Theoretical study of SES solution for extending the electric vehicles autonomy

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Abstract. It is expected that in the near future the propulsion of motor vehicles will be mainly done using electric motors. The fundamental arguments are a much lower cost of travel and elimination of exhaust gases. However, the biggest problem of electric propulsion vehicles is the reduced autonomy. Regarding this disadvantage, there have been several attempts and they will continue to exist in order to eliminate or at least to reduce the phenomenon. Considering that, at present there is no technical solution showing real efficiency. A compromise can be achieved by using a small compact system based on a low cylinder thermal engine that trains an electric generator. This is achieved by means of a mechanical transmission called SES (Secondary Energy System). The main role is to charge the battery on board the vehicle, thus increasing its autonomy.

1. Introduction

It is well known that the main disadvantage of thermal engines is the pollutant products generated by the combustion of fossil fuel which is indispensable for their functioning.

Due to the massive increase in the number of vehicles which are produced and put into circulation worldwide, this area has captured the attention of people with environmental protection responsibilities, and not only, the subject being designed among the first ones of international interest.

ACEA (European Automobile Manufacturers Association) and EC (European Commission) have agreed a drastic reduction in pollutant emission limits, in some cases even by 96% compared to the Euro 1 emission standard in 1992. Recently, the laboratory test of cycle of exhaust gases resulting from the burning of fossil fuel in the internal combustion engine, the so-called WLTP (Worldwide Harmonized Light-Duty Vehicles Test Procedure), has also been modified. It reflects with high accuracy the values of fuel consumption and pollutants emitted, the current test procedure including many factors that can be found when using vehicles in real life.

The fact that the emissions limits at the moment are massively diminished has not led to the end of the production and marketing of road vehicles. On the contrary they came up with challenges in this industry, the manufacturers doing everything possible to develop new solutions to meet the imposed requirements and at the same time achieve the highest efficiency. These aspects have been achieved without great difficulties. Also, it is confirmed that there will be a substantial new reduction in the limits of the polluting emissions and the removal from the production of the diesel thermal engine will generate a reorientation towards other types of vehicle propulsion systems. This will satisfy both the demands of the environmentalists and those of the auto market.
2. Functional analysis
At present, there is a tendency to use electric motors in order to ensure the propulsion of vehicles. Most people consider it is a successful solution. Many researches in the automotive industry managed to raise the potential of electric-powered vehicles, obtaining satisfactory results. However, an optimal and efficient solution to replace and decommission thermal engines has not been found, yet. The main disadvantages are the reduced autonomy, the poorly developed infrastructure and the sources of electricity production worldwide.

Therefore, in order to increase the autonomy of electric vehicles, the researchers tried many considerable innovations to reach the original purpose. This includes the following solutions:

- Equipping vehicles with solar panels to capture solar energy and convert it into electric energy, and then into mechanical energy, as suggested in figure 1 [1]:

![Figure 1. Capture solar energy.](image1)

- Equipping vehicles with turbines for capturing the energy generated by air resistance (wind energy) and converting it into electricity, subsequently into mechanical energy, as shown in figure 2 (a) and figure 2 (b) [2]:

![Figure 2 (a), (b). Wind energy capture.](image2)

- Operation of electric vehicles powered by an aerial, underground or wireless electricity network, as set out in the diagram in figure 3:

![Figure 3. Wireless charging.](image3)
Quick replacement of batteries.

The variants mentioned above bring benefits to the electrical propulsion system, but do not fully solve its problems. It can be concluded that for the transition period, respectively the transition from the internal combustion engine propulsion system to propulsion provided by an electric motor, the hybrid electric propulsion system is the most efficient solution.

It has been proven that the use of internal combustion engines combined with electric motors solves many of the problems presented both by thermal and electric motors. Therefore it would be appropriate to use the electric hybrid propulsion system, at least for a certain period of time depending on the progress of 100% electric vehicles.

All the requirements can be met at a small compact system based on an internal combustion engine designed to operate an electric power generator. The energy which is produced will supply a storage unit, an accumulator, which in turn has the role of supplying the motor / electric motors on board the vehicle. The authors of this study found a solution which is called SES (Secondary Energy System).

The main purpose of this system is to reduce the charge-discharge cycles, the dimensions and mass of the battery in order to achieve a greater autonomy of electric vehicles. The second role is to ensure travel, to the nearest charging station of the electric propulsion vehicle, if the battery runs out of electricity.

3. Theoretical operating models

3.1. The generator

Frequently, generators used in the motor vehicle industry play an important role in charging the battery accumulators, as well as in providing sufficient electricity for all consumers on board the vehicle. They must comply to these two main objectives: to be as simple as possible from the constructive point of view and, at the same time, to have a reduced weight.

Vehicles are usually equipped with a three-phase synchronous AC generator with electromagnetic excitation with radial brushes with claw-shaped poles. The technical solution is considered to be an efficient one due to its economical and constructive simplicity. The aspect of the obtained electromotive force approaches the sinusoidal variation.

The examination of operation and the calculation of the parameters of the synchronous generator can be achieved by using the phase diagrams, presented in figure 4 where the notations in these figures correspond to the following specific sizes [3]:

- \( X_d \) – longitudinal synchronous reactance;
- \( X_q \) – transverse synchronous reactance;
- \( X_s \) – stator dispersion reactance;
- \( U_f \) – phase tension;
- \( R \) – phase winding resistance;
- \( I_f \) – phase current;
- \( \phi \) – the phase angle between the phase voltage and the phase current;
- \( \theta \) – the angle between the idle voltage and the induced electric motor voltage;
- \( \beta \) – the angle between the voltage at the end and the voltage on the phase;
- \( E_0 \) – the voltage on the empty drive induced by the rotor flow \( \Phi_0 \);
- \( E_{5d} \) – the electric motor voltage induces by the longitudinal flow in iron \( \Phi_{5d} \);
- \( E_{ad} \) – the difference between \( E_{5d} \) and \( E_0 \), represents the electric motor voltage induced by the reaction of the induced flow \( \Phi_{ad} \);
- \( E_{aq} \) – the electric motor voltage induced by the transverse magnetic flux \( \Phi_{aq} \).
Figure 4. General phase diagram and simplified diagram of the synchronous generator with apparent poles.

In order to get the size of the generator it is necessary to know the nominal effective power of the internal combustion engine. The basic equations can thus be obtained. This way, first, the power of driving the generator results. Thus, when the speed of the thermal motor is identical to the speed of the generator, the power emerges from the relation:

$$P_{ng} = P_d = P_e - P_{aux} = \beta P_e \quad (1)$$

Next, the following relationship is used to determine power at the generator terminals:

$$P_g = P_d \eta_g = P_e \eta_g \beta \quad (2)$$

If the generator rotor is driven by a mechanical gear that reduces or multiplies the number of rotations, the driving power will be determined using the following relation:

$$P_{ng} = P_d = P_e - P_{aux} = \beta P_e \quad (3)$$

The power from the generator terminals results from the equation:

$$P_g = P_d \eta_g \eta_{am} = P_e \eta_g \eta_{am} \beta \quad (4)$$

If the losses in copper of the stator are not considered, from the simplified phase diagram shown in Figure 3, the active power of a three-phase generator with apparent poles appears. It becomes equal to electromagnetic power, being determined as follows:

$$P_a = P_{em} = 3 \frac{u_i e_0}{x_d} \sin \beta + 3 \frac{u_i^2}{2} \left( \frac{1}{x_q} - \frac{1}{x_d} \right) \sin 2\beta \quad (5)$$
The couple can also be determined starting from the generic relation of defining the couple:

\[ M = \frac{P}{\omega} \]  

(6)

It must be taken into account the fact that when it is required that the transmission be carried out by means of a mechanical gear, the values of the transmission ratio \( i_{am} \), and the values of the transmission efficiency \( \eta_{am} \) shall be considered, resulting in the following equation:

\[ M_{em} = 3\frac{pU_{j}E_{0}}{\alpha x_{d}} \sin \beta + 3\frac{pU_{j}^{2}}{2q} \left( \frac{1}{x_{q}} - \frac{1}{x_{d}} \right) \sin 2\beta \]  

(7)

In the above equations the notations have the following meanings:

- \( P_{em} \) – electromagnetic power [kW];
- \( P_{ng} \) – generator power [kW];
- \( P_{g} \) – power from the generator terminals [kW];
- \( P_{e} \) – the actual power of the thermal engine [kW];
- \( P_{aux} \) – the driving power of auxiliary installations [kW];
- \( \beta \) – coefficient representing the driving power of auxiliary installations (\( \beta = 0.90...0.95 \));
- \( \eta_{s} \) – total efficiency of the synchronous generator (\( \eta_{s} = 0.92...0.98 \));
- \( \eta_{am} \) – mechanical gear yield (\( \eta_{am} = 0.97...0.99 \));
- \( P_{a} \) – active power [kW];
- \( M \) – engine torque [Nm];
- \( \Omega \) – angular output shaft speed [rad/s];
- \( \Omega \) – pulsation (\( \Omega = \omega_{p} \)) [s\(^{-1}\)].

3.2. Battery accumulators

The appropriate battery accumulators operate at all required demands: ensure good use and efficient charging within a specified time, do not require maintenance and do not deteriorate prematurely. At the same time, the specific volume and weight according to the capacity must be as low as possible [4].

Depending on destination, the battery accumulators are designed for:

- start-up;
- stationary;
- traction;
- portable devices.

For cases where the battery accumulators have the main role of providing the electricity needed to ensure the propulsion of the vehicles, the lithium-ion battery accumulators are the most suitable. Instead, for starting the heat engines, lead-acid batteries are used. For example, the discharge capacity of lead-electrode batteries can be deducted using Peukert’s formula:

\[ C_{x} = C \left( \frac{I}{I_{c}} \right)^{n-1} \]  

(8)

- \( C \) – nominal battery capacity [Ah];
- \( I \) – current intensity [A];
- \( I_{c} \) – discharge current intensity [A];
- \( n \) – quality index of electrode plates (\( n = 1,10...1,62 \)).

3.3. Internal combustion engine

Being a small compact system with the main purpose of extending the autonomy of electric-powered vehicles and due to pollution, the thermal engine must be of a spark-ignition type with a small cylindrical capacity, which will ensure the fulfillment of the functional requirements.
3.4. The complete system

Therefore, the proposed system uses a generator driven by an internal combustion engine by means of a mechanical gear. The determination of the optimal modes of operation of this system will be done using the equation of motion:

\[ M_a = M_g + I \frac{d^2 \theta}{dt^2} \quad (9) \]
\[ \theta = \omega t + \beta \quad (10) \]

In the above equations the notations have the following meanings:

- \( M_a \) – training torque [Nm];
- \( M_g \) – the electromagnetic torque of the generator [Nm];
- \( \Omega \) – angle of synchronization [rad/s];
- \( \nu \) – rotor angle [rad/s];
- \( \beta \) – load angle [rad/s];
- \( t \) – time [s].

The current curve provided by a generator which is graphically presented in figure 5, shows that the current intensity provided by a generator of a road vehicle is as higher as the speed of the thermal engine increases.

![Figure 5. Current curve supplied by the generator.](image)

4. Conclusions

The main result refers to the progress that can be made with regard to SES vehicles. This is constituted by an electric propulsion system, associated with a compact and simple system from a constructive point of view, but which has surprising benefits, such as:

- extending autonomy;
- reduced weight of the battery;
- reduction of battery charge and discharge cycles;
- the possibility to move the vehicle even if the electric battery is completely exhausted.

In order to increase the performance and the evolution of electric vehicles it is necessary to intervene with new technical solutions. The system which is presented and analyzed in this paper comes with substantial additions, but for these a well-founded analysis must be carried out from a technical and economical point of view in order to successfully overcome the shortcomings of electric propulsion.
5. References
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