HUNGARIAN JOURNAL
OF INDUSTRIAL CHEMISTRY
VESZPRÉM
Vol. 39(2) pp. 317-320 (2011)

EFFICIENCY AND MASS OPTIMIZATION OF ELECTRIC PERMANENT MAGNET MOTOR DRIVEN VEHICLE

J. POLÁK✉

Széchenyi István University, Department of Automotive and Railway Engineering
H9026 Győr, Egyetem square 1, HUNGARY
✉E-mail: polakj@sze.hu

The propulsion system of road vehicles could be realized with the use of electric motor and a transmission system. Complex analysis of these systems has been the topic of many recent researches, so an existing drive train has been chosen. The systems in this paper consist a permanent magnet 3 phase synchronous motor and switchable, continuously variable as well a constant ratio propulsion system.

The most important variables in this study are the torque, RPM and power of motor, the combined efficiency dimensions and mass of drive train, vehicle mass, speed levels, mode and way of vehicle use. Our target is to create such a drive train, which has the best efficiency and lowest weight at a defined power level.

Keywords: efficiency, mass, optimization, vehicle

Introduction

The solution is an optimized selection, based on the analysis of different construction variants and gear ratios. From construction point of view, the most simple solution is the direct drive electric motor, what requires high size and expensive motor. Gearbox applied in order to extend the RPM range will change dimensions, efficiency and makes the system more expensive. Our goal is to find the ideal combination for the given vehicle.

Dynamic investigation of vehicle drive trains in case of internal combustion engine and electric motor

The combined operation of internal combustion engine and vehicle can be described graphically on a Torque-RPM diagram, where we plot the torque of the crankshaft of the engine in the function of RPM, the constant power curves, the different resistances of the vehicle at different gear ratios and the specific consumption at different load and RPM levels.

The torque of elevation and rolling resistance at the engine crankshaft can be described by the following equation:

$$M_\psi = \psi \cdot G \cdot R_g \cdot i_{hm} / \eta_{hm}$$

The torque of drag projected as a resistance on the engine crankshaft can be calculated by the following equation (See on *Fig. 1*):

$$M_l = 2 \cdot \rho_l \cdot R_g \cdot A \cdot c_v \cdot \pi^2 \cdot i_{hm}^3 / \eta_{hm}$$

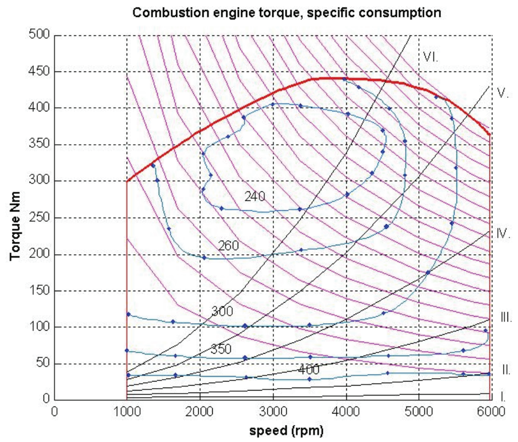

Figure 1: The torque of drag projected as a resistance on the engine crankshaft

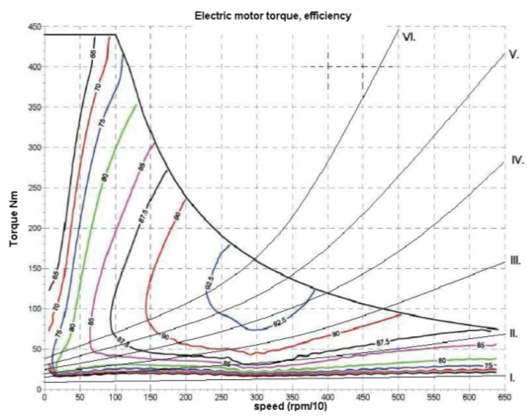

Figure 2: The torque of drag projected as a resistance on the electric motor shaft

Based on the method above, the combined operation of electric motor and vehicle can be described on a *Fig. 2*. In the diagram, you can see the efficiency of the electric motor instead of specific consumption.

The correspondences above gives possibility of stationary study of different motor and transmission combinations, what makes the foundation of further and deeper analysis.

Electric motors applicable for vehicle drive

The heart of all electric driven vehicle is the electric motor. They are existing in many variations, and belongs to the most efficient drive units. Compared to the IC engines, electric motors crates zero emission. Technically there are 3 moving parts on a motor, and estimated lifecycle is definitely longer then IC engines. The applicable electric motors for vehicle drive are the following:

- External excitation motors (coil or permanent magnet)
- AC motors
  a) Reluctance motors (Switched Reluctance Motor, SRM),
  b) MCDC motors
  c) 3 phase Electronic Commutation Direct Current (ECDC) motors
  d) 5 phase ECDC motors
  e) BLDC motors

Different type of electric motors may be classified based on the most important properties *(Table 1)*.

Current state of the art vehicle drives uses 3 phase PM synchronous motors, so we are going to study in this paper this type only. In our environment we have engineering know-how in design as well manufacturing ability.

Table 1: Different type of electric motors

	BDC	**BLDC/PMS**	**AC**	**Cont. excitat.**	**Ext. excitation**	**Reluctance**	**Crossfield**
Power	High	Small	medium	high	good	Good	high
Mass	Heavy	Light	Light	light	medium	medium	medium
Dimension	Big	Small	Medium	small	medium	medium	big
RPM	Low	High	High	medium	medium	high	Low
Cost	medium	expensive	cheap	Very expensive	medium	Cheap	Very expansive

Transmissions applicable for vehicle drive

The following transmission types may be used for electric motors

Constant ratio transmissions

- Chain drive
- Cogged belt drive
- Gear box type
- V-belt drive

Variable ratio transmissions

- Gear type
- Continuously variable transmission
- Planetary gear transmission

Efficiency of transmissions may vary between 20–95%

The value of efficiency of drive defined by technical literature, but these facts concern general situation. In this instance the correct choose of drive is with testing bench.

Studying the transmissions, there are two main types among them: Constant ratio and variable ratio. When selecting a transmission type, two factors are taken into consideration: mass and efficiency. Among this two parameters, also important factors are the complexity of transmission, what defines the manufacturing cost and feasibility for the certain application, as well the necessary auxiliary equipment parameters what has affect on overall mass and efficiency of the unit.

Studying the transmission types for electric driven vehicles available on the market, we may state that there are 3 main types of transmissions:

Chain drive – most of the case on two wheel vehicles

Cogged belt transmissions – commonly used on two wheeled vehicles and smaller four wheel vehicles

Planetary gear transmissions – medium and big sized four wheel vehicles

Small mass, low weight, simple construction, easy and fast repair are the advantages of the chain and cogged belt drives. Meanwhile, because of the constant ratio, it is hard to optimize the transmission for the ideal conditions matching to the electric motor's parameters.

The advantage of applying planetary gear drives are the ability of changing gear ratios. This allows to operate the electric motor on the best efficiency range among different operation environment. Although considering the switching mechanism, it makes a more complex and heavier transmission.

Weight and efficiency optimization of transmission

Motor: By studying weight/power ratio of electric motors, we can state, that the weight increase compared to power increase is smaller. See on *Fig. 3*.

For the mass optimization of a drive train, we can select dependent and independent variables.

Independent variables are: RPM of motor *(n)*, diameter of motor *(Ǿ)*, mass of motor (m_m), efficiency of motor (η_m) gear ratio (z_h), mass of transmission (m_h), efficiency of transmission (η_{hm}).

Dependent variables are the mass (m_{hl}) and efficiency (η_{hl}) of drivetrain.

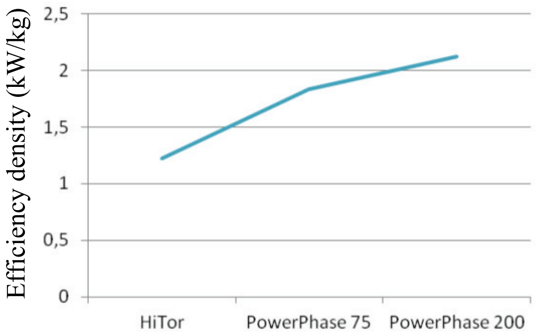

Figure 3: The weight/power ratio of electric motors

Mass of drivetrain depends on the weight of motor and transmission:

$$m_{hl} = \mathrm{f}(m_m, m_h)$$

Efficiency of drivetrain depends ont the efficiency of motor and transmission

$$\eta_{hl} = \mathrm{f}(\eta_m, \eta_{hm})$$

$$m_{hl} = m_m + m_h$$

Weight reduction of PMSM motors can be performed on the following components:

- Weight reduction of Copper *(m_{copper})*,
- Iron rotor mass reduction *(m_{iron})*,
- Magnet mass reduction *(m_{magnet})*.

Other components int he motor (front and rear cover, shaft, bearing etc) mass *(m_{const}.)* may considered as constant elements. Mass of motor consist the mass of these components, so the weigh of the motors equals to:

$$m_{PMS} = m_{copper} + m_{iron} + m_{magnet} + m_{const}$$

Changing the mass and proportions of the above mentioned components have effect on the PMSM motor characteristics, operational properties and efficiency.

By applying transmission, beside the mass of the motor the mass of transmission will count as well:

$$m_{hl} = m_{PMS} + m_h$$

By increasing motor diameter, the torque derived by the motor also can be increased, but this way the inertia moment of motor will increase too, therefore the acceleration to the set point of motor will be slower. The torque is proportional to the dn/dt value of acceleration.

$$M = \theta \cdot 2\pi \frac{dn}{dt} \Rightarrow \frac{dn}{dt} = \frac{M}{2\pi\theta}$$

By studying moment of inertia of the rotor, we can state that the moment of inertia is proportional to the square of the distance measured from the center of rotation.

$$\theta = m \cdot r$$

By application of hub motors, the motor and wheel common moment of inertia needs to be examined. By installing transmission unit, an additional rotating mass gets into the system, where the moments of inertia are cumulated.

$$\theta = \sum_{i=1}^{N} m_i \cdot r_i^2$$

Therefore by increasing diameter of the motor, such motors can be designed, where the increasing torque and reduced RPM (max. 200–1200 RMP) by appropriate optimization the application of transmission unit may be omitted.

By decreasing the diameter of the motor, the maximum torque output will be reduced as well, but the RPM of the motor can be increased (max. 4000–7500 RPM). Although by reaching such RPM range, application of transmission system will be necessary.

Efficiency of drivetrain depends on the transmission and motor efficiency:

$$\eta_{hl} = \mathrm{f}\,(\eta_m, \eta_{hm})$$

Drivetrain efficiency in case of hub motor:

$$\eta_{hl} = \eta_m$$

By applying transmission in the drivetrain, we have to take into consideration the transmission efficiency:

$$\eta_{hl} = \eta_m \cdot \eta_{hm}$$

Visible that the analysis of vehicle drives and motor, the work up convenient transmission system is a complicated mathematical analysis. The first step we make the adequate mathematical relation after we can test the convenient transmission on testing bench. We can get some results and these compare results with results of testing bench.

Summary

Goal of the study, is to develop and create the most efficient and lightest drivetrain and transmission to a given parametric system, (weight, speed, application area, etc.) vehicle. It is not possible to define the optimal drivetrain to a certain vehicle type. Analyzing drivetrain parameters based on the vehicle input data can be chosen the most suitable drivetrain.

For drivetrain analysis, mathematic modeling can be used, which leads to the most suitable drivetrain selection based on the dependent and independent variables considered in the system. By the use of math software, one can simulate and analyze the drivetrains. By studying the results, the drivetrain can be selected and built and tested on test bench. Results of testing can be compared against modeling. This comparison gives feedback for further model creation, also it makes the optimization process examinable and analyzable.

SYMBOLS

M_ψ - torque of elevation and rolling resistance on engine shaft
M_l - torque of drag on engine shaft
ψ - rolling friction resistance
G - mass force of vehicle
R_g - rolling radius
i_{hm} - total transmission ratio
η_{hm} - transmission efficiency
ρ_l - air density
A - Vehicle surface perpendicular to driving direction
c_v - drag coefficient
Θ - inertia moment
n - RPM of motor
m - mass
r - distance measured from shaft
m_{hl} - mass of drivetrain
η_{hl} - efficiency of drivetrain
$\acute{\varnothing}$ - motor diameter
m_m - motor mass
z_h - gear ratio
m_h - mass of transmission
m_{copper} - copper (coil) mass
m_{iron} - iron rotor mass
m_{magnet} - magnet mass
$m_{const.}$ - motor component mass
η_m - motor efficiency
η_{hm} - transmission efficiency

ACKNOWLEDGEMENTS

TAMOP-4.2.1/B-09/1/KONV-2010-0003: Mobility and Environment: Research in the fields of motor vehicle industry, energetics and environment in the Central- and Western-Transdanubian Regions of Hungary The Project is supported by the European Union and co-financed by the European Social Fund”

REFERENCES

1. L. GUZZELLA, A. SCIARRETTA: Vehicle Propulsion Systems, Springer-Verlag, Berlin Heidelberg, 2005, ISBN 978-3-540-25195-8