Hybrid-Electric Vehicles: Design and Application of ECSC - an Automotive Energy Savings Device

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Abstract: - The design and application of an electronically coupled super charger (ECSC), an automotive energy savings device, is reviewed and investigated. The concept is founded on the operational ideas of hybrid-electric vehicles. ECSC extends these ideas to affect the thermodynamic principles of the internal combustion engine (ICE). The concepts and methods of design of ECSC as well as the technological barriers that have prevented any such device fully being made commercially are explored and discussed. The ECSC, in a development of the principles set out here, may form a useful part of future automobiles.

Keywords: - Internal combustion engine, hybrid electric vehicles (HEV), energy savings, design and application

1 Introduction

The global automobile industry is growing enormously with more people than ever being able to afford vehicles. This growth requires the automobile industry to race forward with efficiency improvement so that these people have the opportunity to participate the cleaner future of mobility. In order to stay ahead of this growth every avenue of electronic control and assistance of the Internal Combustion Engine (ICE) should be explored and applied so as to accelerate the introduction of *Electric Era*. The ECSC is a step in the direction of the 'hybrid era' – the interim between the petroleum and electric eras. The 'hybrid concept' can be defined by *store excess energy from the ICE during its efficient periods of operation as electricity and use this energy to assist the ICE during its inefficient periods of operation* [1-3]. The ECSC uses energy stored during cruising to assist engine acceleration during low-rev, acceleration periods. To achieve this, the ECSC system brakes from traditional supercharging systems by offering variable control of the boost [4]. This is opposed to traditional supercharging where the boost offered is directly related (apart from some limited means of restriction) to engine speed or exhaust pressure.

The electronic coupling that is spoken of is the replacement of the mechanical or pneumatic coupling of traditional supercharging with the variable, electronic control. Electronic coupling sounds ideal, but as we shall find out, there are limits to its effectiveness. The ECSC assists the ICE, as do all supercharging systems, by artificially increasing the engines volumetric efficiency. In a naturally aspirated engine the cylinder volume increases to V_S during the induction stroke, but the engine only takes in the lesser volume, V_i, the induction volume. Thus the engine's volumetric efficiency is given by,

$$\eta_{vol} = \frac{V_i}{V_{swept}}$$

With supercharging, the volume taken into the engine is the volume that passes through the compressor (V_{comp}) with each cycle of the engine. Thus, the effective volumetric efficiency of a supercharged engine is,

$$\eta_{effective} = \frac{V_{comp}}{V_{swept}}$$

Design and application ECSC is explored and discussed in this study. The ECSC operates on same principles as electronic traction side of a hybrid-electric power train. The technological barriers that have prevented any such device fully being made commercially are addressed. It is expected that the ECSC will form a useful part of future automobiles development.

2 Application and Design of ECSC

2.1 Operating Principles and Regimes

The goal of the ECSC is to save fuel. To see how the ECSC saves fuel, its operation can be divided into two functions, charge and boost. Charging occurs, generally, during cruising (c) and boost occurs only during acceleration (a). Consider two identical vehicles perform the exact same driving cycle. Vehicle 1 is naturally aspirated and vehicle 2 is fitted with an ECSC. The goal for fuel usage (m) during the driving cycle can be denoted by,

$$(m_{a_1} - m_{a_2}) > (m_{c_2} - m_{c_1})\ or\ (m_{a_1} + m_{c_1}) > (m_{a_2} + m_{c_2})$$

When a vehicle with the ECSC operates over a long period of time, the net energy storage of the system (excluding the ICE) should be zero. The additional power generated by the alternator, over and above normal operating levels ($\Delta P_{alt_{average}}$), minus losses, is what is available to the electric motor for compression. Therefore,

$$\Delta P_{alt_{average}} \times t_{charge} = \left(P_{comp_{average}} \times t_{boost}\right) + E_{loss}$$

For the system to be of benefit, it needs to be shown that the increased energy produced by the ICE is greater than the extra energy taken by the alternator over a complete driving cycle, i.e.

$$\Delta BP_{average} \times t_{boost} > \Delta P_{alt_{average}} t_{charge}$$

To achieve these goals, the operating regimes described in Table 1can be employed.

Table 1: ECSC operating regimes

Operating Conditions	ECSC Response
Low engine speed & high throttle	High boost pressure – no battery charging
Low engine speed & low throttle	No/some boost pressure – battery charging
High engine speed & high throttle	No/some boost pressure – no/some battery charging
High engine speed & low throttle	No boost pressure – battery charging

The boundaries of these regimes can only be determined after exhaustive testing or the development of a thorough model and confirmation of results.

2.2 Internal Combustion Engine (ICE)

Artificially improving the volumetric efficiency increases the amount of air that the ICE has available for combustion. This increases the Mean Effective Pressure, which increases the power output of the engine. From Eastop and McConkey [5] we have

$$P_i = \frac{(MEP)\cdot V_s \cdot N}{2}$$

The airflow rates for naturally aspirated and force aspirated running can be approximately calculated with simple gas expansion/compression laws. To calculate the flow rate of air induced for natural aspiration, the following equation can be used,

$$V_i = V_s \times I \times \eta_{\mathrm{vol}}, \text{ where } I = \frac{2N}{(\text{strokes/cycle})}$$

where N is engine speed in revs per second and the denominator is 4 for a four-stroke engine.

It can be assumed that the volumetric efficiency, η_{vol}, varies only with engine speed. To simplify the matter further we can assume that the restrictions to airflow are entirely in the compressor and ICE head, and not in the filter and ducting. For calculating the airflow, the following equation can be applied [6],

$$p_f = p_o \cdot \varepsilon^n$$

where n is the gas constant for air, and ε is the compression ratio.

The volume of air inside the cylinders, measured at atmospheric conditions, V_i, is not equal to V_S. The ICE compression ratio is given by,

$$\varepsilon = \frac{V_S + V_c}{V_c}$$

As opposed to the effective compression ratio

$$\varepsilon_{effective} = \frac{V_i + V_c}{V_c}$$

Similarly, we have the standard volumetric efficiency and an effective volumetric efficiency for the comparison of the forced charge (at atmospheric conditions) to the swept volume. The naturally aspirated efficiency

$\eta_{vol} = \dfrac{V_i}{V_S}$ and the force aspirated efficiency or effective volumetric efficiency

$$\eta_{vol_{effective}} = \frac{V_{comp}}{V_S}$$

The initial conditions for compressions (when the piston is at BDC) can be written as,

$V_i = \eta_{vol} \cdot V_S$ and $p_o = p_a \cdot \eta_{vol}{}^n$

When the manifold air is compressed

$V_i = V_{comp}$, and $p_o = p_i \cdot \eta_{vol}{}^n$

This ignores the effect that cylinder temperature and fuel vaporisation have on the charge temperature and consequently the initial pressure. An important concept to grasp for the design of the ECSC system is the relationship between manifold pressure and the flow rate of air. When an engine is provided with a particular flow rate of air, from a positive displacement compressor, the manifold pressure will build up so that the same flow rate of air will be forced into the engine. As a result, in steady operation, the manifold pressure will stabilise and will correspond with a definite volume flow rate of air into the engine. Because of this, manifold pressure is indicative of volumetric flow rate. The limiting factors for the provision of boost (on the ICE side of the system) are the maximum cycle temperature and pressure. Many manufacturers of 'bolt-on', aftermarket superchargers advise that the amount of boost provided does not exceed 0.5bar. This is the value we shall adhere to for ECSC design.

2.3 Compressor

The criteria for selection of a compressor are the compressor should have low moment of inertia, should be efficient at low speed, should have low or no internal compression, should be mechanically and volumetrically efficient, and must be resilient to the conditions in the engine bay. Von der Nuel [7] described design, wear and efficiency difficulties of vane compressor. This source is old, but still difficult to reconcile with Buike [2] who suggested that the volumetric efficiency of the vane compressor is superior than the Roots type blowers and the vane compressor is lightweight, compact and ideal for efficiency orientated supercharging. The characteristic of the vane compressor that seems to be of benefit is its suggested higher volumetric efficiency at low speeds. Low speed efficiency will become apparent during the motor design. Von der Nuell [7] used the following equation for the calculation of the volumetric flow rate of the sliding vane compressor,

$$\dot{V}_i = L_c \cdot (\pi \cdot D_c - s \cdot z) \cdot 2 \cdot e \cdot N \cdot \eta_c$$

where L_c is Length of cylinder, D_c is the diameter of cylinder, e is the eccentricity (distance between cylinder and rotor centres), s is the thickness of vanes and z is the number of vanes.

2.4 Permanent Magnet DC Motor (PMDC)

The advantage of the PMDC is its simplicity. With no interaction between field and armature windings, and running on direct current, all there is to control is to vary the armature voltage. The design and speed control calculations [8] for the PMDC can be described through Fig.1.

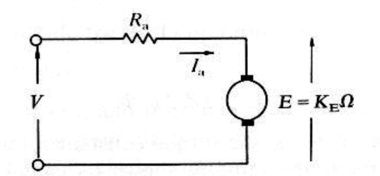

Fig.1: Equivalent circuit of PMDC motor [8]

The conversion of energy in a PMDC motor can be simplified by the following equation,

$$VI_a = R_a I_a^{\,2} + EI_a$$

Which is Power in = Heat loss + Power out. We have the relationship between the Back-EMF and rotational velocity according to the physical parameters of the motor, as defined below,

$$E = \omega \cdot R \cdot B \cdot L \cdot Z/2 = (\Phi \cdot Z/2\pi)\omega$$

where R and L are, respectively, the armature radius and length; B is the magnetic flux density and Z is the number of conductors. These physical parameters of the motor give us the Back-EMF constant.

$K_E = (\Phi Z/2\pi)$ and $E = K_E \cdot \omega$

From this it can be seen that the speed of the motor can be controlled by varying E. It should be noted however that K_E determines the size of the machine. If the speed is too high, K_E will be too small and the armature will not handle the current. This is why the compressor needs to be efficient at low speed.

2.5 Electronics

The difficulty with the selection of the correct battery is the vastly differing loads that electrical system will experience between ECSC boost and non-boost periods. A battery is designed to function properly at one particular current load, as shown in Fig.2. Either a special type of battery that can handle a wide range of discharge currents needs to be found (possibly a non-lead-acid battery) or a splitting of the electrical system, to maintain two batteries, needs to be considered.

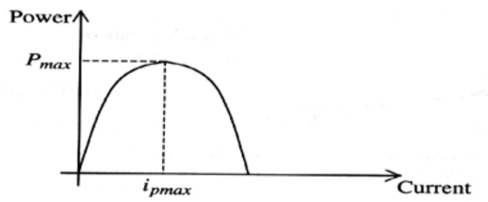

Fig.2: Battery discharge characteristics [1]

The motor will require a supply voltage of over 100V. Therefore a boost converter is required to 'step-up' the vehicles 12V supply [9]. The governing principles of Boost converters are similar to those of AC transformers. We have the following relationship,

$$\frac{I_1}{I_2} = \frac{V_2}{V_1}$$

Where side 1 is the supply side and side 2 is the load side. This is the same as with transformers but instead of a turns ratio, we have a Duty Cycle, D, which is a ratio of the amount of time the switch is off to the time of the cycle. Therefore

$$\frac{I_1}{I_2} = \frac{V_2}{V_1} = \frac{t_{on}}{t_{off}} = \frac{1}{1-D}$$

This is because the current is allowed to flow to the load, from the inductor, when the switch is off and the inductor is charged while the switch is on.

2.6 Control

The common feature is the requirement of engine speed measurement and throttle position sensors for determining the operation regime. One option for control is to have a standalone *pressure-feedback system*. The problems with this system are:

- The ECSC may push engine parameters beyond existing management system control boundaries
- May not be able to share the output of existing sensors between two control systems
- There are many complete engine management systems available that can handle the entire task of managing the engine and ECSC, and would allow greater integration of ECSC into propulsion unit.
- Pressure fluctuations may make system unstable

The second option for control is to have a *linear control system* that calculates the required compressor speed from throttle and engine speed sensors. This is the preferred option as it is most likely to provide the best response times. Push button feedback could be used for initiating irregular operating regimes such as an 'overtake' mode. Battery condition monitors measure all the condition variables of batteries and are available for special purpose applications. The battery condition monitor might be necessary if special batteries are used or battery voltage sensors are not sufficient.

3 Design and Calculations: A Case Study

A 1.5L Mitsubishi Mirage car was used as a target vehicle for the design and introduction of ECSC. The volumetric efficiency curve that has been used is a 'typical' curve and has not been determined or supplied by the manufacturer. The specifications of this car are shown in Table 2.

Table 2: Specifications of 1.5L Mitsubishi Mirage

Make	Mitsubishi
Model	Mirage 1.5L hatch-back
Year	1997
Engine model 4G15	
Swept volume V_s	1469cc (0.001468m^3)
Compression ratio r	9.0:1
Bore x stroke	75.5 x 82.0mm
Maximum power P_{max}	65kW
Maximum torque T_{max}	126Nm
Maximum speed	175km/h
Transmission	
1st	3.583
2nd	1.947
3rd	1.343
4th	0.976
5th	0.804
Reverse	3.416
Body	
Mass	1495kg (without driver & fuel)
12V electrical system	
Battery type	34B19L
Capacity (5Hr)	27Ah
Alternator capacity	75A
Alternator voltage	14

3.1 Airflow

The natural airflow of the engine is shown in Fig.3. The lower limit of boost supply is the stall speed. Idle speed is not the limit because there is no boost provision anyway at zero throttle. The upper limit is defined by the capacity of the ECSC to provide adequate (no less than natural) airflow to the engine without operating beyond its efficient range. The rpm between 4500 and 5000 was considered for design.

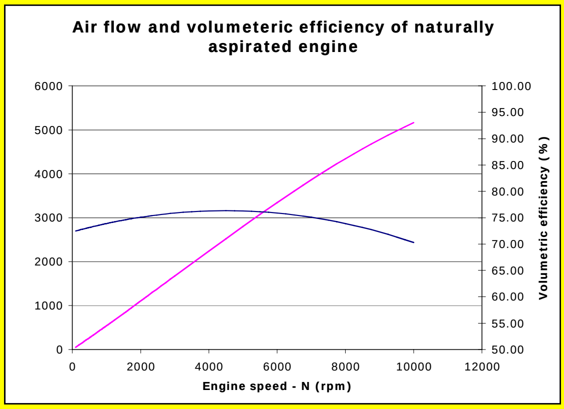

Fig.3: Natural aspiration airflow of design vehicle

To calculate the airflow and effective volumetric efficiency for the full-boost scenario we first set the desired manifold pressures. The maximum boost, which occurs at the lower limits of the rev range, provides an approximate effective volumetric efficiency of $\eta_{effective} = 100\%$ which equates to about 0.5bar over standard atmospheric pressure. 0.5bar above normal operating conditions is about the limit of boost that we want to supply for structure and combustions sake. From there the manifold pressure reduces linearly to zero bar above atmospheric pressure at 5000rpm. Figure 4 shows the effect of this boost regime on the volumetric efficiency and also shows that this equates to only a small rise in volumetric throughput. We do not want the ECSC to operate during cruising and we do not want its maximum performance to be felt only at throttle angles rarely reached.

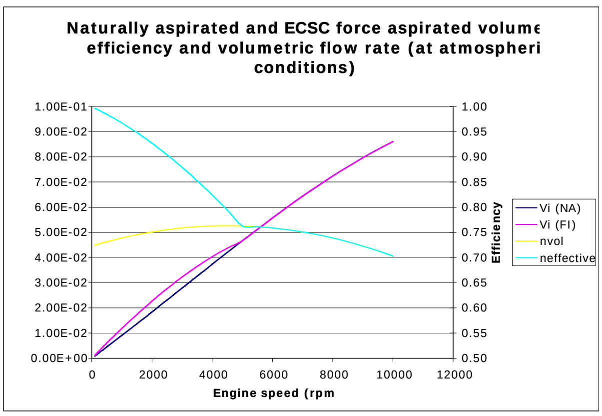

Fig.4: ECSC flow rate and effective engine volumetric efficiency

3.4 Alternator

The alternator should be installed to help the charging rate. Assuming normal $\eta_{alternator}$ of 55% [6] the normal operational output of the alternator can be calculated by,

$$P_{alt_{out}} = IV = 75 \times 14 = 1.26 \text{ kW}$$

$$P_{alt_{in}} = P_{alt_{out}} \div \eta_{alternator} = 14 \times 90 \div 0.55 = 2.291\text{kW}$$

3.4 Compressor

The maximum compressor performance required is about 0.045m^3/s (atmospheric conditions) for an engine speed of 5000rpm (Fig.4). The design of a vane compressor is a balancing act of the different dimensions and components (Table 3).

Table 6 - Vane compressor design considerations

More vanes	Better volumetric efficiency, but lower throughput and higher lower mechanical efficiency
Greater eccentricity	Higher throughput, but poorer volumetric efficiency.
Cylinder length	Greater throughput, but poorer mechanical efficiency

The discharge pressure of the vane compressor can be designed easily by adjustment of outlet position. The design considerations important for this case are a good balance between drum size and cylinder length, to keep inertia low and to minimise the friction of sliding vanes; and to have a low internal compression. Volumetric efficiency of the vane compressor closely matches with the ICE efficiency [2]. Therefore we will assume an efficiency of 75%. If we assume the D_c to L_c ratio to be square, we arrive at $D_c = L_c \approx 13cm$. This is with an eccentricity of one-fifteenth of D_c making the drum diameter about 11.3cm.

3.5 Electronics

Compressor research indicated that a maximum load of 2.5kW could be expected for the compression of the intake air. What this means for the electrical system of the vehicle is that the battery is going to have to handle a large current,

$$P < IV \text{ or } 2500 < I \cdot 12 \quad or \quad I > 208.3\ A \text{ (amps)}$$

The motor load is a low-pressure, pneumatic load; so there is little chance of overload due to start-up or sudden increases of torque and there is no braking required of an inertial system. If we assume that the design requirements are 2.5kW at 4500rpm and basing the design on that of the PMDC from Wildi [9] we can find a design for the motor according to the following procedure, based on the work of Kenjo and Nagamori [8]. All losses were calculated as copper losses and that loss is equal to 10% of the total power. The power balance of the PMDC motor can be given by,

$$VI_a = R_a I_a^{\,2} + EI_a$$

Assuming the input voltage stepped up to ten times the vehicle system voltage, we have

$$120I_a = \left(\frac{120I_a}{10}\right) + 2500 \text{ which gives,}$$

$I_a = 23.15\text{A}$, $E = 108\text{V}$, $R_a = 0.52\Omega$,
$P_{in} = VI_a = 2.778\text{kW}$ and $P_{loss} = R_a I_a^{\,2} = 0.278\text{kW}$.

The Back-EMF

$$E = \omega \cdot R \cdot B \cdot L \cdot Z/2 = (\Phi \cdot Z/2\pi)\omega$$

The Back-EMF constant is

$K_E = (\Phi Z/2\pi)$ and so $E = K_E \cdot \omega$

Therefore, K_E = 0.229 V.s/rad

If we assumed that the motor has a magnetic flux density of $B = 8.516\text{Tesla}$ [8] and $\Phi = \pi RBL$, we arrive at $K_E = \frac{RBLZ}{2}$

Therefore, RLZ = 0.054. If we keep the same relationship between R, L and Z (allowing for an acceptable number of conductors) as the motor in Wildi [10] we end up with an armature size that is impractically small and will not allow large enough conductors to handle the current.

The relationship $E = K_E\omega$ dictates that reduction in the ratio between Back-EMF will result in the reduction of the armature size or flux density. Wildi [8] states that, *"For a given power output, a low speed machine is always larger than a high speed machine"*. The problem here is that we both want to increase the speed and the output. We might then suggest that we keep the same dimensions and reduce the number of conductors (allowing us to increase their size). If we do this and apply the same calculations as above, we end up with a motor with the following specifications; Armature radius (R) = 3.65, Armature length (L) = 11.5cm and Number of conductors (Z) = 12. This is not an economical rotor design, 12 conductors on an armature. We should make the rotor slightly smaller than these specifications and increase the number of conductors. We could also increase the voltage V and hence E , but this would require a better performing Boost converter.

Due to the vast fluctuations in current requirements of the electrical system as a whole, it is sensible to have two separate batteries in the vehicle, one for regular duties and one for compression duties. This scenario then allows the introduction of a more suitable type of battery (than the standard lead-acid type) for the running of the ECSC.

4 Discussion

4.1 Application development

All the electrical supply problems would be a non-issue in a HEV. The Honda insight, for example, operates on a 120V system with generation coming from a DC motor/generator. The ECSC, in this application would provide further assistance and flexibility to the propulsion system. Possibly the most exciting opportunity for the ECSC would be for an entire propulsion system to be designed around the concept. The idea here is to take the hybrid-ECSC combination a step further. In this system the size of the ICE would be reduced significantly and would be designed to run at high levels of boost. The ECSC, in this case, would operate over the entire range of the engines performance. Such a system would be compact and ideally suited to powering a new generation of so-called ‘city-cars’, vehicles such as the Smart Car.

4.2 Design evaluation

4.2.1 Power electronics

The necessary power electronics are being developed [11] specifically for application in Hydrogen Fuel Cell (HFC) vehicles. This application requires the very same voltage increase and current handling requirements as a 3kW ECSC. The design challenge, as stated by Zhu and Xu [11] is making the switching devices to handle the required 350 or so amps. The fact is, though, that such switching devices are being developed for very important technological applications.

4.2.2 Alternatives

An alternative to having the yet-to-be-developed boost converter is to replace the alternator and part of the electrical system with a generator and, battery and other components of higher voltage specifications; for example, a 60V generator and system. The 60 volts could then be stepped up (doubled) for the motor and stepped down for the components that still require 12V. This course of action would drastically reduce current loads but would be a large effort to redesign the larger part of the electric system.

4.2.3 Vane compressor

The system based on a vane compressor has quite some potential if explored in greater detail and taken to a testing stage. The vane compressor should run much more efficiently than Roots type blowers where the suggested 2.5kW load was came from. This should mean that electrical loads would be less, which would allow less expensive power electronics to be employed. Further to this, the lower electrical load may allow that the only modifications needed in the engine bay are the replacement of the alternator and battery with larger capacity units.

5 Conclusions

The ECSC would be able to do anything a traditional supercharger could do, only better. To have the added control over intake pressure, that the ECSC could provide, would be of enormous benefit to efficiency and performance improvement. The concept of electronic coupling, it would appear, is more complicated to implement than it is imagined. This is especially true when working within the restrictions of an unsuitable electricity supply system. Further study is recommended for practically developing a hybrid vehicle with ECSC and testing the performance to confirm its suitability for commercial production.

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