# HYBRID DRIVE APPLICATION FOR HIGH-SPEED TRACKED VEHICLE

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***Abstract***

*Analysis of possible hybrid drive for tracked vehicle solutions and also concept vehicle project is presented in the paper. Study of present tracked vehicle state-of-art shows that in case majority of currently designed and developed military tracked vehicles projects modifications hybrid propulsion is taken into account. Based on that, authors have decided to develop concept hybrid tracked vehicle study. Basic parameters of concept vehicle are described at the beginning: total vehicle mass up to 14 Mg, maximum speed over 60 km/h and also possibility of stealth operation at the low speed using electric energy stored in batteries. Then, analysis of hybrid electric drives configurations is presented. Three versions of hybrid electric propulsions are considered: two series hybrid drives and one parallel. Then final version is chosen for further development with discussion on justification of the choice description. Dynamic model assumptions and modelling methods are described in next section. As a result of simulation, acceleration diagrams for chosen operation modes are shown. As the final stage of concept study, virtual 3D model was built. Virtual modelling methods are used to optimize transmission components layout in a concept tracked vehicle hull.*

***Keywords****: transport, tracked vehicle, hybrid drive, electric drive*

## 1. Introduction

Hybrid electric drives for tracked armoured vehicles are being used since the first years of military application. Mainly due to the lack of proper mechanical transmission systems, electric drive had been used in heavy tanks. The example of electric transmission usage in early heavy tank design could be the St. Chamond tank. The total mass of the tank was about 25 000 kg. The driving mechanism was consisted of a four-cylinder Panhard petrol engine of 80-90 HP and 52 KW generator, providing energy for two electric motors driving right and left track. Steering was performed by varying the electric motors speed. During Second World War electric drive system was used in Porsche heavy Tiger tank prototype (VK4501 (P) / Porsche Type 101) but since the other manufacturer’s prototype had won the competition (Henschel VK4501 (H)). 90 of existing chassis were turned to the Sd. Kfz. 184 Ferdinand heavy assault tanks. In case of Ferdinand, two Maybach HL 120 engines drove two generators providing electrical energy for also two engines driving each track. Total mass of the tank was about 65 000 kg. For over fifty years after Second World War electric transmission remained unreliable and too heavy for wider use in military tracked vehicles [1].

Nowadays, reliable and efficient permanent magnet motors are available, so that military tracked vehicles performance can be improved with using hybrid electric drive technology [2, 3]. The good example of tracked vehicle using hybrid drive technology is SEP (Spitterskyddad Enhets Platform) developed by BAE Systems Land Systems Hagglunds, modular armoured platform (Fig. 1).

*Fig. 1. Tracked SEP vehicle [6]*

Tracked version of SEP. is equipped with the Steyr M16 3.2-litre rated at 130kW. The final drives are connected by a cross-shaft for higher power efficiency in turning manoeuvres. The top speed of the vehicle is 85 km/h.

*Fig. 2. Quinetiq E-X-Drive – hybrid electric propulsion system for tracked vehicles [7]*

Hybrid electric transmission is also offered as a modification kit for existing vehicles. The good example of such solution is E-X-Drive manufactured by British company Qinetiq (Fig. 2).

Technical parameters of offered hybrid electric drive are:

- mass ~400kg,
- volume ~112 l,
- nominal power ~330 kW,
- specific power ~ 0.825 kW/kg,
- power density ~ 2.9 kW/l.

As it was described above hybrid drives are being introduced into service either during modification of existing vehicles or in designing process of new vehicle designs.

Advantages of hybrid propulsion system over mechanical transmissions are:

- reduction of fuel consumption what provides range extension,
- heat and exhaust gas emission reduction,
- more flexible transmission system components location (not related to overall components volume reduction),
- possibility of stealth operation with using energy stored in batteries.

Application of the hybrid electric drives are to be promising way of improving the light and medium armoured tracked vehicles performance. For that reason authors have decided to carry the concept study of hybrid electric driven tracked vehicle.

## 2. Concept Vehicle Basic Parameters

The concept vehicle described in the paper is supposed to be universal platform with tracked propulsion system. Weight and dimensions of the vehicle allow modification the platform depending on the application.

Basic parameters:

- total mass ~14 000 kg,
- length ~6 m,
- width ~3 m,
- maximum speed over 65 km/h.

## 3. Analysis of Hybrid Electric Drive Configurations

As the first variant of electric drive configuration, electric motors propelling each side track were considered (Fig. 3). In this case, high torque and rotational speed range of electric motors is demanded in order to achieve full manoeuvrability in hard terrain and reasonable maximum speed of the vehicle. At present state-of-art of available electric machines, 2-3 speed gearboxes are needed in the driveline. Furthermore, failure of one motor causes complete loss of vehicle's manoeuvrability.

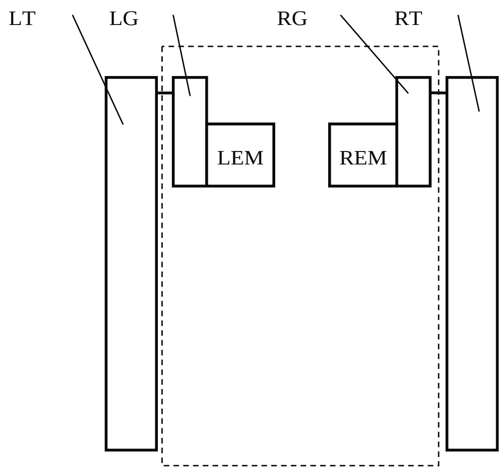


*Fig. 3. First configuration of hybrid propulsion system: LT – left track, RT – right track, LG – left gearbox, RG – right gearbox, LEM – left electric motor, REM – right electric motor*

As an energy source for electric engines, internal combustion engine integrated with electric generator was used. There was no mechanical connection between the engine and tracks so that vehicle with described transmission system could be considered as series hybrid vehicle.

In order to achieve higher speeds and also for providing vehicle manoeuvrability in case of single electric motor failure, two planetary gears and one electric motor was added to transmission system. In the second configuration of hybrid propulsion system, there are three electric motors, one central, and two at each side of the vehicle (Fig. 4).

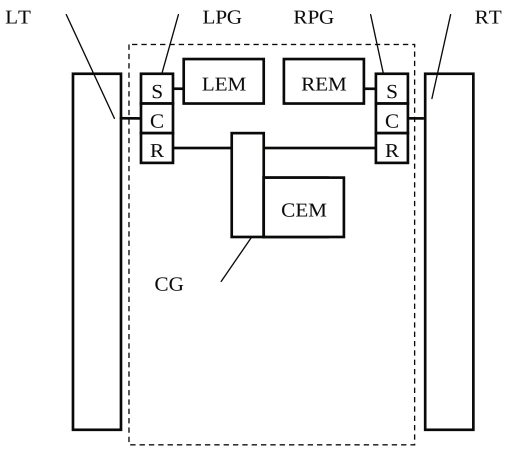


*Fig. 4. Second configuration of hybrid propulsion system: LT – left track, RT – right track, LPG – left planetary gearbox, RPG – right planetary gearbox, LEM – left electric motor, REM – right electric motor, CEM – central electric motor, CG – central gearbox*

As it is shown in the figure, central electric motor is connected through the central gearbox with ring gears of left and right planetary gearboxes. That provides the high speed vehicle performance. Left and right electric motors are coupled with the sun gears of left and right planetary gearboxes respectively. That provides low speed performance and manoeuvrability at all speeds.

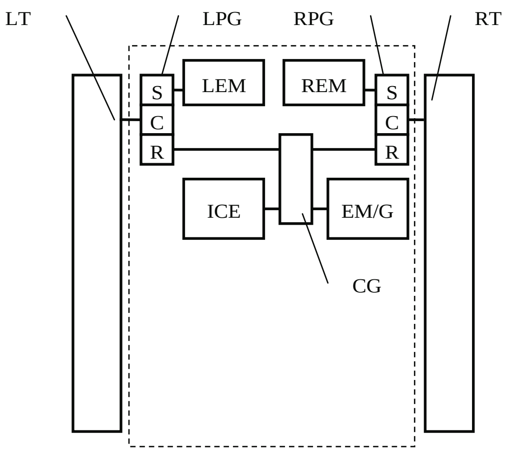


*Fig. 5. Third configuration of hybrid propulsion system: LT – left track, RT – right track, LPG – left planetary gearbox, RPG – right planetary gearbox, LEM – left electric motor, ICE – internal combustion engine, EM/G –electric motor/generator, CG – central gearbox*

As third concept, parallel hybrid electric drive was considered (Fig. 5). In case of two previous configurations internal combustion engine was treated as a part of auxiliary power and not shown in the figures.

In a third case of hybrid drive configuration, internal combustion engine can be coupled with the transmission system so that there is mechanical connection between tracks and the engine. The way of power flow depends on operation mode.

Possible modes of vehicle propulsion:

- low speed with using right and left electric motors (for stealth operation energy supplied by battery, in other case by generator powered by internal combustion engine),

- high speed with using internal combustion engine for propulsion and electric motor/generator in generator mode,
- top speed with using internal combustion engine and electric motor/generator in engine mode (additional energy supplied by battery).

For further investigation the second configuration was chosen. Advantages over the first one are higher speed range without using variable-speed mechanical gearboxes and possibility of vehicle operation in case of single side engine failure. Advantage over third configuration is simplicity of mechanical transmission structure and less complex steering algorithms application.

## 4. Hybrid Electric Drivetrain Model and Simulation Results

Dynamical model was built with using MATLAB SIMULINK environment. In order to simulate resistance force on each track four values were calculated [4, 5]. Forces $P_1$ and $P_2$ were applied for simulation the resistance while turning. Forces $P_3$ and $P_4$ were implemented in order to simulate resistance on each track during straight motion. Forces calculation is shown in dependences (1-4). Equation of motion is shown in dependence (5).

$$P_1 = \left( f\frac{G}{2} + \frac{\mu_s GL}{4B} \right)\cos\alpha - \frac{G\sin\alpha}{2}, \tag{1}$$

$$P_2 = \left( -f\frac{G}{2} + \frac{\mu_s GL}{4B} \right)\cos\alpha - \frac{G\sin\alpha}{2}, \tag{2}$$

$$P_4 = P_3 = \frac{1}{2} f \cos\alpha , \tag{3}$$

$$\mu_s = \frac{\mu_{s\max} GL}{0.92 + 0.15\frac{R}{B}}, \tag{4}$$

where:
f – rolling resistance coefficient,
$\mu_{smax}$ – turning resistance coefficient,
G – vehicle's weight,
B – distance between treads,
L – tread length,
α – slope angle.

$$\frac{M_s i_c \cdot \eta_m \cdot \eta_g}{r_k} = f \cdot G \cdot \cos\alpha \cdot G \cdot \sin\alpha + 0.005c \cdot F \cdot V^2 = \frac{G}{g}\delta\frac{dV}{dt} , \tag{5}$$

where:
$M_s$ – driving moment,
$i_s$ – transmission ratio,
$\eta_m$ – transmission efficiency coefficient,
$\eta_g$ – track efficiency coefficient,
$r_k$ – track sprocket radius,
F – front projected area,
c – drag coefficient,
$\frac{dV}{dt}$ – acceleration,
δ – rotating masses coefficient.

Turning resistance coefficients rolling resistance coefficients values and are shown in Tab. 1 and Tab. 2 respectively.

*Tab. 1. Maximum values of turning resistance coefficient $\mu_{smax}$*

| Surface type | Average turning resistance coefficient ($\mu_{smax}$) values |
|---|---|
| Dry soil, grass, dry clay | 0.8-1.0 |
| Dry soil-surfaced road | 0.7-0.9 |
| Stubble field | 0.6-0.8 |
| Humid clay | 0.3-0.4 |
| Snow | 0.25-0.7 |

*Tab. 2. Maximum values of turning resistance coefficient $\mu_{smax}$*

| Surface type | Average rolling resistance coefficient (f) values |
|---|---|
| Asphalt | 0.03-0.06 |
| Stubble field | 0.07-0.08 |
| Meadow | 0.08-0.12 |
| Sand | 0.1-0.2 |

Mathematic connections in the MATLAB/SIMULINK model are shown in Fig. 6. The model consists of dynamic electric motors model block, kinematic and dynamic models of tracks, dynamic vehicle models including the resistance force and dynamic model of transmission system.

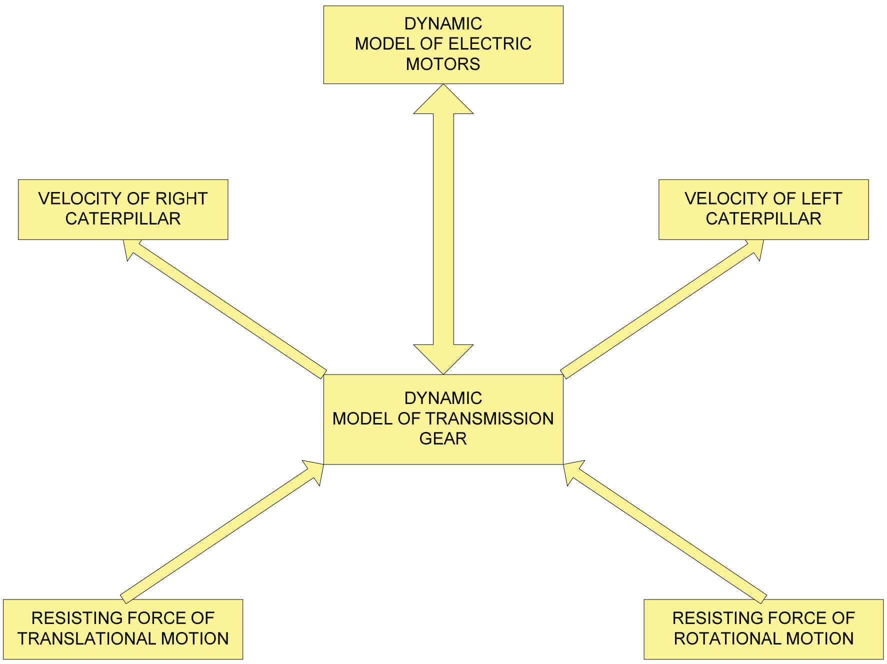


*Fig. 7. Diagram of mathematic model connections*

An example of vehicle’s acceleration for rolling resistance coefficients f=0.01 and f=0.05 is presented (Fig. 7).

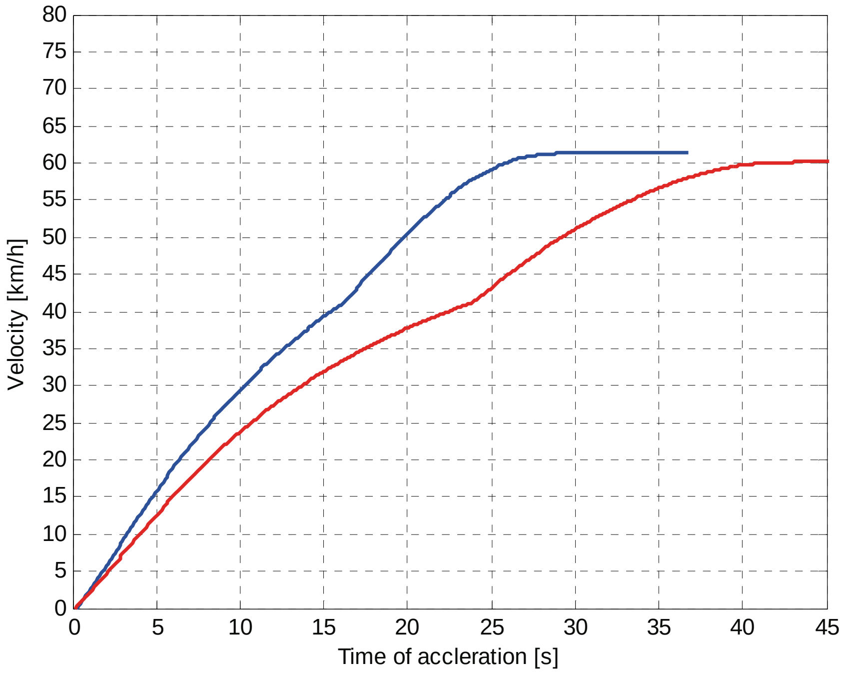


*Fig. 7. Characteristics of acceleration from 0 km/h to maximal velocity: red line – coefficient of resistance: 0.05, blue line – coefficient of resistance: 0.01*

Top speed in case of lower resistance was over 60 km/h and achieved acceleration time from 0 to top speed was 28 s.

## 5. Virtual Model of Concept Vehicle

Virtual model based on 3D software was build in order to optimize the location hybrid electric drive components. Virtual prototyping also is used for presentation of the advantage of hybrid transmission over mechanical transmission system and general vehicle layout. Vehicle dimensions are shown in Fig. 8. Length of the vehicle is equal 6000 mm, width 2980 mm, and height to the hull roof is 1685 mm. Volume of transport compartment is over 10.5 $m^3$.

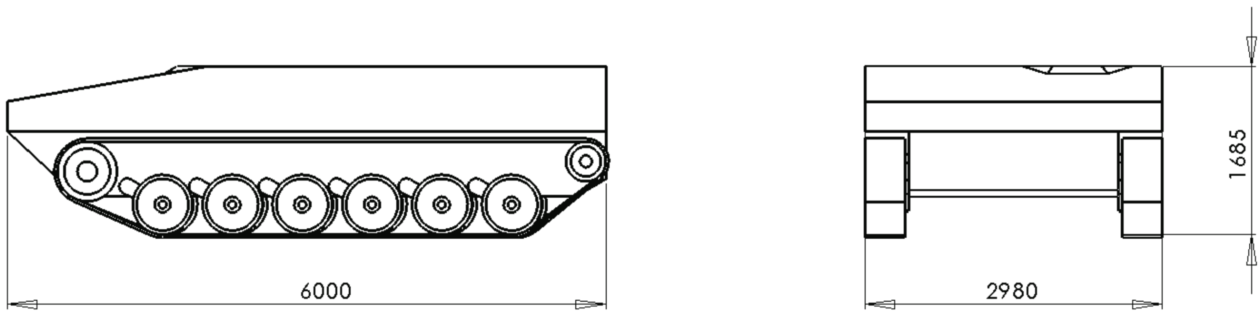


*Fig. 8. Concept vehicle dimensions*

Hybrid electric drive system components layout is shown in Fig. 9. As the power unit is not mechanically connected to the gearbox, it could be moved easily to a different location what provides flexibility in space and mass distribution in the vehicle.

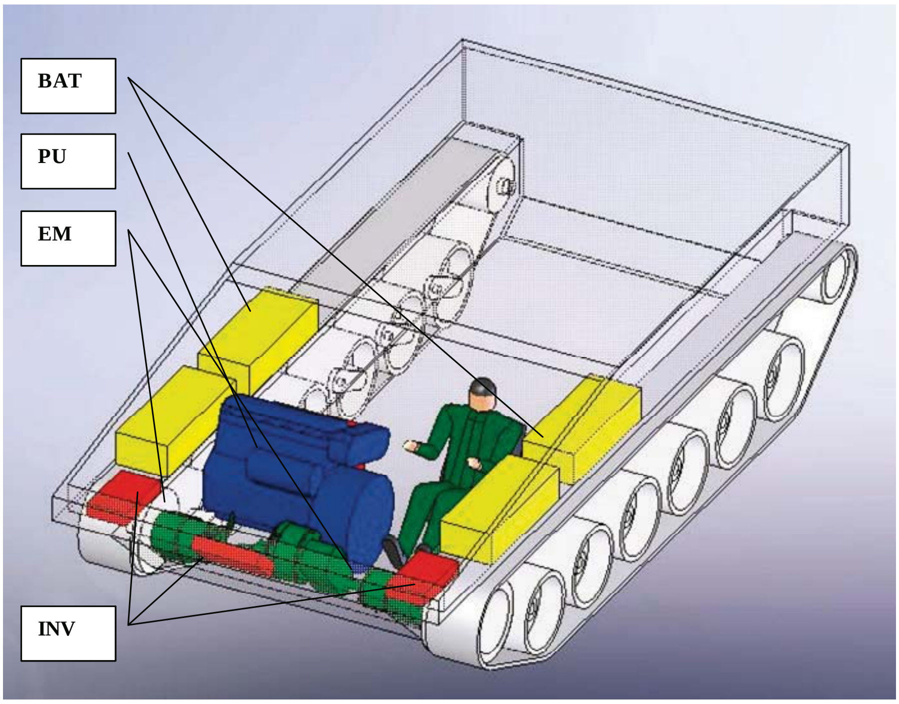


*Fig. 9. Hybrid electric drive components location: BAT – batteries, PU – power unit, EM – electric motors, INV – inverters*

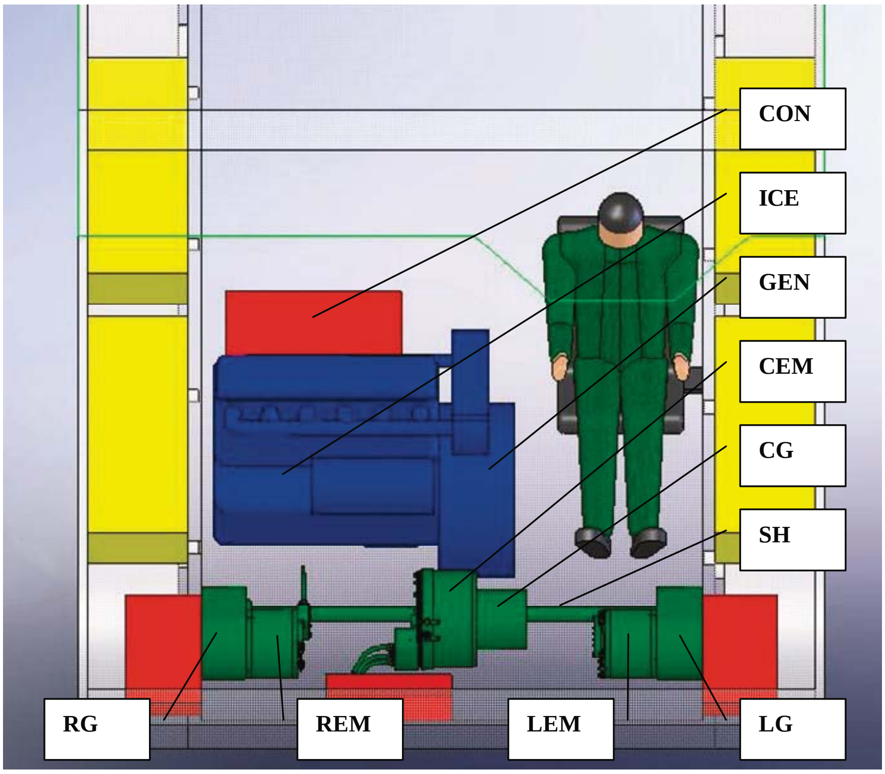


*Fig. 10. Hybrid electric drive components location: RG – right gearbox, REM – right electric motor, LEM – left electric motor, LG – left gearbox, SH – shaft, CG – central gearbox, CEM – central electric motor, GEN – generator, ICE – internal combustion engine, STE – control unit*

Gearboxes, shaft and electric motors are located near track sprocket (Fig. 10). Right and left planetary gearboxes are connected to the central gearbox with the shaft. Both of them are planetary type. Central gearbox is cylindrical type. At very low speeds in heavy terrain only side motors are used due to high torque demand. At high speeds central electric motor is used for propulsion and side motors for steering. Central engine peak power is 145 kW and peak torque 300 Nm. Side engines peak power 125 kW and peak torque 400 Nm.

## 5. Conclusions

Hybrid drive application seems to be a right way of increasing speed, range and internal space organisation flexibility of military tracked vehicles. Using batteries as a source of energy provides new features like stealth operation for a certain period of time during combat missions.

Analysis of existing and currently developed tracked vehicles solutions was performed and main parameters of hybrid electric concept vehicle were formulated. For initially set up parameters a study of possible hybrid propulsion system solution was performed.

Study on hybrid tracked vehicle driving system was done in the following steps:

- analysis of driving system configuration ,
- dynamic model of the vehicle formulation and simulation of vehicle performance,
- virtual prototype formulation with components layout optimization.

Analysis shown that concept vehicle fulfils the initially set up parameters and provides an useful input for further study oriented on development of a new tracked vehicle or modification of existing ones in order to increase their performance.

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