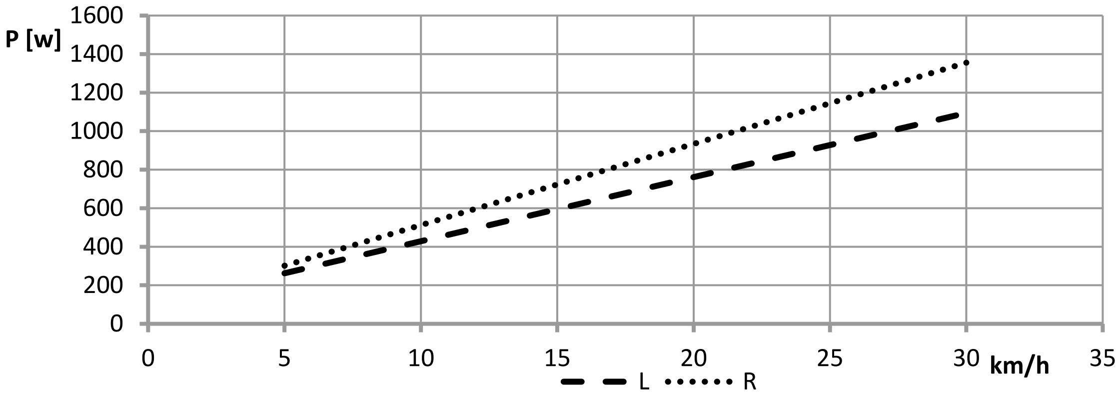

Fig. 12. Average power of resistances of power transmission of left and right side of the vehicle

Power of the inverters increased as speed of the wheels increased. Maximum value reached in maximum speed (34 km/h). Power consumed by right side of the power transmission was higher, because higher were resistances of the engines on this side. Aside of speed, power of one of the engines and transmission was higher (40-50%) in whole speed range.

4. Energetic balance of the hybrid power transmission

Based on results of charging and discharging of the hybrid power transmission battery, measurements of internal resistances, energetic parameters of the power transmission and energetic balance were determined. Based on that calculation, it was possible to determine range of the vehicle. During calculations, internal resistances were took into account. Results were presented in Tab. 1.

Tab. 1. Efficiency of subassemblies of hybrid power transmission

No.	Component	Energy used or produced	Average efficiency
1.	Fuel	50.282 MJ	–
2.	Power generator	10.555 MJ	21%
3.	Power station	9.65 MJ	92%
4.	Battery	9.0 MJ	94%
5.	Average efficiency (inverter – wheels)		75%
6.	Average efficiency of transmission elements (battery – wheels)		70%
7.	Total efficiency		13.6%

To determine energetic balance, calorific value of the diesel oil was determined as 43 MJ/kg. Total energy of a single charging process of the battery was equal to 50.282 MJ/kg, and came from fuel of 1.15 kg. Energy from fuel, powered generator and charged battery with power 10.555 MJ/kg, after sweep to electric energy, this mean the efficiency is equal to 21%, what is satisfied value in Diesel engines.

Charging the battery need 9.65 MJ of energy. During discharging process, the energy level reaches 9.0 MJ of energy. Such amount of energy should be enough to travel at distance of 16 km with speed of 5 km/h. Fuel tank capacity enable to charge the battery more than three times to its full capacity. This enables to travel distance over 50 km on a flat surface.

Efficiency of driving modules reaches 75%. Theoretical efficiency of such module (from engine to wheel) should reach 80-90% and it is depending from module load. Because of precision of elements production and assembly, efficiency was lower (15-20%).

Total efficiency of hybrid power transmission, when combustion engine was turned on, reaches 13.6% (from tank to the wheel).

Efficiency of energy conversion from chemical energy of fuel to the energy converted for wheels powering is quite small. It is caused mostly by low efficiency of combustion engine that power the generator. It is small, naturally aspirated one cylinder compressed ignition engine. His internal resistance is big if compare of power produced. Efficiency of power transmission powered from battery is bigger and reach 70%.

Power consumed by the vehicle in different road conditions (speed, quality and type of the surface), and parameters of the power transmission, it was possible to determine range of the vehicle and speed of the vehicle with power generator.

Vehicle powered only from the power generator, enable to charge the battery in time of 93 minutes. During driving this time is elongated, because some part of the energy is consumed by the wheels of the moving vehicle. This time can be elongated or if road resistance will be higher than power generated, battery will never be fully charged. In case of totally discharged battery, maximum vehicle speed is about 20 km/h, when moving on a concrete or asphalt, without charging.

5. Conclusions

1. Laboratory investigation of hybrid power transmission subassemblies enable for verification of their characteristics and parameters. It was stated that electric engines of the vehicle enable to reach 7 Nm of torque, without temporary torque of 20 Nm. Battery parameters measurements enable to estimate vehicle's range for different driving modes.
2. Energetic parameters were set of the hybrid power transmission. Efficiency of the energy consumption was 70% when vehicle used only battery and 13.6 when power generator was turned on. Generator charged battery in 93 minutes. During one charging cycle generator used 1150 g of fuel.
3. Internal resistance of power transmission that definitely has the biggest resistance in right rear wheel. His resistances were about 23% higher than other wheels. This was confirmed by static measurements of torque made with use of dynamometric key.

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