

Application of the internal combustion engine as a range-extender for electric vehicles

Abstract: The article reviews the available solutions of range-extenders with internal combustion engines designed for use in electric vehicles. The using of the on-board range-extender aims to increase the range of an electric vehicle, which is still significantly limited. This fact is connected with relatively small capacity of currently used electric energy storage systems. The development of secondary cells with performances allowing the driving range of electric car to be comparable to average car with combustion engine still faces considerable difficulties. For this reason, the use of the internal combustion engine for propulsion of range-extenders for electric vehicles becomes nowadays more and more popular. In this paper range-extenders from the following companies are described: FEV Aachen, Kolbenschmidt Pierburg together with FEV, AVL list GmbH, Lotus Engineering with Fagor Ederlan, Mahle Powertrain Ltd. and General Motors for Chevrolet Volt / Opel Ampera. High efficiency, low exhaust emission and low noise & vibration obtained with a compact dimensions are priority in the development of these devices.

Keywords: *internal combustion engine, electric vehicle, range extender, exhaust emission, noise, vibration*

Zastosowanie silnika spalinowego w celu zwiększenia zasięgu pojazdów z napędem elektrycznym

Streszczenie: W artykule dokonano przeglądu dostępnych rozwiązań pomocniczych generatorów prądu o napędzie spalinowym z zastosowaniem dla pojazdów elektrycznych. Użycie dodatkowego pokładowego generatora spalinowego ma na celu zwiększenie zasięgu pojazdu elektrycznego, który w dalszym ciągu jest w istotny sposób ograniczony. Fakt ten jest związany z ograniczoną pojemnością dostępnych akumulatorów energii elektrycznej. Opracowanie ogniwi o parametrach pozwalających samochodom elektrycznym uzyskać zasięg jazdy porównywalny z przeciętnym samochodem z napędem spalinowym napotyka spore trudności. Z tego względu wykorzystanie silnika spalinowego do napędu generatora energii elektrycznej w samochodach konstruowanych pierwotnie jako czysto elektryczne staje się obecnie coraz powszechniejsze. W materiale opisano m.in. konstrukcje generatorów energii elektrycznej opracowane przez FEV Aachen, Kolbenschmidt Pierburg wspólnie z FEV, AVL list GmbH, Lotus Engineering razem z Fagor Ederlan, Mahle Powertrain Ltd. oraz General Motors dla pojazdu Chevrolet Volt / Opel Ampera. Priorytetem w konstrukcji tego typu urządzeń jest uzyskanie wysokiej sprawności, niskiej emisji spalin, hałasu i drgań przy zachowaniu kompaktowych wymiarów.

Słowa kluczowe: *silnik spalinowy, pojazd elektryczny, zasięg, emisja spalin, hałas, drgania*

1. Introduction

In recent years, more and more dynamic development of the zero-emission electric vehicles is observed. This is due to the introduction of more stringent legal requirements forcing vehicle manufacturers to further reduce CO₂ emissions. Another factor increasing interest in electric vehicles are very high prices of traditional fuels. However, obtaining by electric vehicle the range and performance corresponding to the average car with a combustion engine requires the use of expensive batteries which have a large volume and weight. This fact leads to the existence in the design a compromise between performance, availability of space in the vehicle and the cost. Currently, the activities of the automotive industry has been strongly committed to the development of new solutions and alternative technologies for electric drive systems and hybrids.

One of the applicable solutions to overcome the limitations caused by the currently available battery

technology is the use of vehicle on-board energy-converting devices of traditional fuel, such as gasoline into electricity. The use in the electric vehicle of an additional generator allows to get an acceptable range and performance of the car by using a relatively small expanded (i.e. also not very expensive) electric battery pack. Due to its primary function of such a fuel converter it became known as range-extender. In short it is an auxiliary power unit consisting of electronic controlled combustion engine of a relatively small displacement and electric generator, which supplies the energy needed to pack the vehicle.

Below an overview of several solutions of range extender which appeared on the market recently is presented.

2. FEV Wankel Range Extender

At the SAE 2009 World Congress FEV Motorentechnik GmbH Aachen presented range extender for an electric vehicle, in which the generator is driven by a single-rotor Wankel engine of a

cylinder displacement 0.295 dm^3 (Fig. 1)[5]. Using the engine of this type allows for a significant reduction in the level of vibration and noise emissions.

An additional advantage of the Wankel engine in this application are extremely small dimensions and low curb weight.



Fig. 1. FEV Wankel Range Extender presented at SAE 2009 World Congress [5]

Rys. 1. Zespół prądowórczy z silnikiem Wankla zaprezentowany przez FEV na Kongresie SAE 2009

Electric power the device is 18 kW, weight 63 kg (14 kg the engine generator 49 kg), dimensions: length 650 mm, width 250 mm and height of 275 mm.

The development version of the device presented above has been used in 2010 in a prototype electric car, the Fiat 500 named Liion [9]. The view of the vehicle Fiat 500 chassis powered from lithium-ion batteries with marked range extender placement is presented in Fig 2.

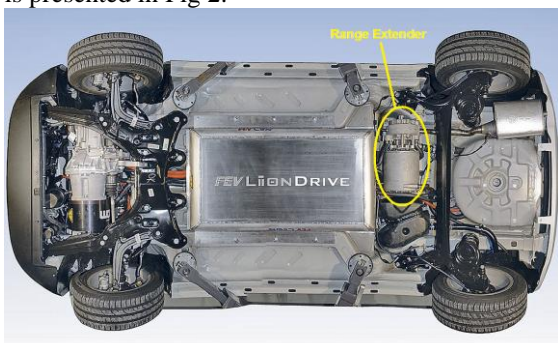


Fig. 2. Chassis of Fiat 500 Liion prototype [7]

Rys. 2. Widok podwozia samochodu Fiat 500 Liion z zaznaczonym położeniem zespołu prądowórczego

Range Extender is installed in place of the fuel tank. The former was replaced by a smaller tank with a capacity of 12 dm^3 . Auxiliary power unit (APU) provides increased vehicle within 306 km of emissions of 80 g/km of CO_2 in the extended range mode.

In the engine designed by AIXRO for automotive structural changes in the intake, fuel injection and exhaust aftertreatment has been introduced to meet requirements for reduced emissions.

3. KSPG – FEV V2 Range Extender

In September 2011, Kolbenschmidt Pierburg (now KSPG) together with FEV presented the concept of compact on-board auxiliary power unit for electric vehicle basing on the V-2 90° spark ignition engine with a vertical crankshaft [10]. A general view of the device model is presented in Fig. 3.

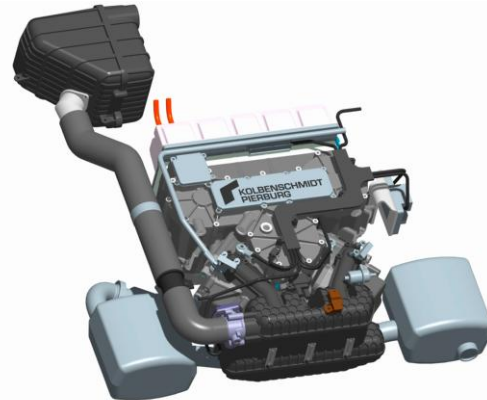


Fig. 3. Overall view of Kolbenschmidt Pierburg - FEV range extender concept [4]

Rys. 3. Widok ogólny modelu agregatu prądowórczego KSPG – FEV

Two synchronous electric generators with permanent magnets (PMSM) with four pairs of poles connected in series are driven from the engine through a gear train. The use of two generators driven by gears from the engine allows for a significant reduction of irregularity of running of V-twin cylinder engine. The idea of using of generator rotors as V-twin engine flywheels is shown in Fig 4

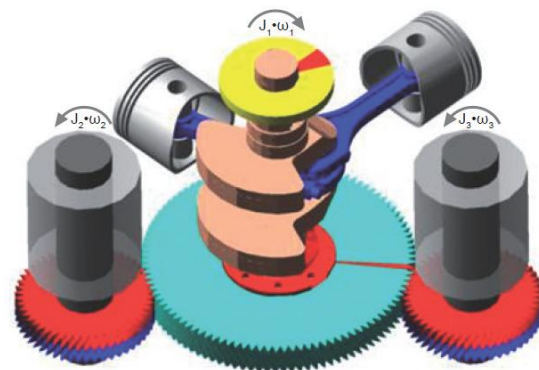


Fig. 4 The idea of V2-engine vibration reduction in KSPG - FEV range extender [1]

Rys. 4. Idea tłumienia drgań silnika o układzie cylindrów V-2 przy wykorzystaniu wirników generatorów jako kół zamachowych

The innovative vibration reduction system presented in the figure above is called FEVcom. Beyond the fuel tank and the radiator all of the components are mounted on the support frame. The use of the engine with vertical shaft allows for a very small total height of the range extender. The result is that it can be easily mounted instead the spare wheel even in relatively small car. Such positioning of the team is also optimal in terms of NVH. Noise and vibration during start and operation will be significantly reduced. The project also includes easy assembly and disassembly of the unit. Basic Specifications KSPG - FEV Range-Extender is presented in Table 1

Table 1. Basic technical data of KSPG - FEV range extender [10]

Tabela 1. Podstawowe dane techniczne zespołu prądotwórczego KSPG - FEV

Length x Width x Height [mm]	665x550x355
Curb weight [kg]	62
Engine displacement [dm ³]	0.799
Engine power [kW/RPM]	30/4500
Generator rated power [kW]	2x15

Nominal power of the device has been determined based on a calculation of the average power demand of segment A car traveling at 100 km/h the hill with a slope of 3%.

The engine has two valves per cylinder, fuel injection into the intake pipe and meets the emission standard Euro 6. The cooling system is common for an internal combustion engine, generator and inverter.

In March 2012, featured range extender is presented in the demo car Fiat 500 with electric drive [9] (Fig. 5).



Fig. 5. Cross-section of rear end of Fiat 500 with KSPG - FEV Range Extender [12]

Rys. 5. Widok przekroju tylnej części nadwozia samochodu Fiat 500 z dodatkowym zespołem prądotwórczym KSPG - FEV

One can see on the above picture, that the range extender is placed in Fiat 500 instead of the spare wheel.

4. AVL Wankel Range Extender

The first version of AVL range extender with Wankel engine was presented in 2010 in a prototype electric car Mini Cooper [6]. Basic single rotor version of the engine has a displacement of 0.254 dm³ and an output of 15 kW at 5000 RPM, which after modifications can be increased to 25 kW at 7000 RPM. A slightly bigger version of the engine has a displacement of 0.357 dm³ and holds a power of 36 kW at 7000 RPM, while the largest double rotor engine has a power of 50 kW. The functional model of AVL Wankel Range Extender was presented at the Fig. 6.

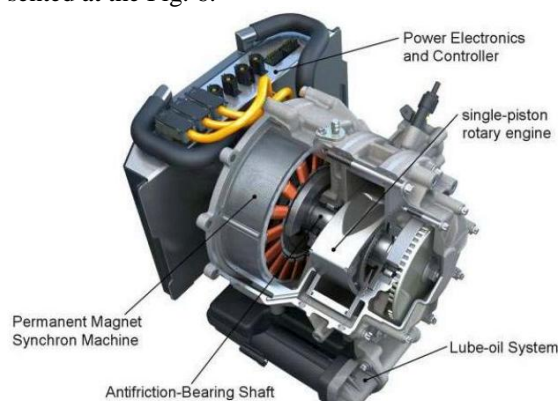


Fig. 6 AVL Wankel range extender concept [6]

Rys. 6. Model zespołu prądotwórczego firmy AVL

The smallest range extender with a power 15 kW has a curb weight 29 kg. Together with inverter, electronics cooling system and interface connecting it to the vehicle cooling system the weight equals 65 kg. Dimensions of such an auxiliary power unit is as follows: length 490 mm, width 980 mm and height 400 mm.

The prototype car has a set of batteries for electrical energy storage of 10 kWh. This allows you to beat the 30 km in pure electric mode. The AVL range extender with a power of 15 kW and 10 dm³ fuel tank, range is increased to at least 200 km. The car holds a good acceleration time from 0 to 100 km/h in 12 s.

The development version of AVL range extender is used in the conceptual model of the Audi A1 e-tron (Fig. 7) [8].

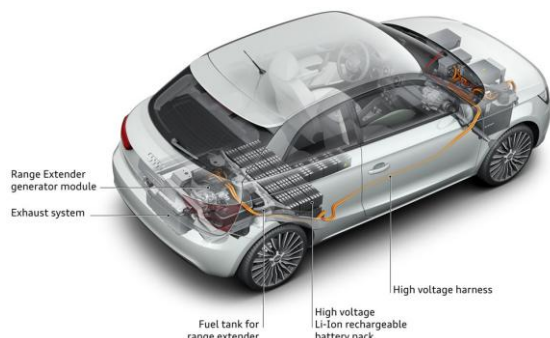


Fig. 7. Audi A1 e-tron drivetrain [8]

Rys. 7. Układ napędowy pojazdu Audi A1 e-tron

Audi e-tron also has the range extender with a power 15 kW, but with a slightly larger 12 dm³ fuel tank that allows you to extend the range an additional 200 km. Car with a curb weight 1190 kg obtains a top speed of over 130 km/h and accelerates from 0 to 100 km/h in 10.2 s.

5. Lotus Engineering - Fagor Ederlan Range Extender

Lotus Engineering in cooperation with Fagor Ederlan offers several types of range extenders. Lotus company is responsible for developing internal combustion engines, while Fagor Ederlan provides electric generators and controls [11]. All three versions of the range extender is built based on in-line spark ignition engine and mounted directly on the crankshaft generator with permanent magnets. The basic version of the naturally aspirated engine has three cylinders and a displacement of 1.299 dm³ (Fig. 8).



Fig. 8. 35 kW Lotus&Fagor range extender with 1.3 dm³ in-line naturally aspirated engine [11]

Rys. 8. Widok zespołu prądotwórczego Lotus – Fagor o mocy 35 kW z trzycylindrowym silnikiem rzędownym o objętości skokowej 1.3 dm³

This unit obtains the nominal power of 38 kW at 3500 RPM. Output power of generator in this case is 35 kW. The same engine of the supercharged version with a compressor driven by the crankshaft obtains 58 kW at 3500 RPM, giving a generator power output of 55 kW. There is also a two-cylinder version based on the basic engine. Its displacement is 0.866 dm³, maximum power 23 kW at 3500 RPM, while the generator obtains 20 kW at the output. Internal combustion engines have been optimized for the relatively low rated speed, with the result that it was perfectly adequate to use 2 valves per cylinder. Engines were made in flexi-fuel technology enabling the use of various alternative fuels including alcohols. Engines characterized by the relative weight of its own from 45 kg to 58 kg. Curb weight of the complete generator set with two-cylinder engine is 70 kg and the supercharged 1.3 dm³ engine - 101 kg. There is a possibility to mount the range extender vertically or horizontally. Depending on the vehicle all the units are prepared to meet the Euro 6.

6. Mahle Powertrain Range Extender

In 2011, the Mahle Powertrain Ltd. offer was increased by a compact range extender with a nominal power of 30 kW at 4000 rpm (Fig. 9) [2].



Fig. 9. Mahle Powertrain Range Extender [2]

Rys. 9. Zespół prądotwórczy Mahle Powertrain

The range extender was built on the basis of a two-cylinder, in-line spark ignition internal combustion engine with a displacement of 0.9 dm³ with fuel injected into the intake pipe. Similarly, as in the other solutions the electric power generator is mounted directly to the engine crankshaft. Weight of a range extender is 70 kg, the minimum specific fuel consumption equals 240 g/kWh. Overall dimensions of the device are: length 416 mm, width - 327 mm, height - 481 mm. MAHLE range extender is designed for use in the C-segment vehicle. The unit can be mounted either vertically or horizontally.

The prototype demonstrator vehicle with Mahle range extender is built on the Audi A1. In pure electric mode, by using energy storage battery 14 kWh, this vehicle has a range of 70 km. Using MAHLE Range Extender increases the range to 500

km, as allowed by the fuel tank with a capacity of 25 dm³. CO₂ emissions specified in the NEDC cycle is less than 45 g/km.

7. Chevrolet Volt/Opel Ampera Range Extender

Range extender presented in the conceptual version of the Chevrolet Volt in 2007 was based on a in-line three-cylinder turbocharged spark ignition engine of 1.0 dm³ displacement connected to the generator with maximum power of 53 kW. This engine was made in flex-fuel technology, which meant that could work on, among others, the ethanol and E85.

Version of vehicle produced in series since 2010 received the in-line four-cylinder naturally aspirated engine of 1.398 dm³ displacement generated power of 63 kW at 4800 RPM. The engine is paired with a generator rated at 55 kW [3]. General view of Chevrolet Volt engine is presented in Fig. 10.



Fig. 10. Chevrolet Volt Ecotec engine [3]
Rys. 10. Silnik samochodu Chevrolet Volt

Chevrolet Volt Ecotec engine belongs to the GM Family 0. Variable valve timing system is used

for both intake and exhaust. The engine has been optimized to obtain high efficiency, therefore, is designed to operate on gasoline of RON 91 or higher. Chevrolet Volt Ecotec engine belongs to the GM Family 0.

Unlike other solutions described here the propulsion system of Chevrolet Volt has a mode designed for operation at high speeds, in which the internal combustion engine through a planetary gearbox transmits power to the propulsion system of the vehicle. Under normal circumstances, internal combustion engine drives a generator, which, depending on the needs transmit electricity to the battery pack or directly to the vehicle traction motors.

8. Summary

As described above, the problems in the development of new technologies for storage of a correspondingly high amount of electricity in the batteries of acceptable weight and volume make that paradoxically the development of the electric vehicles industry opens up new opportunities for combustion engines producers. Many technologies of batteries are tested and developed, but it seems that there is no solution, which could revolutionize the market of electric vehicles at least in the next few years.

The priority in the design of internal combustion engines for range extenders is a high efficiency, low emissions with small dimensions of power unit at very limited noise, vibration and harshness (NVH).

In this case sector of small engines can be developed. It can be relatively simple four stroke SI engines operating at moderate rotational speed. There is also a chance for renaissance of Wankel or another sophisticated constructions such as not described above barrel engine from Duke company or spherical engine from Hüttlin/Innomot AG.

Nomenclature/Skróty i oznaczenia

APU Auxiliary Power Unit / *generator pomocniczy*
NEDC New European Driving Cycle / *nowy europejski cykl jezdny*
NVH Noise, Vibration and Harshness / *hałas, drgania, uciążliwość dźwięku*

PMSM Permanent Magnet Synchronous Motor/*silnik synchroniczny z magnesami trwałymi*
RON Research Octane Number/*badawcza liczba oktanowa*
RPM Revolutions per Minute/*obrotów na minutę*

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