Automotive Electrification: The Non-Hybrid Story

Bruno Lequesne, *Fellow, IEEE*

***Abstract*—The electrification of the automobile has a long history. Electric and hybrid vehicles are actually only a small part of it, albeit presently the most visible and the one getting the most attention in popular media. This paper will focus on the rest of the story, that is, aspects of transportation electrification other than hybrid or fully-electric propulsion systems. Recent progress (last 10-20 years) and current work on the electrification of road transport, from chassis to powertrains, will be reviewed with a focus on electromechanical systems. In the process, the numerous challenges engineers have overcome or have yet to solve will be highlighted, thus illustrating the many different ways electrical engineering is making its mark in providing more performant, more efficient, safer, and more pleasant means of personal transportation.**

***Index Terms*—Automotive, transportation, electrification, motor, generator, machine, drive, actuator, power steering, suspension, brake, injector, solenoid, piezo, starter, alternator, hybrid, supercharger, starter-generator, fuel pump, sensor.**

I. Introduction

THE electrification of road transport started in the early years of the automobile with electric cars, and may well go back to and culminate with such a technology. This could happen either with battery as the energy-storage medium or fuel cells as a means to provide on-board energy. However for most of its history and including now, propulsion has been dominated by internal combustion (IC) engines, due in large part to the energy density of gasoline that is orders of magnitude larger than that of stored electricity. This dominance is far from over, with gasoline (or natural gas) engines making steady progress as well. Interestingly actually, it is an electric accessory, the starter motor, that provided the IC engine with a superior advantage over electric propulsion, with a convenient and safe way to start the engine. Then for many years, cars were very much a mechanical system, with electricity limited to the ignition, headlight, and starting functions [1]. This started to change in the 50s with the introduction of the car radio, in the 60s with electronic fuel injection, and with the first on-board controllers and computers in the 70s. These advances already illustrate the multifaceted motivations behind electrification: Starter motors for convenience, radios for pleasure and entertainment, fuel injectors and controllers for improved engine performance, typically better torque density, better efficiency and lower emissions, the latter two becoming issues in the 60s and 70s. These motivators are still behind modern electrification efforts, with the more recent addition of safety. Anti-lock Braking Systems (ABS) and airbags are examples of the latter trend and are both part of electrification, with a need for sensors, controllers and electric solenoids or motors.

In the last 20 years however, electrification has come to components across virtually every function of the car. The biggest enabler has been the advent of powerful processors that can control and enhance most mechanisms, provided they are electrified at least to a degree: The controller indeed needs sensors and actuators to accomplish its desired outcome. Countering this has been cost, particularly of power electronics and motors, but thanks to a natural downward trend the trade-off is increasingly favorable to broad electrification.

How much are cars electrified nowadays? Recently, Emadi [2] introduced a so-called electrification factor, defined as the on-board electric power divided by the total power on the car. This is an attractive metric, which can be readily measured and shows steady progress. Unfortunately, because propulsion will always constitute the largest portion of on-board power, the electrification factor is destined to remain in the single digits until the engine itself is hybridized. Such a definition thus overemphasizes propulsion systems and does not do justice to the diversity of electrical components now seen on vehicles, which can be upwards of 20 electric motors and 100s of millions of lines of code [3]. Should one then perhaps look at how many electrical engineers design a car and its components? Of course this is difficult to measure, but hopefully this paper will provide at least a flavor for not just the diversity of electrified systems in today's car, but of the numerous challenges automotive electrical engineers have overcome, from materials to modelling, from cost reduction to system integration, from noise reduction to variability reduction in mass production.

In this paper, a number of electrification examples will be examined, focusing first on body then on powertrain electrification. The emphasis will be on motor, actuator, and power electronic technology. In so doing, a simple descriptive or historical narrative, available elsewhere [4], will be avoided in favor of a focus on the technical challenges each of these

Bruno Lequesne is an independent consultant with E-Motors Consulting, LLC, Menomonee Falls, WI, USA (email: bruno.lequesne@ieee.org).

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applications faced. The section on powertrains will inevitably touch on hybridization, but will do so only in the sense that hybridization can be seen, at least in its milder forms, as engine improvement rather than engine replacement. Other aspects of automotive electrification, for instance controls, entertainment, computer systems, communication (vehicle-to-vehicle, vehicle-to-land, etc), autonomous vehicles, are outside the scope of this paper.

Little will be said concerning voltage levels. Indirectly, this shows that much can be done at low (12V) voltages. Just the same, many in the industry expect a shift to dual, 12V/48V systems in the near future. This will facilitate further electrification, particularly for higher power systems such as starter-generators with minor hybrid functionality, covered in the last section.

II. Vehicle Handling (Chassis) Electrification

Vehicle handling, how well the car maneuvers around curves, avoid obstacles, and comes to smooth stops is based on steering, brakes, and suspension, see Fig. 1. Together they allow the driver to adjust the course of the car and to ride as smoothly as possible over the intended route. All three of these components can be electrified, with one long-term motivator being the integration of the three functions together for improved comfort and safety. This goal is starting to be realized with coordinated steering and braking during emergency maneuvers [5]. The first step, however, is to electrify each of them. Interestingly, steering provides perhaps the best success story to date in the field of automotive electrification as electric power steering is becoming a standard feature on modern automobiles.

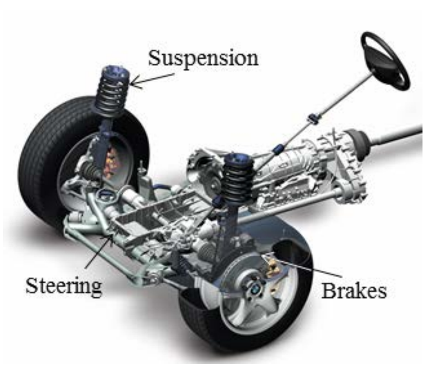

Fig. 1: Steering, brakes and suspension on a front axle (© BMW, used with permission)

A. *Electric Power Steering*

1) Background: Steering at first was purely mechanical, with a gear mechanism linking the steering wheel to the front axle. This changed in the first part of the 20th century on trucks and heavy vehicles, and in the 50s hydraulic steering assist was introduced on passenger cars. While very effective, hydraulic assist suffers from the flaw that the hydraulic pump must be powered at all times, even though steering occurs only occasionally in the course of vehicle operation. This is a fuel economy penalty of as much as 4%. Electric steering on the other hand provides power on demand. This gave steering electrification a significant boost, but still various obstacles needed to be overcome, mainly cost, torque ripple, and safety.

2) Hardware configuration: Electric power steering is conceptually simple: An electric motor is linked to the steering system via a gear (for instance, as shown in Fig. 2, to the steering column). Sensors mounted on the steering wheel provide input from the driver (torque in particular) to the controller. This determines how much assist to provide. In so doing, the controller uses other sources of information as well, such as road condition, brakes on or off, etc. For safety a mechanical link from the driver to the wheel is maintained as a fallback in case of failure.

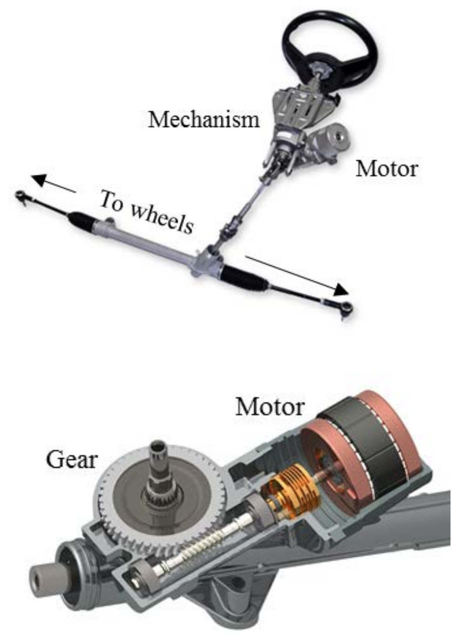

Fig. 2: Electric power steering system (Images © Nexteer, used with permission)

3) Torque ripple: Ripples in the torque produced by electric machines are generally small compared to those produced by other mechanisms, and are rarely a problem. This came to be an issue here only because they can be felt by the driver on the steering wheel. Although inconsequential in terms of performance, it could be a distraction or a concern for a customer accustomed to a smooth hydraulic steering system. In this case, it was easier to solve the problem than to attempt to educate the public and risk market rejection, "easier" being understood as a relative term.

Motor technology quickly focused on permanent magnet (PM) brushless motors, because the power rating, less than a 1 kW, is too small for induction, and switched reluctance has too much torque ripple to be a serious contender despite its fault-tolerance advantages. The torque-ripple problem was solved by using any and all known solutions, and still more needed to be done. In principle, a synchronous PM machine with a sinusoidally-magnetized rotor produces a flat torque [6]. This however met with two obstacles, one a matter of trade-off with other motor features, the other one of practical implementation. For instance a toothless stator has no cogging torque, but a much lower torque density. Similarly, saturation can create ripple by producing harmonics, but is welcome to the extent that higher magnetization means more torque per volume [7].

Every method to reduce both the cogging torque (when the motor is not excited) and the torque pulsations during excitation was examined [8-9]. The solution included careful machine design, from optimally-shaped and -magnetized magnets to special stator-tooth design, for instance with phantom slots. In phantom slot designs, small indents on the tooth pole multiply the frequency of this kind of torque by a factor of two, making the natural filtering by the mechanical system more effective [10-11]. It was also necessary to develop a finer understanding of the controller's role in producing torque ripple, due in part to commutation issues [12] or to the discrete nature of controllers [13]. In the latter case, a trade-off is critical between finer steps and ripple minimization. In the process, the practical issue of the accurate measurement of increasingly small torque pulsations came to the forefront [14].

Once solutions were devised, the next hurdle consisted in ensuring their applicability in mass production. Everything, from magnet placement and magnetization to rotor eccentricity and sensor accuracy comes with a tolerance that can affect output performance. However, tight tolerances come at a cost, and considerable studies were needed to understand the impact of dimension deviation on torque ripple. This made it possible to identify which dimensions are critical and need a tight tolerance, and which are less so. Robust engineering techniques such as those developed by Taguchi [15] were adapted to electrical machines in general [16] and PM synchronous drives in particular [17]. Looking for instance at magnet misplacement (resulting either from actual misplacement or poor magnetization), Fig. 3 (from [10]), even minor errors of a fraction of a degree can cause a torque ripple. The key is to select design parameters, in terms of magnet design for instance, that lead to the least torque ripple in the presence of tolerance.

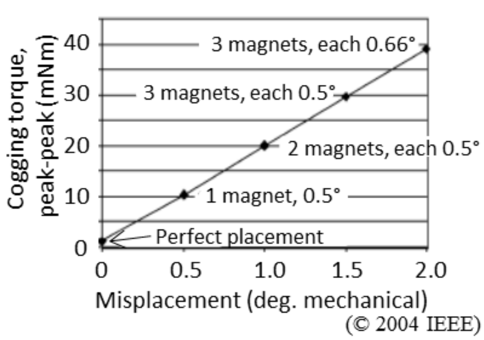

Fig. 3: Impact of magnet misplacement on cogging torque (Fig. 3 in [10])

4) Fault tolerance: Fault tolerance is a necessity in any safety-critical system such as steering. Ultimately, this is achieved in electric-power steering systems by retaining a mechanical linkage between the driver and the wheels, as a fallback mechanism, as is done with hydraulic power steering. It is however not sufficient because this should be a rare and last resort option. The answer came with careful design, redundancy, and fault detection and recovery mechanisms. Careful design is a matter of increasing margins (e.g., temperature limit for the electronic switches), or stringent manufacturing processes (for instance, extra steps to minimize insulation damage during motor assembly). Redundancy is a challenge because too much can be counterproductive, as redundancy adds components and complexity thus making the probability of a failure actually higher than in a simple system. A fail-safe design is therefore an exercise in getting the optimum amount of redundancy, enough to provide good fallback operation, but not so much as to make the system unwieldy. It should be noted also that electrical systems can be and usually are safer than alternatives, thanks to the presence of sensors and computers that can monitor the system and the possibility of a reconfiguration as needed (see [18] where this case is made for a by-wire system, where the mechanical linkage is actually removed).

Overall, the solution includes a number of parallel paths. At the system level, Failure Mode Effect Analysis (FMEA) techniques have a long history and are widely used in safety-critical and automotive systems [19].

On the hardware side, one step consists in understanding the failure modes and looking at how they can be avoided or mitigated by design. The motor and its drive are at the heart of the question, because the motor shaft is mechanically linked to the steering. In this respect, it has been shown that PM drives can be on par with switched-reluctance machines in terms of fault tolerance [20], but with added complexity, and noting also that switched-reluctance machines can after all experience faults, too [21]. A careful investigation of redundant features is therefore necessary, see for instance [22-23]. Dividing the drive into two parallel 3-phase systems (resulting in a six-phase configuration, with as added bonus a reduction in torque ripple) is a simple and effective measure. Designing the machine with an inductance large enough to limit any short-circuit current is another critical element, due to its effectiveness in preventing the overheating of the machine in case a short circuit occurs [20,23-24]. Winding short circuits are a primary concern in PM machines, because a rotating PM rotor sustains the short circuit current until the rotor stops.

Once a design is selected, an important step consists in devising fault detection algorithms. The literature is rich on the subject of electric machine fault detection, see for instance [25]. However, much of the work was done for larger industrial induction machines, motivated by their high maintenance cost. These techniques needed to be adapted to PM motors, which differ in terms of the presence of magnets and the absence of slip. The slip is critical because it modifies the frequency pattern of fault signatures in the current waveforms. Further, power steering systems always work in dynamic condition, unlike industrial drives where a steady-state regime is more common. This is a key difference because fault detection often relies on measuring harmonics such as those in the current, and this requires filtering out the fundamental. Such filtering is much easier when the fundamental frequency is fixed. New approaches such as wavelet detection techniques were thus developed for this application [26-28].

In another respect, in the course of power steering development it was realized that the machine could be used to detect load failures, thus enhancing overall fault protection in ways that are impossible in purely mechanical or hydraulic systems. Gear faults for instance generate torque pulsations that are reflected in the current [29]. This is shown in Fig. 4 where a system similar to that shown in Fig. 2 was tested with damaged gear teeth.

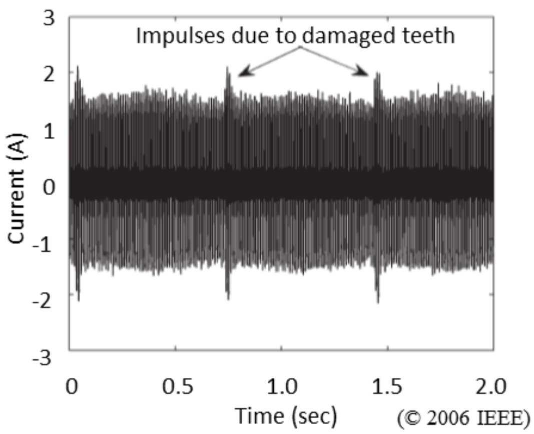

Fig. 4: Current in a motor driving a gear with two damaged teeth (Fig. 4 in [29])

The focus on fault tolerance has been so far on the hardware. Software is a critical part of it, not only in terms of algorithm reconfiguration, but also in terms of possible faults (or errors) in the software itself. This is an increasingly important problem in automotive design, with cars now hosting millions of lines of code, and a particularly acute one when safety is involved, see for instance [30-31] specifically for power steering or by-wire systems.

B. Brake Electrification

Braking systems are generally hydraulically driven. Some electrification came about in the form of anti-lock braking systems (ABS), introduced in the 70s and generalized in the 80s when cost was reduced and it was realized that safety sells cars (Fig. 5). Shown in Fig. 5 are the controller, the electric motor that pressurizes the hydraulic brake fluid, and some of the solenoid valves that open or close the lines to each of the four wheels. Not explicitly shown are pressure and wheel-speed sensors (the latter typically Hall-effect or variable-reluctance). The valves open and close at some frequency, with the opening duty cycle corresponding to the desired pressure for each wheel. That pressure level is determined by the amount of wheel slip observed at each corner.

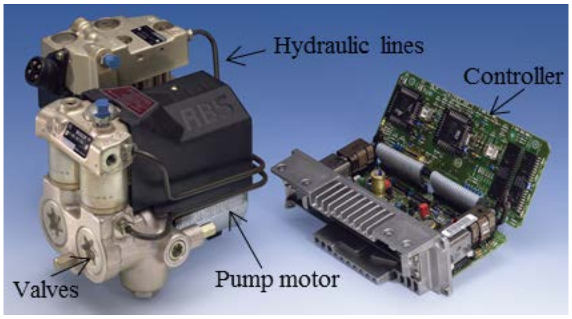

Fig. 5: ABS system (© Bosch, used with permission)

On electric and many hybrid vehicles, most braking is provided by reversing the propulsion motor and absorbing the vehicle kinetic energy, so-called regenerative braking. In so doing, energy is recuperated. However, regenerative braking alone is not sufficient and mechanical brakes are still needed. This is because of power levels. Strong or “panic” braking corresponds to a lot of kinetic energy dissipated in a short time. For regenerative braking to take care of all braking needs including panic braking would require very high power ratings for the components, inverter and battery in particular, for relatively little energy saved cumulatively since such braking occurs infrequently during vehicle operation. Therefore regenerative braking is designed for the more common regular braking action and the mechanical brakes take over as needed. In electric vehicles, the mechanical brakes are generally hydraulically actuated with the hydraulic lines energized from an auxiliary electric motor functioning as a pump [32].

Interestingly, electric machines directly mounted on the axle for braking purposes have been used for many years on heavy vehicles (trucks, buses, mining vehicles), mostly to spare the friction brakes and prevent them from overheating, for instance during a long descent [33-35]. These machines are called either retarders or eddy-current brakes and are in essence induction generators with solid steel rotors where the braking energy is dissipated. The braking torque per volume is very large at driving speed, but decreases proportionally to speed below a certain level (like an induction motor close to synchronism). Therefore such brakes alone can only slow down, but not stop, the vehicle.

A fully electric friction brake, whereby an electric motor drives the caliper and brake pads onto the braking disk, instead of oil pressure, is possible [5,36-37]. There are a number of advantages, such as vehicle-assembly simplification, the elimination of hydraulic fluids (an environmental benefit), and better control. In these systems, the motor rotary motion is mechanically transformed into linear motion, to activate the caliper (see Fig. 6). In this case, the switched-reluctance motor is a strong candidate, because of its ruggedness, fault tolerance, and relative insensitivity to heat compared to PM motors (brake pads can reach several hundred degrees) [37]. Torque ripple, vibrations and noise are not a concern here, relatively to the steering application. Conceptually similar systems, for drum brakes, are common on trailers where a simpler DC brushtype motor is used. Electric is preferred on trailers because an electric wire is easier to run from the car to the trailer than a hydraulic line. Electric brakes are also used on aircrafts, and are being introduced as parking brakes. These solutions, however, have yet to become a viable alternative for regular brakes. Perhaps this requires a rethinking of the brake system, whereby the electric brake is not actuating a regular caliper like a hydraulic system, but performs that function in some novel way. This may provide new advantages unavailable from a disk brake. There is research on going in this space, see for instance the wedge-brake concept [38-39].

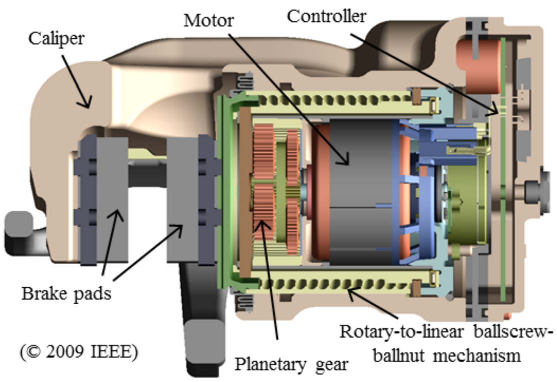

Fig. 6: Schematic of an electric brake (Fig. 1 in [37])

C. *Suspension Electrification*

Suspension systems, with springs and dampers, make the ride more comfortable for the car occupants and reduce the vibrations and thus the wear experienced by the car body. A suspension is analogous to an LC filter which dampens as much of the road irregularities (acting a noise input) as possible, so that the car cabin remains at ideally a constant level. However, the sensitivity of both the car body and the passengers to vibrations varies with frequency, such that a non-linear and adaptive filter would be desirable. In addition, if controllable, it would be possible to adjust the ride quality from "sporty" to "smooth" to accommodate the wishes of the driver. A fully active suspension, where the system would actually change the car level on demand, or that of some wheels, would be even better by providing consistent body leveling regardless of load, and by controlling the car pitch during strong maneuvers. Electrification is one means to achieve this, and comes here therefore with a different motivation, namely comfort.

Early suspension control was achieved with controllable air springs [40]. A more effective, albeit more expensive option was developed in the last 10-15 years by placing magnetic particles in the damping fluid, in such a way that its viscosity can be controlled magnetically, see Fig. 7. This "magnetorheological" fluid and the related actuators required significant development, in particular to devise the right particle materials, coating, and oil to prevent sedimentation of the particles over time. Along with material research, magnetic design and controls needed to be thought out, particularly to address residual forces due to hysteresis in the iron particles [41]. Such suspension systems have become common on sporty and luxury vehicles, and the technology is being adapted to other uses such as engine-mount design.

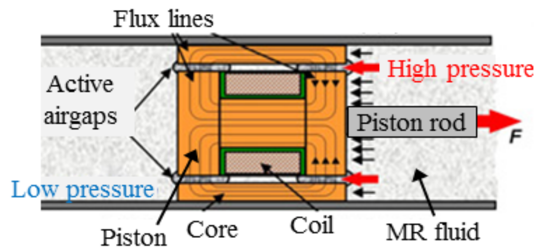

Fig. 7.a: Principle of operation

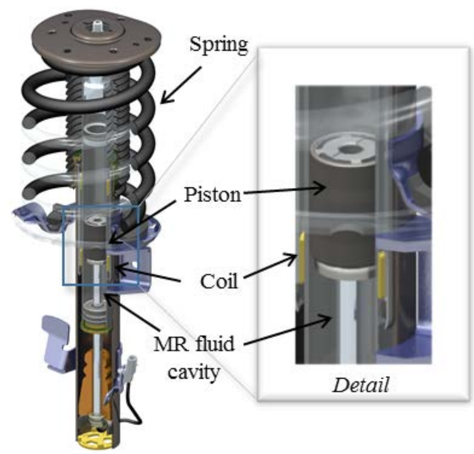

Fig. 7.b: Suspension cutaway
Fig. 7: Magnetorheological (MR) suspension
(Images © BWI, used with permission)

Another approach altogether consists in placing an electric machine in the suspension, to act as either a generator or a motor to absorb the energy from the bumps in the road or to level the car during maneuvers. Such systems could be semi-active, or fully active. The most immediate solution is a linear motor, and this has been proposed and studied by a number of companies and researchers, see Fig. 8 [42-43]. These can provide very comfortable rides, but at a price, both cost and weight as these systems must be able to handle 10 kW or more (2.5kW per actuator [44]). Another solution with the promise of a more compact package consists of using a rotary motor with a ballscrew mechanism to translate the linear motion into rotation, see Fig. 9. Such a gear system makes it possible to reduce the torque requirement of the machine (by increasing its speed), thus the machine size [44].

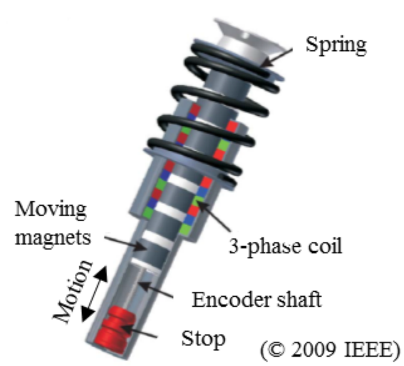

Fig. 8: Linear machine for active suspension (Fig. 8 in [43])

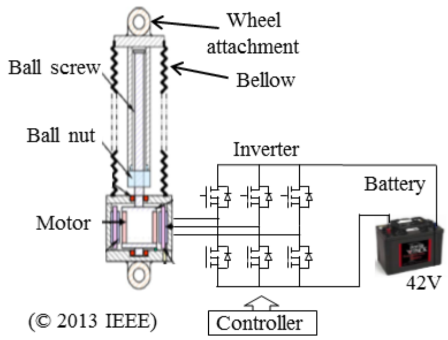

Fig. 9: Suspension with rotating machine (Fig. 1 in [44])

An interesting question is whether such electric suspension systems can be used to generate energy from the road vibrations and recharge the battery. While this is appealing in principle, the reality is actually more sobering. In [44], the average regenerative power is estimated to range from 25W on a smooth highway to 200W on a rough road, with 70W as an expected average for a normal local road. When it is recalled that to be effective as a suspension, each actuator is rated on the order of 2.5kW peak (10kW total), and peak power by and large determines size and cost, it becomes clear that a 70W average regeneration potential is too low to constitute a motivation for active suspension. These systems are developed for comfort and superior handling, not regeneration. Of course, with a fully bi-directional inverter, regeneration is possible and might as well be included as long as the energy storage can absorb it without added complexity, but it is a minor side advantage.

III. Engine Electrification

Engine electrification, aside from the spark plug, started in earnest with the engine controller, usually referred to as the ECU or Engine Control Unit more recently complemented by the TCU or Transmission Control Unit. Computer controls however are most effective when engine peripheral systems are electrified, and a number are already or will soon be. Below are a few examples, with an emphasis on motor/power electronic technology rather than on their impact on engine performance.

A. Fuel injectors

Fuel delivery into the engine has been taking place closer and closer to the combustion chamber, initially in the carburetor, then in the intake manifold and now often directly in the chamber itself (for gasoline engines; in diesel engines, direct injection appeared much earlier, in the 1920s, and is the fairly standard way to introduce fuel into the combustion chamber). With direct injection, fuel can be injected more precisely and in a way that makes for more complete combustion, improving engine response while minimizing emissions (see Fig. 10) [45]. Progress in fuel injector technology has been key in this development.

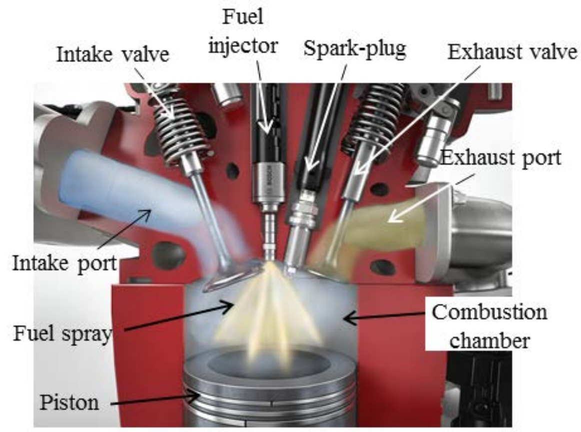

Fig. 10: Direct fuel injection with modern fuel spray pattern (© Bosch, used with permission)

Electronic fuel injection was first accomplished, and still is in many cases, with a solenoid opening a valve that allows the fuel under pressure to be spread in the air stream, for good vaporization of the fuel, see Figs. 11.a-11.b. Solenoids are perceived as the simplest possible kind of electromagnetic actuator, and they may well be in terms of construction. However this glosses over a number of technical challenges. The magnetic parts are made of solid steel and eddy currents must be taken into account, both those induced by the excitation voltage and also for fast actuators those due to motion. The fact that the excitation is typically a step voltage, as opposed to periodical like in a regular machine, makes the use of frequency models impossible. Furthermore in the case of fuel injectors, airgaps are small, on the order of a fraction of a millimeter. This, combined with strict requirements for fuel injection, namely fast actuation, precise and repeatable openings in a hot environment, have made fuel injectors perhaps the most advanced solenoid technology. For instance, it is this application that motivated the development of finite-element-analysis (FEA) codes capable of accommodating airgaps of varying dimensions [46]. At the same time, various efforts took place to provide faster yet accurate algorithms, in order to speed up engineering trade-off studies [47-50]. This involved in particular simplifying the geometry and reducing the eddy current problem to a single dimension, namely penetration depth. Nowadays, multiphysics involving fluid dynamics along with electromagnetics is the next frontier, both based on FEA or simpler models, as well as tests [45].

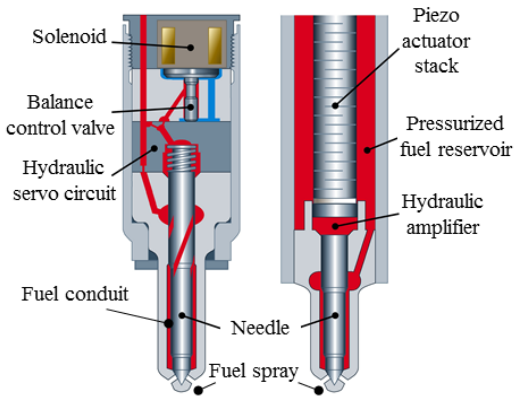

Fig. 11.a: Fuel injector principles: solenoid based (left) and piezo actuated (right) [51] (© Delphi, used with permission)

Fig. 11.b: Cutaway of a solenoid injector (© Bosch, used with permission)

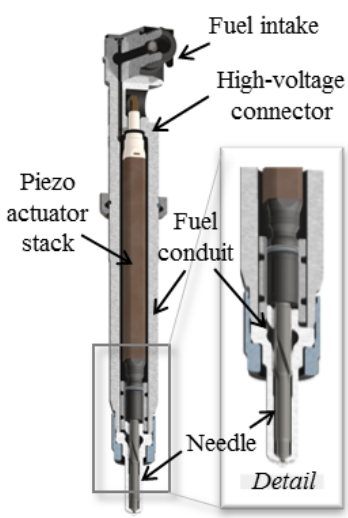

Fig. 11.c: Cutaway of a piezo injector (© Delphi, used with permission)

Fig. 11: Fuel injectors

In parallel with solenoid injector development came the introduction of piezo actuators, first for diesel engines some 10 years ago. Piezo actuators are, in a nutshell, a stack of disks made usually of a ceramic material. Each disk when subjected to voltage changes dimension by a small amount, so that one of the stack surfaces moves, see Figs. 11-12. The amount of motion is very small, and a hydraulic amplifier is usually needed. These actuators are larger than solenoid systems (some 4 times longer – the figures are not to scale), more expensive, and require a higher voltage on the order of 100V or more. The high voltage is provided by a boost converter, such as the one on Fig. 12, bottom left. Yet, they are used on many engines due to the rapid and precise opening they generate [52-53].

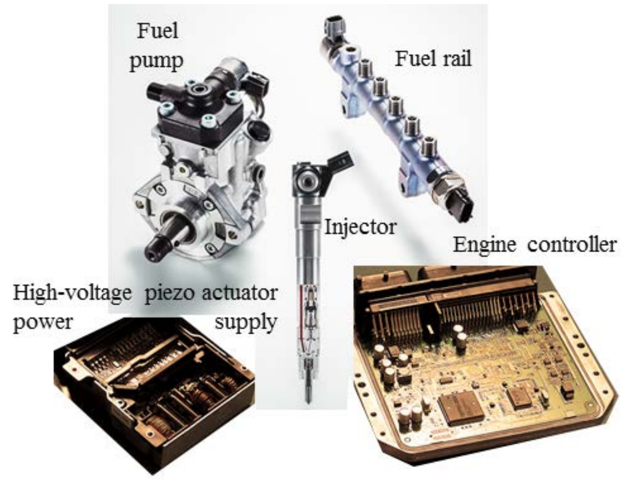

Fig. 12: Diesel piezo injection system (© Denso, used with permission)

A more recent challenge for fuel injector design is the desire from engine designers to have several fuel injection events per engine cycle, an initial opening, the main opening, and also a post opening, etc., all with a goal to generate a more ideal fuel spray and flame propagation into the cylinder. This requires yet faster actuation, and perhaps more importantly more repeatable openings and closings so that the metering of the fuel into the engine is consistent from cycle to cycle and from cylinder to cylinder. Part of the problem is for motion to begin from a well-defined, repeatable state. Therefore bounce, eddy currents or hysteresis lingering from a previous opening must be eliminated. This is a challenge for both piezo [52] and solenoid [54] technologies. In some cases, ballistic motion is used whereby the injector never fully opens, and whether such plunger trajectories are more or less repeatable than starting the closing motion from a full open position is the object of on-going research [45].

Both solenoid and piezo technology are still being developed and used on new engines, and it is not clear that piezo will overtake solenoids. Solenoids have the advantage of a smaller size, lower cost, and simpler excitation, and it may be a matter of improving their performance sufficiently to allow them to hold to at least part of the market, so that both approaches will co-exist depending on fuel type, performance expectation, emission and fuel-economy standards, etc [53]. This unless another approach overtakes them both, such as some “smart material”, magnetostrictive or other [55].

B. Electronic throttle control

Many drivers may be surprised to learn that the mechanical linkage between the gas pedal and the engine was lost a while back, and replaced with a by-wire system. In essence, the gas pedal movements are detected by sensors. Their signals are processed by the ECU which then sends commands to an electric motor controlling the throttle plate. The ECU also takes into account other factors such as engine condition and temperature, road condition, etc to determine the degree and the rate of the motor motion, see Fig. 13 [56]. The motor is typically a bushtype DC motor connected to the throttle plate by a gear, such that the motor accomplishes several rotations while the throttle plate moves 90°.

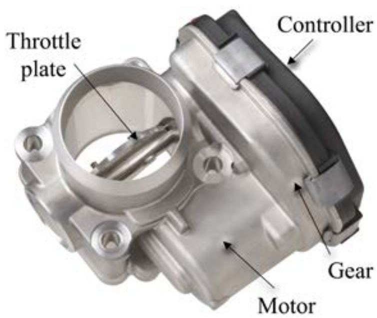

Fig. 13: Electronic throttle unit
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C. Valvetrains

Air is admitted into the engine combustion chamber through the intake valve, and burned gases flushed out through the exhaust valve (see Fig. 10). These two valves are conventionally actuated by a camshaft that is linked to the crankshaft via the timing chain (or belt) and rotates at half the engine speed. While very effective, it makes for constant valve profiles in terms of duration in degrees, even though it would be desirable to adjust both timing and lift as a function of engine speed, load, etc [57]. Valve mechanisms have therefore been the object of significant work over the years, which is now bearing fruit.

1) Camless systems: The possibility of directly actuating the engine valves with an electromagnetic actuator was envisioned around 1980. The leading contender at the time, Fig. 14, was a direct acting actuator with two springs and two coils. The motive energy comes from the springs. It is latched and released by energizing or de-energizing the coils. The addition of permanent magnets to achieve the latching function was considered as well [58-61].

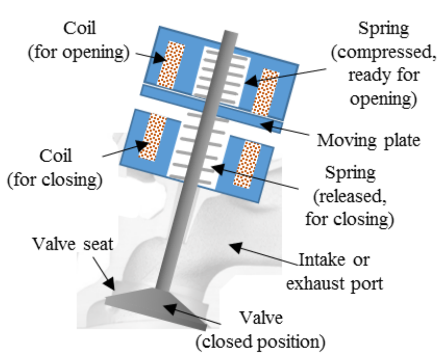

Fig. 14: Example of electromagnetic camless actuator

One challenge for these actuators was to learn how to get the fastest travel time while using the least moving mass, with an ambitious goal of less than 4ms for a 10mm lift. The time T for this spring-mass pendulum system to go from fully open to fully closed is approximately given by:

$$T = \pi \sqrt{\frac{m_t}{2k}}$$

where k is the spring stiffness and m_t is the total moving mass, i.e. the sum of the moving plate or plunger mass, the valve mass and 1/3 of the mass of each spring. Increasing the spring constant k reduces the travel time, but this requires a stronger latching force thus a larger plunger (bigger m_t) to accommodate the larger flux holding it. In the end a point of diminishing return is reached [60].

Perhaps the biggest challenge was to ensure a low enough seating velocity for the valve, which is a metal disk landing on a metal valve seat. In essence, an almost zero (less than 0.1m/s) seating velocity v_s has to be attained consistently, while making sure that the valve never fails to close. The latter is expressed as a positive seating velocity: $0 < v_s < 0.1$m/s. $v_s > 0$ is an absolute requirement over the expected life of the engine, which includes hundreds of millions of valve closings. Encouraging results were achieved in the lab, based on sliding-mode control or other methods, with position sensors or with flux observers for sensorless operation [62-63], and have been claimed on experimental vehicles [57,64]. Another difficulty was cycle-to-cycle variability, which leads to variations in engine performance such as emissions.

Other mechanisms for full electromechanical valve actuation have also been proposed, for instance a cam driven by an electric motor. Such a system has the advantage of retaining the cam system that provided the smooth and reliable seating known of mechanical systems [65].

In the end however, other mechanisms providing most of the advantages of variable valve actuation at a fraction of the cost, complexity, and risk emerged and some are now commonplace. A couple of them, involving a significant mechatronic component, are mentioned now.

2) Continuously-variable valve systems: High-end engines now feature valve systems with continuously variable lift and duration.

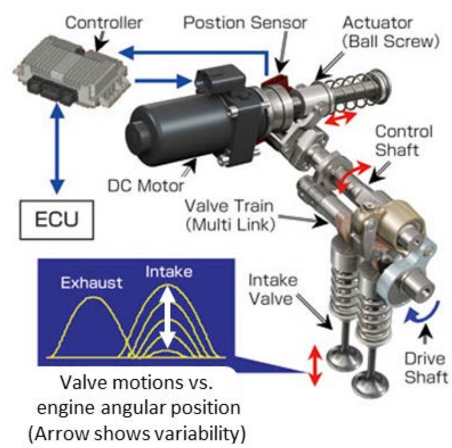

Fig. 15: Continuously variable valvetrain system
(© Hitachi Automotive Systems, Ltd., used with permission)

In short, an electric machine, typically a PM brushless motor, drives a mechanism that adjusts the position of the camshaft, or adjusts the relative position of the cam and its corresponding valve [66]. Fig. 15 shows an example of such a mechanism which results in a valve lift variable from full profile down to very low lifts. The challenges are smooth mechanical action and robust controls over time so that the valve profile is controlled precisely over the lifetime of the engine.

3) Electric cam phasers: Another system, called a cam phaser, shifts the camshaft position relatively to the engine, so as to delay or advance the valve event. These are common now and generally hydraulically actuated. Some efforts are underway to electrify these devices, in order to get broader control range and more control authority at low engine speed when oil pressure is low. They would even make it possible to preposition the camshaft before the engine starts thus minimizing starting emissions, as the starting process generates a disproportionate amount of emissions especially when the engine is cold. The challenge here is to produce a compact, flat system, as cam phasers are mounted at the end of the camshaft and affect engine length (see Fig. 16). Harmonic drives have been proposed, with a flat PM brushless DC motor such as an axial motor [67-68].

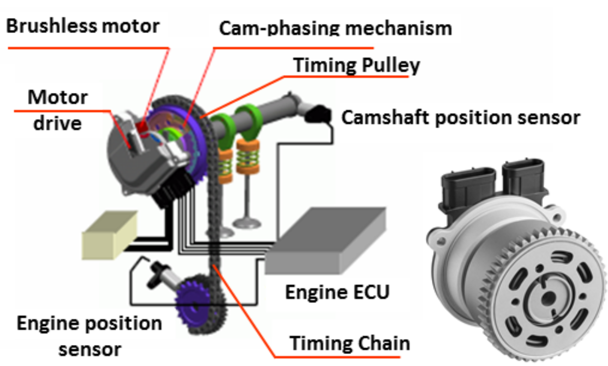

Fig. 16: Electric cam phaser system (Image on left: © Denso; image on right: © Delphi; both used with permission)

D. Role of electrical drives in superchargers and turbo systems

Superchargers like turbochargers compress the intake air before it enters the combustion chamber. In so doing, they increase the amount of air available for combustion. They are equivalent to having a larger combustion chamber except pressure can be varied depending on driving conditions, while the size of the combustion chamber obviously cannot. These devices are gaining market acceptance as they enable engine downsizing as well as fuel-consumption and emission reductions. Turbochargers get their motive force from the exhaust gas stream with a turbine driven by exhaust-gas pressure, while superchargers are either mechanically or electrically driven. Turbochargers have the notable advantage of using exhaust energy that would otherwise be wasted[1], but cannot be effectual until the combustion process has generated sufficient exhaust pressure, resulting in a "turbo lag". Superchargers on the other hand provide pressure on demand, but do use considerable power (more than 1kW). Sometimes both are used, the supercharger during transients and during starting, the turbocharger otherwise. Which of the supercharger or turbocharger will be the winning technology, or whether both will coexist in the marketplace, is a matter of debate [70-73].

Electrification can contribute in various ways. Focusing on superchargers first, Figs. 17-18, an electric drive has advantages over its mechanical counterpart. In particular it enables the use of centrifugal pumps over positive-displacement systems. Positive-displacement units work at lower speeds and thus can be driven by the engine belt, while centrifugal pumps require much higher speeds that preclude a belt drive but are compatible with an electric motor [70]. Higher speed here is at least 50,000 rpm, typically 70,000 rpm and even much higher. Such speeds are a challenge for any machine design and their automotive use will necessitate considerable development in terms of motor design, materials, mechanical robustness, and controls. The fact that the automotive voltage is low is a special challenge for the motor at such speeds, as is the controller which must be designed with a high fundamental frequency [70]. Note in Fig. 18 the use of a switched reluctance machine, a machine type well suited for wide speed ranges.

Turbo systems, defined here as turbines driven by exhaust pressure, can be electrified as well. There is considerable work on turbines using ranking cycles in the exhaust stream to power a generator to charge batteries. In essence, these would look like the supercharger shown in Fig. 18 but working in reverse from the pressure in the exhaust pipe. Such systems face similar issues concerning design for high speed with both switched reluctance and axial PM motors being experimented with [74-75]. Turbo generators can be used in conjunctions with a supercharger, with the electrical energy produced out of the exhaust typically being more than that needed to power the supercharger [71].

There are other approaches to recovering the exhaust energy. An intriguing possibility is to use thermoelectric generators based on the Seebeck effect [76]. Low efficiency, cost, size, and the introduction of a back-pressure in the exhaust stream currently limit application prospects in the foreseeable future. This said, thermoelectrics may find their way in cars to heat or cool seats [77] or coffee cups, applications where cost and benefits are seen very differently.

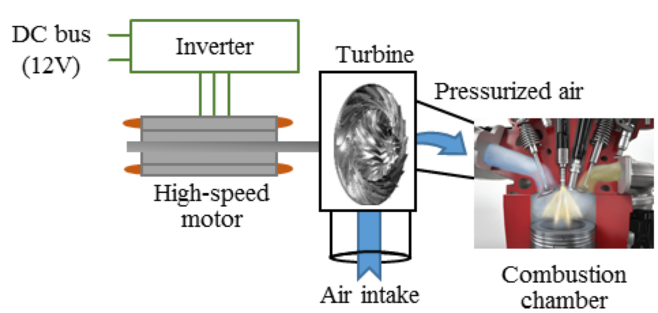

Fig. 17: Principle of supercharger

[1] In conventional vehicles driven by internal combustion engines, about a third of the fuel energy is wasted in the exhaust stream [69].

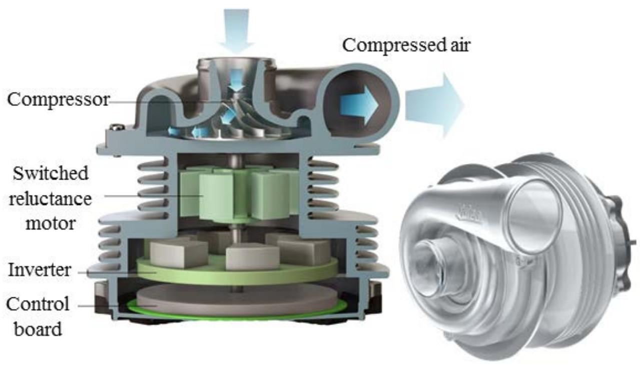

Fig. 18: Example of supercharger
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E. Other engine accessories

A number of other engine accessories could include an electric motor driving a mechanical or pumping system. For the electrical engineering team, the difficulty is usually one of meeting challenging cost levels.

For example, water and oil pumps are currently driven by the engine accessory belt. Driving them electrically would bring about more engine-control flexibility, especially during engine starts when the engine is cold.

Air conditioning is another pump generally driven by the engine accessory belt. The development of an electric alternative, usually a brushless DC motor [78], has been motivated by the need to provide uninterrupted comfort to the passengers of hybrid vehicles whose engine is designed to be off as often as possible. The difficulty is to do so at a reasonable price for drives that are typically in the several kW range, or consider its cost as the overall price of hybridization. Note however the convenient cooling of these drives with the air conditioning refrigerant, a strong incentive to integrate the power electronics with the motor in this case [78]. Integration of the power electronics with the motor is always debated in automotive applications, with generally no clear answer.

Fuel pumps have been electrified for decades with a brushtype motor providing on-off pumping. There is no concern about sparking between the brush and commutator, because the gas tank is saturated with gasoline and gas fumes leaving not enough oxygen for gasoline to combust [79]. Those pumps in the past sent the maximum fuel ever needed to the engine with the surplus returned to the tank, a simple but inefficient method. Controlled pumping, so that just the right amount of fuel is delivered to the engine, was proposed a couple of decades ago and is in production now as electronics cost has come down sufficiently to meet the expected benefit. Once power electronics are introduced to control the motor, brushless motors may be used for yet higher performance and more importantly smaller packaging [80], see Fig. 19.

In this fuel pump image, Fig. 19, one may notice the concentrated stator windings. This winding topology is becoming increasingly popular in automotive applications, with multiple benefits: Lower manufacturing cost as the coils can be wound individually before assembly of the motor, higher slot-fill factor, and shorter end turns. In the meantime, research has shown ways to design these machines to limit or even overcome their limitations compared to distributed-winding motors, at least in brushless PM machines [81-83].

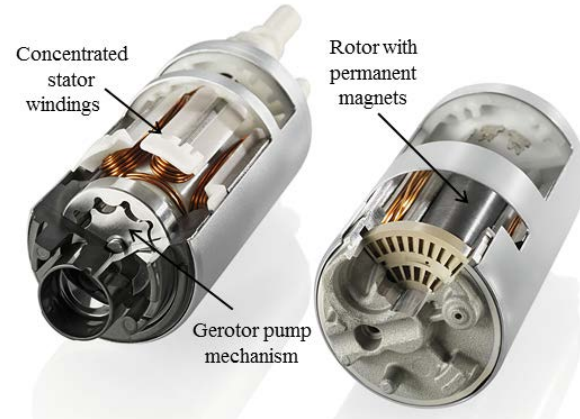

Fig. 19: Brushless fuel pump
(© Continental, used with permission)

F. Starters, generators, and starter-generators: Segway to hybridization

1) Starters and generators: These machines have been a mainstay of engines, generators from the beginning to supply spark energy for ignition and starters since their invention in 1911 [1]. In fact at first a single motor was used for both functions, although the practice was quickly abandoned due to the different requirements: High torque at low speed for starters, wide speed range for generators. The starter motor has been a DC motor since the beginning, driving the engine during the start process via a gear which is clutched out as the engine accelerates. The generator was also a DC motor until the 50s, when it was replaced by the Lundell generator, a 3-phase synchronous generator with a diode-rectifier (Fig. 20). The generator is driven by the engine via a belt with a gain of generally 2.5:1 to 3:1.

The Lundell generator was improved in the last twenty years to allow more power to be generated in both absolute terms and per volume: Magnets were placed between the claws on the rotor, mainly to reduce leakage flux [84]. New windings with pre-formed bars were used in the stator, to allow better slot fill, heat removal, and thus power density [85], with this technology now used on induction or PM starter-generators as well. Water cooling was introduced for the same reasons. Twin-coil motors were developed, essentially two motors back-to-back on the same shaft. The twin-coil configuration is preferable at higher power levels to avoid prohibitively high rotor leakage fluxes between the claw poles [85]. It also makes for a longer rotor, rather than one with a larger diameter, which is favorable in terms of inertia per torque and belt-drive design.

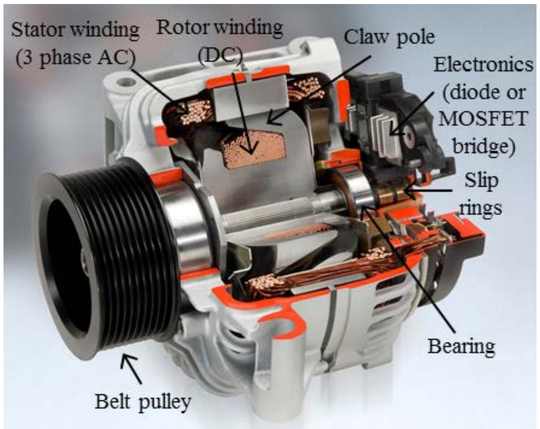

Fig. 20: Lundell alternator (© Bosch, used with permission)

Along the way, significant efforts were expanded to model these machines either with FEA [84] or with equivalent magnetic circuits [86-87]. The difficulty in this case is the 3D nature of the machine geometry, and the fact that the claws are made of solid steel. More recently, multi-physics is starting to play a role to better master the cooling of the devices, both FEA-based or with simpler algorithms to cut on computing time [88-89]. On the power-electronics side, the diode bridge is being progressively replaced by an active bridge, which improves performance by giving control of the phase relationship between voltage and current [90]. This is critical at lower speeds where power output is limited.

Attempts were also made to use so-called SMC (Soft Magnetic Composite) materials [91]. SMC are low cost and allow intricate shapes, because manufacturing uses a mold. They are therefore well suited for machines with 3D configurations. So far however, their advantages have not been sufficient to overcome their drawbacks, mostly their lower permeability.

Alternatives to the Lundell for generation only have been investigated over the years, such as PM brushless [92] or induction [93]. The studies focused on cost, introducing clever power electronic topologies such as a dual SCR bridge [92] or one diode rectifier with full power rating paralleled with a MOSFET bridge for control [93]. However these efforts were not sufficient to see non-Lundell generators in mass-produced vehicles until new functionalities, see next section, were added to the system.

2) Starter-generators: Starter-generators, or machines that combine both functions into one device, made a comeback some ten years ago in part due to the increased in on-board power demand which narrows the gap between starting and generating requirements. Another key driver was the introduction of “stop-start” or engine-off idle, a feature where the engine is stopped when the car is at a standstill, at a traffic light for instance. This feature alone can save significant fuel with gains as high as 5-10% reported [94] at least in urban traffic. They are increasingly common on new vehicles, particularly in Europe.

When the machine is meant to do just starting and generating or little more, the technical consensus has been to place it on the belt drive, simply replacing the alternator [85,95-105] (Fig. 21), as opposed to in-line with the engine which is more of a hybrid-vehicle topology. The different approaches are due to power level. A machine placed on the engine driveshaft naturally has a larger diameter, therefore can easily accommodate larger torques. It is thus a good fit for a higher level of hybridization. Conversely, in that location it is difficult to reduce it efficiently to the size sufficient for just starting the engine. At the same time, belt drives are very effective for driving several kilowatts of power but are difficult to scale up for full hybridization.

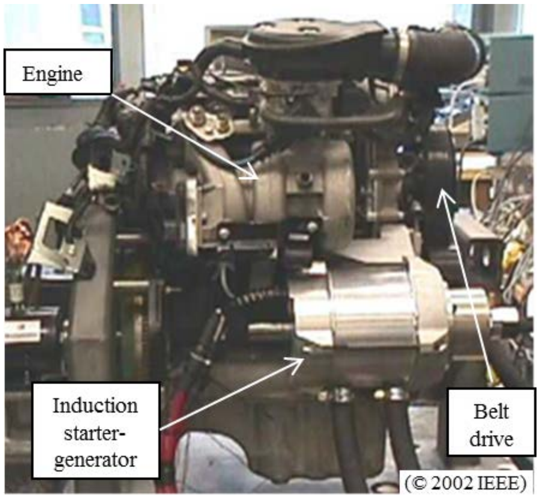

Fig. 21: Belt-driven starter generator mounted on engine (Fig. 1 in [98])

Concerning the machine type, it is important to recall that despite all the recent improvements mentioned earlier, the Lundell machine is a relatively inefficient machine. Further, the use of PM brushless and induction topologies for hybrid and electric vehicles has generated significant developments for these motors in automotive applications, facilitating their introduction in starter-generator applications. PM brushless machines have therefore been considered [85,100], even switched-reluctance [85], although induction appears to have a significant lead in challenging the Lundell [85,97-98,100,102], reaching production [104-105]. Although both PM and induction machines are well adapted to the application, induction seems to have an edge due to several factors: Primarily, lower cost (no magnets); also, given the very wide speed range (1 to 10), larger than in hybrid and electric-propulsion applications, PM machines lose some of their efficiency advantage as many operating points require field weakening in which operating mode the PM machine is a field-excited machine just like the induction. Further, induction machines can be designed with a lower pole count, meaning a lower frequency, which helps at high speed both in terms of core losses in the machine and inverter design and control. This said, the advantages of the induction machine and its use in production should not mean the Lundell days are over. It has demonstrated its capacity in addressing both generating and starting functions effectively on various production vehicles and it will remain the lowest cost solution for the foreseeable future [85,99,101,103]. Machine comparisons for this application can be found in [85,100,105].

Concerning voltage levels, some starter-generators operate at 12V, however many use higher voltages such as 42V [96,99,101] or 115V [104-105]. Starter-generators, especially if more functionality is expected of them, may be the impetus behind a generalization of a dual 12/48V system, with a DC-DC converter linking the two. 48V is a desirable level as it is comfortably under 60V, the level considered a threshold in terms of human safety. However, a dual voltage system or just a change in voltage level standard is costly and a number of issues still need to be resolved, especially concerning electrical contacts. The challenge is that arcs in air across a contact can be sustained if the voltage is over 18V [106]. Overall, however, 48V is a good trade-off, avoiding the higher voltages typical of hybrid vehicles with the concomitant need for extra safety precautions, yet enabling many features including lower levels of hybridization, superchargers, etc. 48V will also facilitate the electrification of many accessories in trucks or commercial vehicles. The spread if not the standardization of this higher voltage will also make economies of scale possible across various transport vehicles for motors, inverters, relays, contactors and other components, something still needed for the electrification of many functions.

Whether belt-driven starter-generators will become mainstream or not will depend on a couple of technology evolutions. One reason conventional cars don't stop their engines at idle is that the starter-motor mechanism was limited in terms of number of starts over its expected life. This has changed recently with the introduction of heavy-duty starter systems, so the stop-start feature does not require a starter-generator any more. In fact, such a robust starter along with a conventional alternator is the lowest-cost way to achieve stop-start. On the other hand, once a machine can do both starting and generating, that is, is fitted with a bi-directional inverter and a bi-directional belt drive, other features become possible such as a degree of launch assist (helping with car acceleration, beyond just starting the engine) or engine braking and energy recovery. These additional features help the value proposition compared to the conventional system with separated generation and starting mechanisms.

3) Starter-generators or hybrids?: This paper has purposely avoided the topic of vehicle hybridization. However, with starter-generators, the distinction between conventional automobiles and hybrid vehicles is becoming as much a question of semantics as of technology. Some authors and manufacturers indeed classify starter-generators as hybrids, although usually calling them "micro-hybrids". Others prefer to consider a car a hybrid only if it is moved or decelerated by electrical means, which starter-generators do not typically do. But, why not have the starter-generator contribute to the car motion? After all, if the starter-generator starts the engine, it can also provide at least some occasional power boost or contribute to engine deceleration [99,105]. Then, the distinction between the starter-generator function and engine assist is one of power level and control complexity. In other words, there is a clear continuum between the starting and generating functions and vehicle powering. In that sense, with starter-generators being introduced to the market to make fuel gains possible during idle, it is only logical to think that over time, such systems will grow in both power and control complexity and encompass launching ability, engine power boost as well as regenerative braking. At that point, hybridization will be standard on all vehicles.

Of course, launch and brake assists involve relatively low levels of energy compared to that expanded over a typical trip. However, as the cost of power electronics and other technologies comes down, it is equally reasonable to believe that the level of hybridization will gradually go up relatively to engine power. Therefore, while the press gives much publicity to electric vehicles and full hybrids, a well-deserved publicity given the engineering achievements and market promise they represent, a much more silent revolution is happening whereby the much simpler starter-generator is quietly becoming standard, and will open the door to a very gradual, but real, hybridization. Instead of a grand entrance with full electrics, hybridization may well establish itself quietly through the back door opened by the starter-generator.

IV. Conclusion

This paper gives a flavor of the diversity of technologies and issues involved in automobile electrification. Concerning electromechanical energy conversion alone, electrification covers many applications, from fuel injectors to suspension with many motor controls in between. The challenges and solutions faced so far have involved material development, such as magneorheological fluids for suspension or piezoceramics for injectors, design for manufacturing, issues of torque ripple and motors for power steering, involved modeling techniques for fuel injectors or Lundell alternators, with now multiphysics as a new frontier of mathematical development. Mechanisms are often key enablers, rather than the motor and electronics, for instance with electrified valvetrains, but precise electromagnetic control is often pushed beyond current state-of-the-art as in multi-pulse injection applications. Other times, motor configuration is key as in the trade-off between linear and rotary motors for suspension. Motor and power electronic designs can also be challenged, for instance in high-speed superchargers. In all cases however, cost always comes as the final arbiter of what will or will not be electrified.

The paper's focus on electromechanical energy conversion left aside other technical developments, for instance the considerable studies around electromagnetic interference, electric contact science (many failures of electrical components are traced back to the contactor), or the vast array of sensors used or under development for position or speed sensing (engine or wheel), oil or fuel quality and level sensors, tire-pressure sensors, exhaust sensors such as oxygen sensors, just to give just a few examples. Nor was it meant to overshadow other aspects of automotive electrification, such as entertainment systems, antennas for wifi, controls and computers, vision systems for collision avoidance and lane keeping, and communication between the car and its environment. Indeed the time may come soon where more electrical engineers are employed in the design of a car than mechanical engineers.

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Bruno Lequesne (M’85-SM’89-F’97) received the Certified-Engineer degree from the Ecole Supérieure d'Electricité, France, in 1978, and the PhD degree in electrical engineering from the Missouri University of Science and Technology, Rolla, MO, USA, in 1984. He worked for 30 years in the automotive industry on transportation electrification research before starting his own consultancy, E-Motors Consulting, LLC, in 2014.

His automotive involvement includes working at General Motors Research Laboratories (1984-1999) and Delphi Research Laboratories (1999-2006). In September 2006, he moved to the Delphi Powertrain Division to manage a group within the Advanced Powertrain Engineering organization (2006-2009). After a year at the University of Alabama, he joined Eaton Corporate Research & Technology group to focus on the electrification of commercial vehicles (2010-2014). Since starting his consultancy, he has contributed to the automotive, aerospace and renewable energy industries, working on motors, actuators, and systems. His research interests are in the design and adaptation of electric machines, actuators and sensors to systems for those industries.

Dr. Lequesne holds 49 patents with 4 more pending, primarily on sensors, linear actuators, and automotive applications. He is the recipient of ten Best Paper Awards, seven from the IEEE- Industry Applications Society (IAS), and three from the Society of Automotive Engineers, including the Colwell (2000) and the Bendix (2007) awards. He was elected an IEEE Fellow in 1997, and received the IEEE IAS Gerald Kliman Innovator award n 2007. He is also past president (2011-2012) of the IEEE IAS and is currently on the steering committee of the IEEE Transportation Electrification Community.