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METHODS OF MAXIMIZING POWER EFFICIENCY FOR HYBRID VEHICLES

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Key words: Auxiliary energy storage device, Energy harvesting, Hybrid electric vehicles, Maximum power point tracking, Start-Stop system, Supercapacitors.

This paper proposes a new system that gathers numerous methods and devices which help improving the energy management for both conventional vehicles (with a greater benefit for those equipped with a start-stop system), as well as for hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs), by using energy harvesting devices (including regenerative braking) and auxiliary energy storage devices (AESDs) that consist in a bank of supercapacitors combined with a pack of Li-ion cells, designed to improve the efficiency, convenience and reliability of modern cars. Apart from the thermal energy available mainly from the exhaust system, electromagnetic and solar energy sources can be exploited, in combination with a maximum power point tracking (MPPT) converter. Since the thermal efficiency of the internal combustion engines (ICEs) is pretty low (below 40 %) for both petrol and Diesel powered vehicles, a part of the wasted energy can be recovered, stored for a certain amount of time and then used for different purposes.

1. INTRODUCTION

Nowadays, energy management and energy consumption are very important, especially for battery powered portable equipment, wearable devices, as well as for vehicles. This means that every drop of energy saved or recuperated translates into higher range and lower emissions, either for conventional vehicles, which are equipped with ICEs, as well as for HEVs, PHEVs [1, 2], and EVs.

Since most of the modern conventional vehicles feature start-stop systems, every restart of the ICE produces wear to its internal components, given that the lubrication system depends on rotary motion which is not available prior to (and during) the cranking period and for this reason, an auxiliary electric actuated oil pump should be used, together with other dedicated systems. Moreover, the need of auxiliary or battery powered subsystems (fluid pumps, power steering, air conditioning, heating elements) capable of maintaining all the comfort and safety features of the car is growing, therefore, additional electrical power should be available either from the main 12 V battery, or from different energy storage sources (such as a 48 V Li-ion auxiliary battery).

When talking about motor vehicles, the most common energy harvesting sources available can be divided into two categories, based on the state of the powertrain: stationary (photovoltaic cells, electromagnetic waves) and motion dependent (thermoelectric generators placed near the exhaust pipes of the ICE, electromagnetic shock absorbers, piezoelectric energy harvesting devices, kinetic energy recuperation). A part of these sources listed above is presented in Fig. 1.

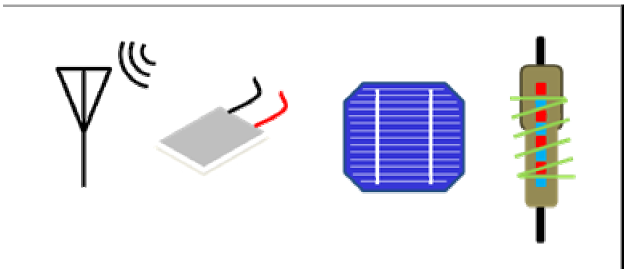

Fig. 1 – Energy harvesting sources suitable for implementation in automotive systems (from left to right: electromagnetic radiation Rectennas, thermoelectric generators, photovoltaic arrays and electromagnetic shock absorbers).

During parking, the energy harvested from the electromagnetic shock absorbers, as well as the energy recovered from the heat dissipated by the ICE (after cooling) are almost zero, so the remaining energy harvesting sources are either the photovoltaic (PV) cells or the electromagnetic radiation (EMR) [3]. Besides this, each light emitting diode (LED) used for exterior lighting (both headlights and tail lights) can be used for energy harvesting.

While idling in traffic jams or in the city at the traffic lights (when the vehicle stands still), the intensity of the headlights (mainly during the night) can be dimmed at a very low level of intensity, thus saving a reasonable amount of energy (considering that every headlamp uses around 35 W for the low beam only) [4], which can be later used for restarting the ICE or for other purposes. This feature can be also linked with the information provided by the navigation system or by the light sensors and cameras, which can determine the level of light available in a certain area.

During winter or cold weather, the energy stored within the AESD can be used either to heat up the seats and the interior of the vehicle, the engine oil or the coolant fluid of the ICE, as well as preheating the combustion chamber of each cylinder by the means of glow plugs, in order to improve the cold start performance of the ICE and to reduce the emissions. This can be done either at a predetermined programmable moment in time or every time the vehicle is unlocked. In addition to this, while being parked, vehicles can feature an onboard electric charger used for the AESD, as well as for heating or cooling purposes.

Besides this, the stored energy can be used for vehicle's start-stop system, mainly because without the use of an

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AESD, some estimations show that conventional ICE powered automobiles should be driven around 12 km in order to restore the energy taken from the 12 V battery during every start [5], meaning that after a few consecutive restarts, the lead-acid battery won't be charged enough to ensure the high demand of power needed for cranking.

The novelty of the proposed system consists in combining different energy storage elements and harvesting devices which offers significant advantages over classic designs.

The rest of this paper is organized as follows:

- Section 2 offers an overview of the proposed system, which can be implemented on conventional ICE powered vehicles, HEVs, PHEVs or EVs.
- Section 3 reveals the dimensioning methodology for the AESD, mainly based on the requirements of the start-stop system, which were derived from data collected during traffic jams.
- Section 4 presents some additional automotive applications that could be implemented using similar systems.
- Section 5 represents the conclusions of this article, which also include perspectives for future works.

2. OVERVIEW OF THE SYSTEM

The proposed system should be able to harvest energy from different sources (both when the vehicle is parked and when it's being driven or it's idling), as already mentioned in the previous chapter, to convert it, store and deliver it to particular devices (in certain conditions), therefore the block diagram of the entire system is presented in Fig. 2.

Because some energy harvesting sources (such as EMR and thermoelectric cells) provide small amounts of electric power at a low output voltage, this should be stepped up in the range of a few volts, allowing the electronic circuits to work properly, therefore, additional circuitry is needed. In order to validate the previous statement, several simulations were performed using SIMPLS, which is an analog simulation tool dedicated for switched mode power supplies (SMPS). As a result, the schematic of the energy harvesting element, together with the resonant step-up oscillator, the voltage doubler and the load used for the simulations are presented in Fig. 3.

Simulations show that by using an Armstrong oscillator (which is composed mainly by a transformer, a normally-ON JFET transistor and a capacitor, designed to create a positive feedback, which leads to oscillations) [6], followed by a voltage doubler (which can be designed either using a single or even multiple stages), the output voltage of the

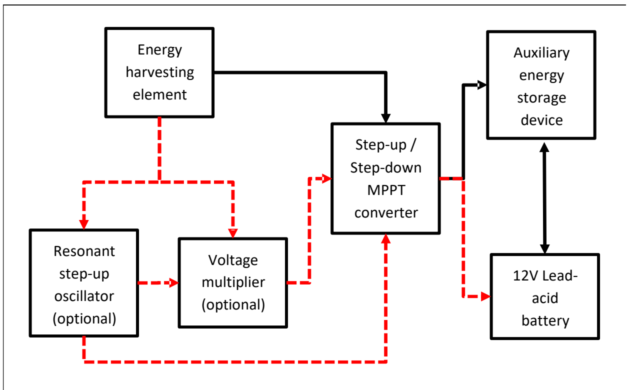

Fig. 2 – Overview of the proposed energy harvesting system.

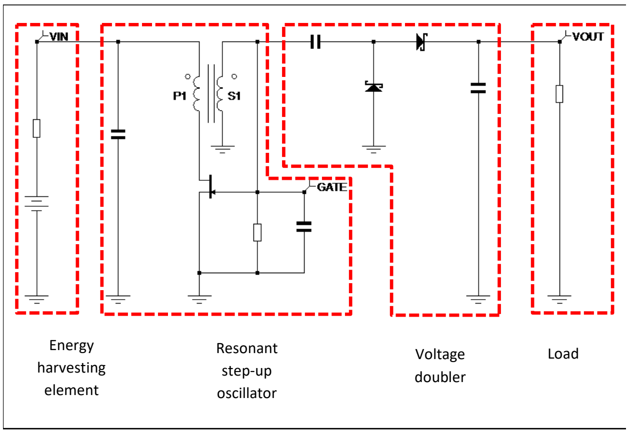

Fig. 3 – Schematic of the energy harvesting element, together with the resonant step-up oscillator, the voltage doubler and the load that have been used for simulations.

energy harvesting element can be stepped up from around 50 mV, to 1.4 V in about 1 second, as shown in Fig. 4.

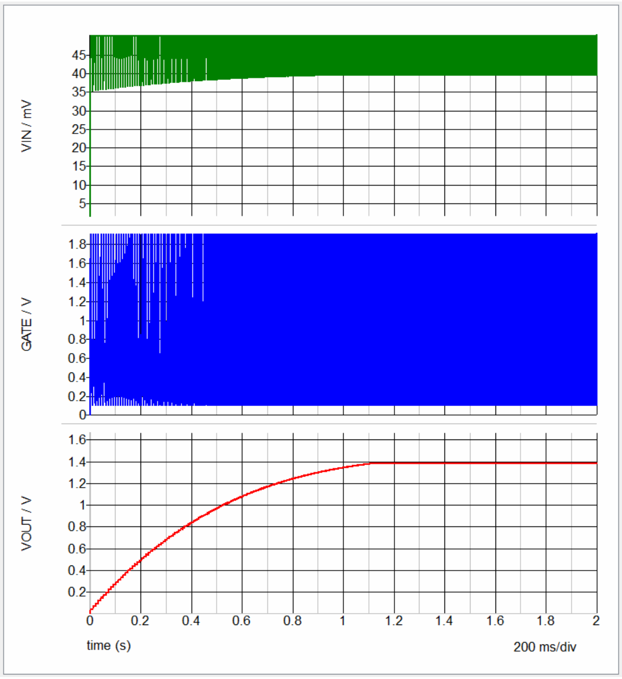

Fig. 4 – Simulated waveforms for the step-up self-resonant oscillator.

In addition to this, since the energy amount provided by the harvesting elements is very low (whether if we are talking about PV cells or other energy sources), in order to achieve the best power efficiency while keeping the cost of the system at a reasonable level, a simple analog [7] or digital [8] MPPT converter should be used.

Regarding the minimum necessary input voltage for the MPPT device to work, it can be biased using a low quiescent current step-up switching regulator, capable of starting-up from a few hundreds of millivolts or even around 1 V. On the other hand, its input voltage rail (converter's powertrain) can be either supplied directly from the output of the energy harvesting element (or series connected elements), or through the resonant step-up oscillator combined with a voltage multiplier, thus being able to provide the required voltage level (Fig. 2).

When talking about automobiles (because this system is designed for the automotive industry), besides the gear selector's position, brake and clutch's position (for the vehicles equipped with manual transmission), external temperature, seatbelt lock and engine coolant temperature, one of the main constraints for the start-stop system to work is the state of charge (SOC) of the 12 V lead-acid battery, therefore an AESD (comprised of Li-ion cells and supercapacitors) should be used. This hybrid configuration offers both the advantages of Li-ion batteries (high energy density) and supercapacitors (high power density), without being harmful for the electrochemical process [9], while requiring a reduced number of cells. Moreover, by using supercapacitors, which can be charged and discharged at very high current rates, an additional benefit is represented by increasing the efficiency of regenerative braking.

3. AUXILIARY ENERGY STORAGE DEVICE DIMENSIONING

In order to be able to properly design and dimension the AESD, which is intended to supply the start-stop system of a vehicle, a series of measurements (collected during real life driving) should be considered for determining the number of engine restarts and therefore the necessary amount of energy that should be stored within.

To achieve this, a 2012 Diesel powered Volkswagen Golf 6 GTD was used to gather relevant information (such as the vehicle's speed, engine's braking torque, engine's speed, etc.) during over a hundred trips, which included city driving and traffic jams, by applying the same methodology as also presented in [1] and [2].

Considering the graph presented in Fig. 5 (which was obtained by measuring vehicle's speed during a 52 minutes trip), while driving in traffic jam conditions, the ICE of the vehicle should be restarted tens of times in a short period of time, meaning that the alternator will not able to recharge the 12 V lead-acid battery while running, therefore the Start-Stop system will operate just a few times before reaching the safety under voltage lockout (UVLO) for the battery. Moreover, the energy saved while the ICE is shut off will be wasted during the recharging phase. In order to overcome this inconvenience, the necessary energy amount should be provided from alternative sources (other than vehicle's alternator) and stored in the AESD, to avoid overstressing the 12 V battery of the car.

When studying the Fig. 6, which depicts the vehicle's speed versus driving time, it can be easily noticed that

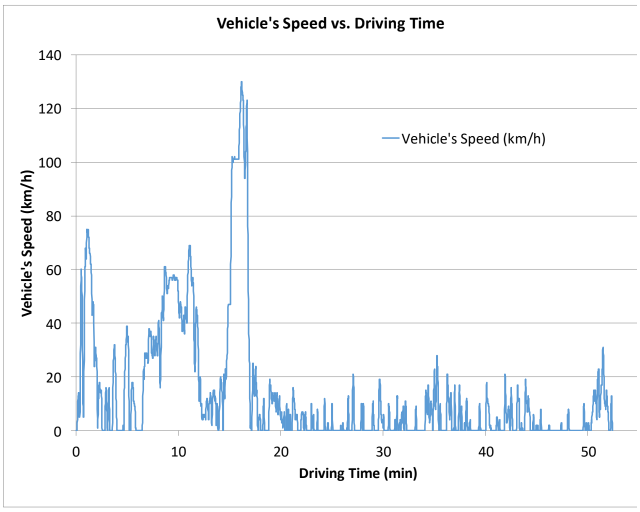

Fig. 5 – Example of measured vehicle speed versus driving time for a 52 minutes trip.

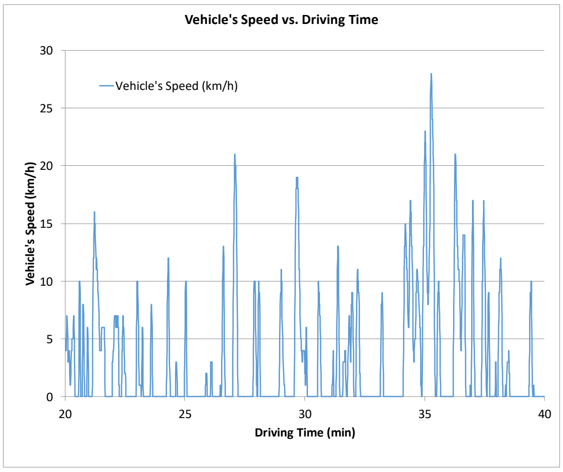

Fig. 6 – Example of measured vehicle speed versus driving time during 20 minutes of traffic jam.

during 20 minutes of traffic jam, the vehicle was set in motion 40 times, mostly for very short driving distances and periods of time (from 4 to 15 seconds), while most of the idling periods ranged between 15 and 50 seconds. Consequently, the AESD should be able to provide enough energy for restarting the ICE over 100 times within one hour. Moreover, because sometimes the engine will be shut off just for a few seconds, this means that the energy stored inside the supercapacitors should be enough for at least 4 or 5 consecutive restarts, before being recharged from the Lithium batteries.

Considering the nominal power output of an engine starter of 2 kW, for the cars equipped with a start-stop system, the mean value of the current drawn from the battery is about 200 A, at a voltage of 10 V (due to the internal resistance of the lead-acid battery, combined with the resistance of the wires). Instead of classic two-stage engine starters, the vehicles equipped with start-stop systems should use a belt starter alternator (BSA) unit, which reduces the total restarting time from 800 ms to around 400 ms [5, 10–12]. In order to calculate the necessary amount of energy required, (1) should be used:

$$W(\mathrm{Wh}) = P(\mathrm{W}) \times t(\mathrm{h}), \qquad (1)$$

where P is the power (expressed in Watts) and t is the time (expressed in seconds).

Therefore, the energy drawn during every engine start-up will be reduced by 50 %, from 0.44 Wh to 0.22 Wh, allowing for more restarts, while using the same amount of electrical energy.

On the other hand, based on ICEs characteristics (required starting torque, idling rotational speed), the BSA can be optimized for better efficiency, by using mathematical modeling, as presented in [13].

To ensure a voltage rail which is compatible with the existing one (12 V nominal), the AESD should integrate a suitable number of supercapacitors and Li-ion cells, connected in series or in a series-parallel configuration (depending on the required capacity).

Since most of the supercapacitors available on the market are rated below 3 V [14] and considering a maximum allowable voltage of 2.5 V for each element when charged, this means that 6 series connected ultracapacitors will provide a total voltage rail of 15 V.

From the laws of physics, the relationship between voltage and current for capacitors is given by (2):

$$i(t) = C\frac{\mathrm{d}v(t)}{\mathrm{d}t}, \quad (2)$$

where $i(t)$ is the variation of current over time, C is the capacitance (in Farads), $v(t)$ is the variation of voltage and t is the time.

For calculating the necessary capacitance (in Farads), first we assume a depth of discharge (DOD) of around 30 %, from 15 V down to 10 V, at no load. Assuming that the current is constant during start-up, (2) can be translated into (3), as follows:

$$C = \frac{I \times t}{V_C - V_D}, \quad (3)$$

where I is the current (expressed in amperes), t is the time (in seconds), V_C is the voltage (expressed in volts) across the bank of supercapacitors when they are fully charged and V_D is the voltage (in volts) when they are discharged at a certain level.

Since the number of restarts between recharges was chosen to be 10, the necessary equivalent capacitance will be around 160 F. This means that the capacity of each supercapacitor should be around 960 farads and the maximum output current capabilities should exceed 200 A, so the closest available value (taking also into account the leakage of the supercapacitors) is 1200 F, these devices being also capable of delivering a maximum current of 930 A for very short periods of time [13], similar to a high capacity 12 V automotive start-up lead-acid battery [15].

In order to calculate the stored energy inside the bank of supercapacitors, (4) should be used:

$$E = C\frac{V_C^2 - V_D^2}{2}, \quad (4)$$

where E is the energy (in joules), C is the equivalent capacitance (in farads), V_C is the voltage (in volts) across the bank of supercapacitors when they are fully charged, and V_D is the voltage (in volts) when they are discharged at a certain level.

It can be found out that the total amount of energy stored is around 22500 joules, which translates into 6.25 Wh, by the aid of (5):

$$W(\mathrm{Wh}) = \frac{E(\mathrm{J})}{3600}, \quad (5)$$

where W is the energy expressed in Wh and E is the energy expressed in joules.

However, the useful energy amount available will be around 3.47 Wh, since the assumed DOD is only 30 %.

Besides the bank of supercapacitors, which will be solely used to restart the ICE, the AESD will also include a pack of 4 series-connected Li-ion cells (with a total nominal voltage of 14.8 V), which should be able to provide the energy needed for 100 restarts of the ICE (enough for driving one hour in traffic jams), without the need of recharging. The capacity of the Lithium battery pack should be chosen taking into account a maximum DOD of 70 % and a maximum charging level of 80 %, in order to maximize its lifespan [16], meaning that only 50 % of its nominal capacity can be utilized, therefore using (6), it results that each cell should be rated at around 11.1 Wh (with a nominal capacity of 3000 mAh) and should be capable of high discharge current rates:

$$W(\mathrm{Wh}) = \frac{1}{\mathrm{DOD}(\%)} \times W_{start}(\mathrm{Wh}) \times N, \quad (6)$$

where W is the energy (expressed in Wh), DOD is the depth of discharge (in percents) for the battery pack, W_{start} is the energy (expressed in Wh) required for a single engine restart and N is the number of desired ICE restarts.

When possible, between each restart of the ICE, the bank of supercapacitors will be charged using the Li-ion battery pack, meaning that the energy deployed within 400 ms (during start-up) will be recovered in 20 s, at a charging current of 10 A (which translates into around 3 C discharging rate for the lithium cells).

While being parked, the power consumption of a passenger car can vary between 25 mA and 50 mA, depending on its installed equipment [17], so the energy stored by the AESD can ensure the power needed by the electronics for another several days (depending on its capacity), while the main 12 V battery remains fully charged, even without engaging any of the energy harvesting devices.

This AESD should feature active cell-balancing circuits [18], allowing for a correct and efficient method of charging both the batteries and supercapacitors, as well as an intelligent battery management system (BMS) which should be adaptable to the driving conditions. Moreover, it should be able to disconnect the AESD from the main 12 V battery, as well as separating the supercapacitors from the Li-ion batteries, when needed.

Moving from the power consumption to the power generation side, a very important source of energy can be harvested by using a panoramic sunroof equipped with an array of PV cells, which usually are used just for ventilating the cabin during summer.

Considering that the available solar power density is around 100 mW/cm² [19, 20], which means that the power output of a PV array is 130 W/m² (at an average efficiency of 13 % [7]), while the area of a regular car sunroof is 0.21 m² (at a size of 300 mm x 700 mm), the amount of harvested solar energy will be about 25 Wh, assuming a 90 % efficiency of the MPPT converter.

In addition to this important energy source, which is available both when the vehicle is stationary, as well as when the car is in motion, the average amount of kinetic energy that could have been recovered during engine braking (Fig. 7), corresponding to the trip presented in Fig. 5 is approximately 280 Wh (without taking into account the efficiency of the power converter), so it could be sent to the 12 V battery or redirected to the AESD.

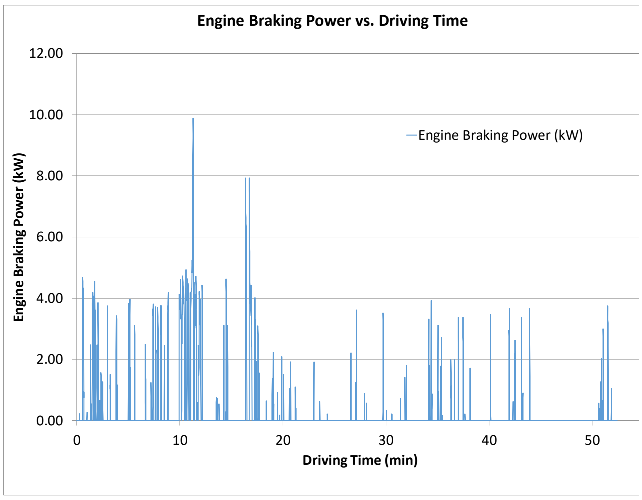

Fig. 7 – Example of engine braking power versus driving time for a 52 minutes trip.

This can be realized either by using the BSA as an additional braking system (besides the intrinsic engine braking power) or it can be used as a main braking system, by letting the valves of the ICE open during all four strokes, because the supercapacitors which compose the AESD have the ability to absorb a high amount of energy within short periods of time. This translates into a more efficient braking function, while minimizing the wear of the brake pads and disks.

Regarding the energy harvested from the EMR (by the means of a rectenna), the average levels of power range from about –25 dBm to –10 dBm [19 – 21], thus, by using (7), this translates into up to 100 μW of harvested energy:

$$P_{\mathrm{mW}} = 10^{\frac{P_{\mathrm{dBm}}}{10}}, \tag{7}$$

where P_{mW} is the power expressed in mW and P_{dBm} is the power expressed in dBm.

In addition to all these energy harvesting sources that were presented, thermoelectric generators (TEG) and electromagnetic shock absorbers should be taken into consideration for this purpose.

4. ADDITIONAL FEATURES AND FUNCTIONALITY

Since most of the modern vehicles are equipped with GPS navigation systems, the energy management can be adjusted based on some requirements like the speed limit over a certain area, distance to destination or the time remaining to destination. Moreover, predefined or fully customizable profiles of energy management should be accessible to the driver, depending on his/her personal needs, especially in case of HEVs or PHEVs. As an example, in some situations (similar to the graph presented in Fig. 5), the electric energy stored within the high voltage battery (when talking about HEVs or EVs) or into the AESD should be preserved for traffic jam situations or city driving conditions which are about to come and the driver is aware of, therefore allowing the ICE to be used just at moderate and high driving speeds, therefore optimizing the fuel consumption.

A very important function of the proposed system is to monitor the voltage of the 12 V main battery of the vehicle, as well as charging it when needed and triggering an alert message to the owner (via a wireless network [22]), either on a portable (phone) or a stationary device, when a faulty condition is being detected (through diagnostics equipment [23]) or a certain voltage threshold is reached. Therefore, any electrical problem that may drain the battery can be avoided. In addition to this, the system should be able to disconnect certain electronic modules from the main battery, at least while the vehicle is parked.

In order to improve both the reliability of the vehicle and the efficiency of the proposed system, since the fuel consumption for 5 seconds of idling is equivalent with a restart of the engine (according to [12]), based on navigation information or on driver's input, different start-stop profiles should be implemented within vehicle's engine management system.

A fraction of the electric energy stored within the AESD can be used to preheat the oxidizing catalytic converter (OCC) and/or the Diesel particulate filter (DPF), therefore minimizing both the amount of harmful exhaust gases that are being produced, as well as the time needed for these devices to reach their optimal operating temperature.

In addition to all these methods, in order to reduce the emissions inside the cities, trapping devices for exhaust gases can be used for temporary storing and compressing them during city driving, while recovering a part of the energy using the thermoelectric effect. Once the engine control unit (ECU) of the vehicle senses highway driving conditions (based on sustained highway speed driving or using more advanced algorithms), the exhaust gases can be safely released into the atmosphere.

5. CONCLUSIONS

This paper offers a collection of methods for optimizing the energy consumption of automobiles, mainly based on energy harvesting elements combined with electrical energy storage devices (comprised of a pack of 4 series-connected Li-ion batteries, rated at 3000 mAh and a bank of 6 supercapacitors, each rated at 1200 F), focusing on the utilization of a start-stop system.

Starting from some potential available energy harvesting sources, several simulations of some particular blocks composing the proposed system were done in order to evaluate their feasibility in the automotive environment.

On the other hand, based on real measurements performed during driving in several traffic jam situations, some theoretical estimations were made, with regards to the necessary amount of energy required for restarting the ICE whenever is needed, by using a BSA as one of the main components of the start-stop system.

In addition to this, some calculations were made in order to determine the amount of energy that could be harvested by using a PV sunroof.

Moreover, compared to the existing systems that use the energy harvested by the PV sunroof just for ventilating the cabin during summer, the system proposed in this article utilizes that amount of energy manly to supply the Start-Stop system.

In contrast to the conventional start-stop systems, which use absorbent glass mat (AGM) lead-acid batteries, capable of restarting the ICE only a few times before reaching the UVLO threshold, the AESD proposed in this paper is designed to allow up to 100 engine starts within one hour, without overstressing the 12 V battery.

Another important energy source that should be exploited is the kinetic energy available when the vehicle is decelerating or braking, which can translate into maximizing the lifespan of the brake pads and disks, in an efficient way.

Besides the benefits of reducing both emissions and fuel consumption for conventional or hybrid vehicles, this system can bring other advantages which improve both reliability of the powertrain, as well as the comfort of the driver and passengers.

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