IMPROVING ELECTRIC VEHICLE ENERGY EFFICIENCY WITH TWO-SPEED GEARBOX

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ABSTRACT

This research focuses on improving electric vehicle energy efficiency with two-speed gearbox. Traditionally, the electric motor of an electric vehicle is coupled to driving wheels with a single-speed gearbox. Electric motor as a traction motor enables such drivetrain but with a single-speed gearbox the electric motor must operate in wide speed range. The use of wide speed range forces the motor to work in non-optimal speeds which effects on its energy efficiency. The possible energy efficiency improvement of electric vehicle with multi-speed gearbox is examined in this research. The benefits of two-speed gearbox were evaluated based on the simulation results provided by a developed simulation model. Evaluations were done by comparing the energy consumptions of the reference model to the model that utilizes a two-speed gearbox. Simulations also included an optimization study for determining the optimal gear ratios in order to minimize energy consumption. The results reveal that it is possible to improve energy efficiency with two-speed gearbox but it is heavily dependent on the motor efficiency map which in turn depends on the electric motor type. The benefit of a two-speed gearbox was slightly better in higher speed driving cycles.

Keyword: - *Electric vehicle, energy efficiency, transmission, simulation etc.*

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1. INTRODUCTION

Based on Eurostat statistics, 2015, it can be stated that the reduction of new registered cars emissions is based on the improved internal combustion engine (ICE) technology. Statistics shows that in 2013 only 4 percent of new registered cars used alternative fuels. In the statistics, alternative fuels are referred as liquefied petroleum gas, natural gas, electricity and other alternative fuels. Even when hybrid cars are taken into account the majority on new registered cars are powered only with traditional fuels, diesel or petrol. It is clear that in the future ICE technology will reach its limits and reduction of emissions will saturate. This will lead to increasing need of cars using alternative fuels. European commission, 2011, stated a goal that in 2050 conventionally fuelled cars will be phased out of cities. In this case, conventionally fuelled cars are referred as non-hybrid vehicles using internal combustion engines. Nevertheless, this will increase the need and importance of electric vehicles (EV) as crucial members of future car fleet. One of the major differences between ICE vehicle and EV performance is the achieved driving range. Nowadays ICE vehicles' have superior range compared to EVs and this is one of the main reasons why popularity of EVs has not raised. Although most of the daily driving is done at urban areas and extensively long driving range is not that essential, driver needs some certainty that car has enough range for whole day needs. Improving the range of EVs would promote the popularity of them. Increase of range can be done by growing the battery capacity, but the size, weight and cost sets limits for this. Another way to enhance the performance of EV would be improving the energy efficiency of the vehicle. Key component of the EV is the traction motor and allowing it to operate at its best possible efficiency would be one way of improving EV's energy efficiency. Total efficiency of electric motor and control system are only about 86 percent. Traction motors used in EVs' need to provide enough torque for acceleration and hill climbing and power for high speed cruising. With suitable motor and reduction gear combination sufficient driving characteristics are achieved and there is no need for multispeed transmission that is required with ICEs. In traction application, electric motor uses wide speed range and thus it is not operating at optimal efficiency. These characteristics leads to an idea of multi- 2 speed transmission use in EV to improve its efficiency by moving the operating point of electric motor to more efficient region.

1.1 OBJECTIVES

The main interest in this research is examining the effects of adding two-speed gearbox to EV's powertrain. As stated earlier, there is potential to improve EV efficiency by using traction motor at its optimal area of efficiency. In addition, inverter and its efficiency is also considered in this research because it is also dependent on the operating point. Energy consumption comparison between fixed gear ratio gearbox and two-speed gearbox is done and effect to the overall EV energy efficiency is examined. Another objective is to examine whether introducing two-speed gearbox reduces the driving cycle dependent energy consumption. This means that with properly selected gear ratios the electric traction motor and inverter would operate on their optimal operating area despite the used driving cycle and the losses caused by the motor and inverter would be independent from the driving cycle. An optimization study is required to determine the best suitable gear ratios to achieve energy savings in different driving cycles.

1.2 SCOPE

This research focus on passenger car size EV which has two-speed gearbox in its drivetrain. Only the two-speed gearbox's effect on the traction motor and inverter behavior and the effect on the overall energy efficiency of the EV is considered. Most suitable gear ratios to be used in various driving cycles are found. The possible weight increase and multi-speed gearbox's efficiency are taken into account. On the other hand, friction losses of the clutch during the gear change and costs of implementing of the multi-speed gearbox are ignored.

1.3 METHODS

The effect of multi-speed gearbox in EV powertrain is evaluated with simulations. Simulation is carried out with Matlab/Simulink and reference model, that is equivalent to real life EV with single-speed gearbox, is created. After the reference model is verified to match real life EV at sufficient accuracy, the model can be developed further by adding two speed gearbox to it. The evaluation of two-speed gearbox effect to EV's energy efficiency can be done by comparing developed model to a reference model. Comparison of energy consumption between driving cycles is done and traction motor operating points during cycles are plotted to the efficiency maps. Also, the losses of motor and inverter in different driving cycles are determined to explore the cycle dependent losses. At the end, evaluation of multi-speed gearbox utility in EV's drivetrain is done.

2. ELECTRIC VEHICLES

There are many different possibilities for EV drivetrain topology. Used traction motor defines the need for possible gearbox and the number of traction motors per driven axle determines the need of differential. Schematic EV powertrain with single-speed reduction gear is presented in figure 1and it shows that from the motor to wheels the powertrain is mechanical and thus components used are similar to conventional vehicles. The energy storage of EV is usually an electrochemical battery, often referred only as battery. During charging the energy from the grid is converted to a potential chemical energy and during discharging the chemical energy is converted back to electric energy. The specific energy, the energy capacity per unit battery weight (Wh/kg), is dependent on the battery type. The battery discharge and charge efficiency is dependent on the type, but also on the state of charge (SOC) of the battery. Usually the discharging efficiency is at its highest at high SOC values and it decreases with the SOC. Nissan Leaf uses Lithium-ion batteries (Nissan Motor 2017) and these batteries have specific energy of 80-130 Wh/kg and efficiency above 95%. On the other hand, same quantity of specific energy but efficiency only from 75% to 85%. The energy is supplied from the battery to the motor via motor controller and inverter that provides sufficient waveform for the motor. The efficiency of inverter is high, usually around 97%, but a solution to provide 99% efficiency has also been reported. The main component of the EV is of course the electric motor. The efficiency of the motor is dependent on the torque and speed. The type of motor defines the efficiency of the motor and different types of motors are presented later in this work. It is notable, that electric motors have significantly better efficiency than ICEs, but they also have limited region for maximum efficiency.

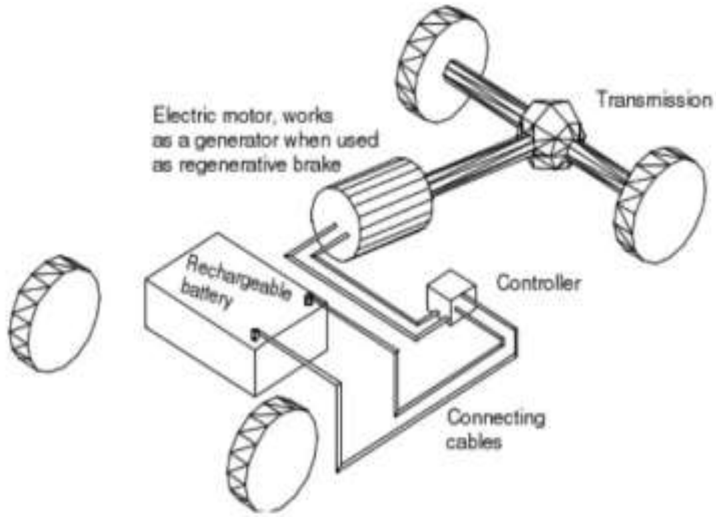

Fig -1 Schematic EV powertrain.

The estimation of possible energy efficiency improvement of EV can be done if the energy distribution of the vehicle is known. Loshe-Bush, Duoba, tested and evaluated Nissan Leaf performance at Argonne National Laboratory. In the figure 2 is presented the energy distribution of year 2012 Nissan Leaf. Majority of the energy is consumed to overcome resistance forces but a significant share is also powertrain losses. They evaluated that in city driving cycle powertrain losses are more than 20 % of total energy consumption which leaves possibility of improvement. In the powertrain losses contain losses of the motor, inverter and the mechanical powertrain. In electric vehicles, the mechanical powertrain is simple, usually containing reduction gear and differential. Because the powertrain is simple, it can be assumed to have high efficiency and thus the motor and inverter can be assumed to contribute a major part of the powertrain losses.

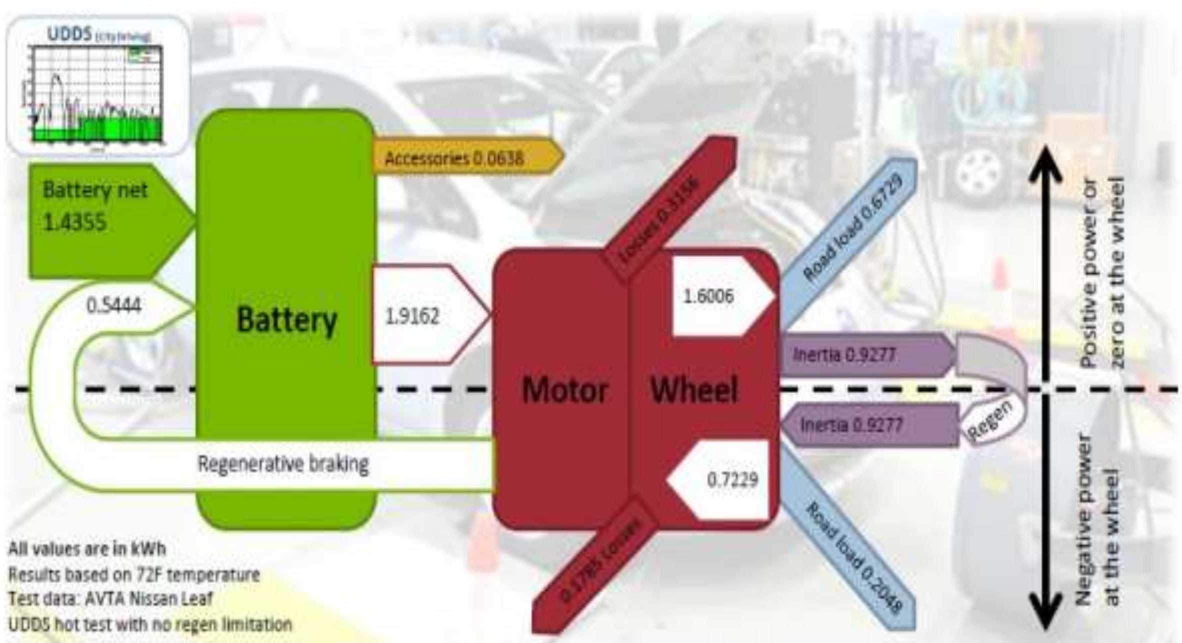

Fig -2 Nissan Leaf energy distribution at UDDS cycle

3. MULTI-SPEED TRANSMISSIONS

There are many competitive options as transmission of a passenger vehicle. There have been several studies of different transmission configurations for EV from commonly used single gear with fixed gear ratio to multi-speed manual transmissions and continuously variable transmissions (CVT). Because the efficiency of the transmission has major role in this research, the efficiencies of different multi-speed transmissions are considered. With CVT vehicles traction motor, ICE or electric motor, can operate at the ideal operating point. In mass production vehicles' the CVT technology that is used is almost in every case pulley transmission, in which the main component is variator. Power is transmitted with the help of friction via a chain that run between two axially adjustable taper discs. The discs' diameter can be varied thus the chain runs between two adjustable diameters. Figure 3a presents the operating principle of a variator. Another CVT configuration is toroidal variator. The variable gear ratio is achieved by swivelling the friction gears, figure 3b.

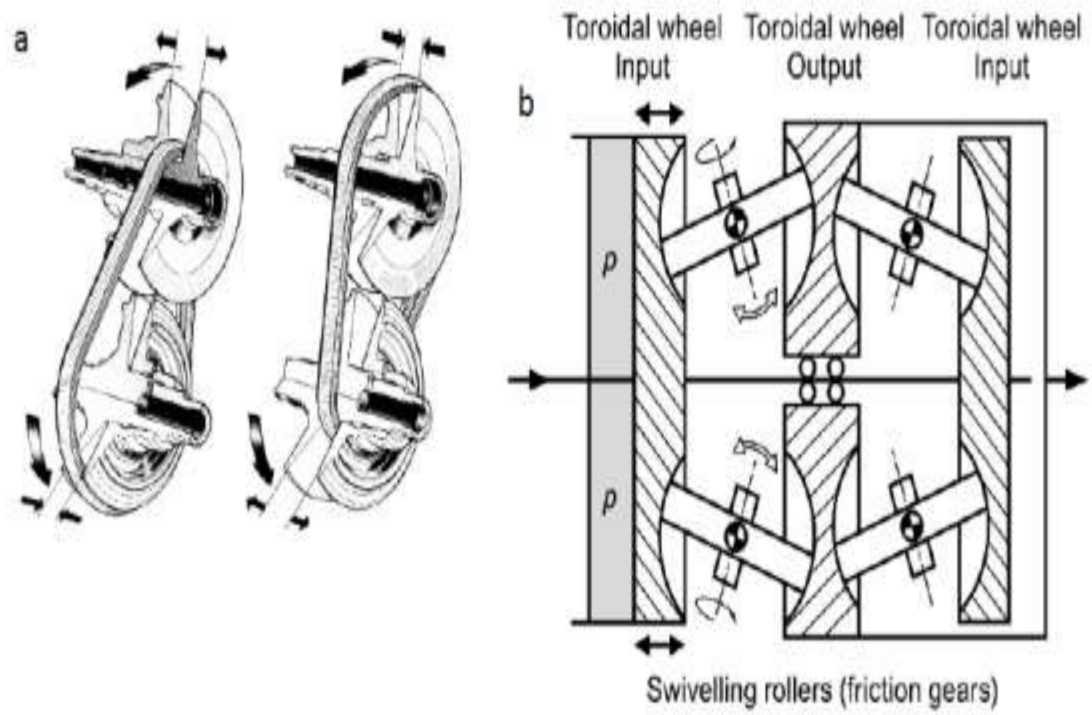

Fig -3 CVT configurations. Pulley (a) and toroidal (b)

The major drawback with CVT is the poor efficiency, compared to traditional gear transmission. The traditional CVT that is used with ICE vehicles has efficiency of 85% but with EVs more simple construction can be achieved i.e. no torque converter is needed, thus efficiency of 90% can be achieved. The achieved improvement in electric motor performance and energy efficiency with implementation of CVT may be even out due to the poor efficiency of the transmission. In the table 1 is listed efficiencies of different types of gearboxes. The automatic transmissions with various gear ratios use planetary-type gearboxes. Developed Simpson type two-speed planetary gear for EV application. They calculated that the transmission gear mesh would have average efficiency around 98%, but the built prototype, that contained also clutches, had measured efficiency only 85%.

The planetary gearbox enables the gear ratio change without engaging and disengaging individual gears this feature can also be achieved with dual clutch setting. Their solution also included only two gear pairs per gear, which increases the efficiency of the transmission, because the efficiency of single gear pair is high as chart 1 show. For this research, the powertrain efficiency can be evaluated based on the table 1. The simulated vehicle is assumed to have reduction gear and differential. If the reduction gear is implemented with spur gear, it has high efficiency as chart 1 shows. For the differential, the bevel gear is most likely the choice, so it would have poorer efficiency than the reduction gear.

Type of gearbox		η (%)
Gear pair	Spur gear	99.0–99.8
	Bevel gear	90–93
Mechanical transmission with splash lubrication	Passenger car	92–97
	Commercial vehicle	90–97
Automatic transmission with various gear ratios (AT, DCT)		90–95
Mechanical continuously variable transmission		87–93
Hydrostatic continuously variable transmission without power-split and mechanical part		80–86

Chart -2 Gearbox efficiencies

4. SIMULATION MODEL OF AN ELECTRIC VEHICLE

The vehicle model is constructed in Matlab/Simulink environment and it includes a speed controller to follow the reference speed defined by the driving cycle. The schematic block diagram of the model is presented in the figure 4. The supplied power of the motor, to meet reference velocity, can be calculated with the help of supplied torque and the rotation speed of the motor. The actual power demand and energy consumption is determined by multiplying the motor power with the efficiency of the motor, inverter and battery. The efficiency of the differential and reduction gear are taken into account at block TR eff. Transmission and battery efficiencies are assumed to be constant while motor and inverter efficiencies are defined by the efficiency maps' of each component. In the vehicle model the negative power supplied by the motor is assumed to be used for recuperation. Because the electric motor acts as a generator in recuperation, the recuperation efficiency is also dependent on the motor and inverter efficiency maps. Different data sources were discovered to find parameters for the model. Grillaert, Pace, concluded freewheel test for Nissan Leaf, to determine the coefficients for rolling resistance and aerodynamic drag and came out with results of cr 0.013 and cd 0.27. They assumed that the car has frontal area of 2.5 $m2$. Nissan reports similar official value of 0.28 for cd. The chosen parameters are listed in chart 3 and some variables are estimated by the author, such as the motor inertia, because no reliable data was available. The final selection of each parameter is done to achieve the optimal achievable simulation results i.e. energy consumption of the vehicle model matches the measured data in different driving cycles as accurate as possible.

The simulation results are compared against actual measured dynamometer data. They measured year 2012 Nissan Leaf energy consumption at Argonne National Laboratory in different driving cycles and conditions. These results are used to verify the reference model.

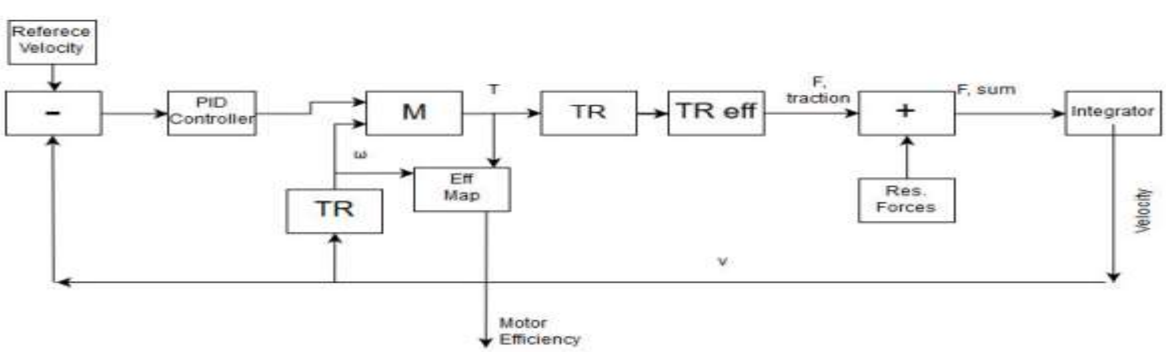

Fig -4 . Schematic block diagram of the vehicle model. Electric motor (M), Transmission (TR).

Vehicle mass, m_v	1700	kg
Wheel dynamic radius , r	0.31	m
gravitational acceleration, g	9.80665	m/s^2
Rollign resistance coeff, c_r	0.01	-
Aerodynamic drag coeff, c_d	0.29	-
Vehicle frontal area, A_f	2.276	m^2
Density of air, ρ	1.2	kg/m^3
Final drive ratio	7.9377	-
Differential gear efficiency	0.98	-
Reductio gear efficiency	0.93	-
battery efficiency	0.95	-
Auxiliary power, P_{aux}	280	W
Motor moment of inertia, J_m	0.01	kgm^2

Chart -2 Vehicle model parameters

	Reference (kWh/100km)	Model (kWh/100km)	Delta (kWh/100km)
NEDC	14.38	13.65	-0.73
ECE-15	12.01	11.89	-0.12
UDDS	12.15	12.53	0.38
HWFET	14.25	14.17	-0.08

Chart -3 Simulation results and measured energy consumption

4. CONCLUSIONS

The possibilities of two-speed gearbox utilization were discovered quite narrowly in this research and only the effect on the traction mode efficiency was considered with simple gear changing strategy. Gear ratios are also selected based on a rather simple optimization. The gear changing strategy could be chosen in a way, that the motor provides always the best efficiency for traction and regeneration. In addition to improving energy efficiency, the gear changing strategy could be selected to improve vehicle driving characteristics and different driving modes could be provided. This research revealed some topics for future research. One topic could be finding proper motor-inverter combination to be used with two-speed gearbox and evaluate the improvement in energy efficiency. Another matter to view could be the effect of gear changing to energy consumption and finding the suitable strategy for it. This research offer basis for all mentioned topics and the model created in this research can be easily modified for different type of vehicles that use different types of motors.

5. ACKNOWLEDGEMENT

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