Proceedings of 2001 International Symposium on Power Semiconductor Devices & ICs, Osaka

The Future of Electronics in Automobiles

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Abstract

The present 14 V automotive electrical system will soon become 42 V. New electrical features and electrification of present mechanically driven functions will provide commercial opportunities for a new high volume application of power electronics. Cost and the thermal environment present difficult challenges to device designers. SiC is shown as a promising material for this environment. A new high efficiency power supply design using the existing automotive alternator is presented.

Introduction

The demands being placed on a car's electrical system today are unprecendented, and the future promises even greater challenges. An internationally accepted system of 42 V has been proposed to service the electrical needs of future cars [1]. Not since 6 V was replaced by 12 V in the early 1950's has the car's electrical system experienced such a fundamental change [2]. Along with the change in nominal system voltage have come recommended standards for reduced voltage transient levels (see Fig. 1). For the semiconductor industry these are glad tidings indeed, as the new specifications not only reduce the cost of devices for a given application, but *require* the use of silicon in others. The value of 42 V was proposed in 1996 by participants in an 18 month series of workshops at MIT. Considerations of safety and economics, particularly of semiconductor devices, led to the final recommendation. Fig. 2 shows the economic impact (in terms of Si area) of system voltage and application margin (ΔV). It shows 42 V to be nearly an optimum with respect to this criterion [3].

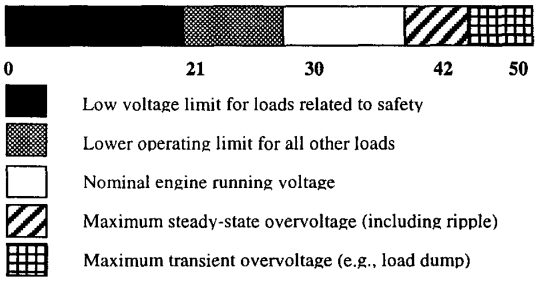

Fig. 1 Proposed voltage specifications for the 42 V PowerNet.

The present electrical system uses a 12 V Pb-acid battery which, when the engine is running, results in a nominal system voltage of 14 V. Scattered throught the vehicle are up to 70 electronic control units (ECUs) that provide a variety of data processing and control functions, e.g., determining optimum shift points for the automatic transmission, controlling fuel injectors, or controlling the multiple functions contained in a door. Many of these ECUs contain discrete power switching electronics as well as a microprocessor. For example, while an antilock braking system (ABS) uses hydraulic actuators, the valving is controlled by power electronic devices. Other applications of power electronics in today's car include automatic transmission clutch solenoid drivers, fuel injector drivers, electronic ignition systems using high voltage (450 V) IGBTs, and electronic throttle drivers.

The basic electrical system architecture consists of a bus connecting the alternator/battery supply to one or more junction boxes containing fuses and relays. From here wires formed into "wire harnesses" supply electrical functions such as lights, horn and power seats through, mainly, manually operated mechanical switches. The wiring in a midsize car today weighs about 35 kg, and the cost of the electrical system is more than the engine and transmission combined. So while electric vehicles are not common, financially today's car is more electrical than mechanical.

The Automotive Environment

An appreciation for the automotive environment is necessary to understand the present and future challenges for automotive power electronics. One view of the environmental factors affecting automotive electronics can be found in [4], which was developed in 1978 by the Society of Automotive Engineers. Operating ambient temperatures can range from as low as –40 °C up to the high values illustrated in Table 1 for various vehicle locations. Equipment using the radiator cooling loop can experience coolant temperatures as high as 120 °C at 1.4 Bar [5]. These extremes pose a difficult challenge to the design of automotive power electronics, and they are likely to be even more challenging in future vehicles. Other environmental concerns include thermal cycling and shock, mechanical shock and vibration, humidity, immersion, salt spray, and exposure to abrasives and chemicals [4,6].

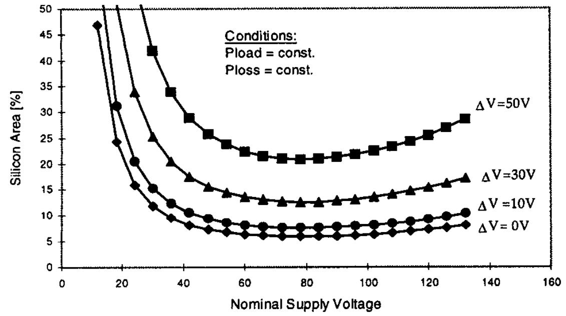

Fig. 2 Effects of nominal system voltage and application margin (ΔV) on required Si area for switching a constant power with constant loss [3].

Solid state switches are well suited to a multiplexed electrical architecture, in which switching of individual loads is controlled remotely via signals multiplexed on a communications bus. The benefits are substantial improvements in electrical harness weight and complexity, and a reduction in the number of required terminals and splices [7]. This architecture has been of interest since at least the early 1970s but has had limited application in 14 V systems because of the cost of the necessary electronics [8]. Smart-power MOSFET-based devices with integrated control and circuit protection functions are now available, making the design of a multiplexed system easier, but costs are still high relative to non-multiplexed alternatives for 14 V systems [3].

The economic impracticallity of using silicon for all power switching in the 14 V car results from the required voltage rating of these devices. Figure 3 shows a phenomenon known as a "load dump transient." It results from the sudden unloading of the alternator and the long time constant of the field current. Because of the possibility of this transient, power semiconductor devices, as well as all electronic equipment, must be rated for at least 60 V, or about 5 times the nominal system voltage. This required overrating makes silicon economically unattractive compared to relays. One of the significant benefits of a 42 V system constrained by the specifications of Fig. 1 is that electronic switching becomes economically competitive with relays and provides important opportunities for new safety, convenience and comfort functionality in the car.

While the higher voltage level of future vehicles will facilitate application of power semiconductors for load switching, it also poses a much greater challenge for connectors and circuit protection because of the increased sustained arcing distance and energy levels at the higher voltage [9]. To deal with this, a more sophisticated fusing and protection scheme will be necessary. Such schemes will likely incorporate sensing, signal processing, and semiconductor switching to achieve the desired level of coordinated circuit protection. For example, signal processing can be used to sense the current transient as a connector is being separated, initiating the opening of a semiconductor switch to disconnect the circuit and prevent arcing at the connector contacts. Achieving the required levels of sophistication and reliability at low cost will be a major challenge in integrating semiconductor switches into automotive fusing and protection schemes.

Vehicle Location	Max Temp (°C)
Exterior	85
Chassis	
Isolated	85
Near heat source	121
Drive train high temp location	177
Interior	
Floor	85
Rear deck	104
Instrument panel	85
Instrument panel top	177
Trunk	85
Under hood	
Near radiator support structure	100
Intake manifold	121
Near alternator	131
Exhaust manifold	649
Dash panel (normal)	121
Dash panel (extreme)	141

Table 1 High temperature extremes in automobiles by location [4].

Advanced Electrical Features

Car manufacturers have a long list of functions they would like to incorporate in their products. Many of these will only appear in concept vehicles in the foreseeable future, others will arrive in the market when the economics are attractive.

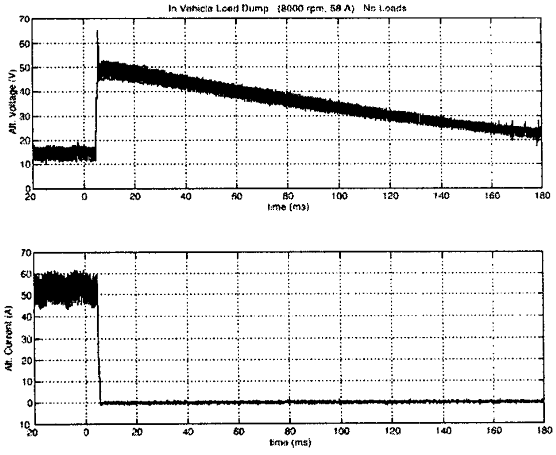

Fig. 3 Typical load dump transient. The voltage is measured at a tail lamp. The initial spike is the alternator L(di/dt) voltage, while the longer transient is due to the alternator field decay.

But they all rely on electronics, for both control and actuation, and fall into one of two classes – *infotainment* (information/entertainment) and *x-by-wire* where *x* indicates a function, e.g., "steer." The infotainment class has received lots of hype, principally because its members, e.g., back seat TV and video games, are visible to the consumer. The x-by-wire class, even though it has possibilities for improved safety, fuel economy or environmental impact, has received less attention in the popular press because the benefits aren't as tangible as those of, e.g., a mobile internet connection. In this paper we will address the x-by-wire class of innovations as it represents the most interesting application opportunities for power silicon in the car.

In addition to the added functionality provided by X-by-wire systems, a strong motivation for electrifying functions is to eliminate the constraint of having all engine driven accessories located at the front of the engine and driven through the unibelt (formerly "fanbelt"). So it can be expected that the water pump, power steering pump and air conditioner will eventually all be electrically driven.

The Integrated Starter Alternator (ISA)

On January 9, 2001 a front page article in the New York Times stirred public interest in the car's electrical system [10]. The article described Ford's announcement that the model year 2004 Explorer SUV will have an optional "electrically assisted gasoline engine" to "sharply increase fuel efficiency and reduce emissions." The heart of this innovation is the integrated starter alternator (ISA), which is mounted directly on the engine's crankshaft in place of the flywheel.

The ISA is designed to do three things: serve as a high power 42 V alternator, make possible start/stop operation of the vehicle, and provide regenerative braking. It is anticipated that these latter two functions will make a major contribution to improving the Explorer's fuel economy. One reason is that the ISA is controlled to provide regenerative braking. Because of this there is a desire among some manufacturers that the upper limit in the 42 V bus specifications be 55 V.

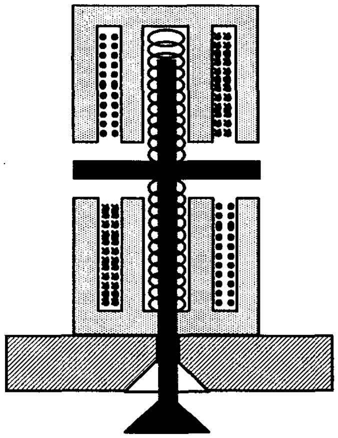

Fig. 4 A conceptual drawing of one design for an electromechanical engine valve.

The implementation of idle stop requires features beyond a high torque starter. When the engine is off a means must be provided to maintain vacuum in the brake assist system, oil presssure in the automatic transmission, and ventilation or air conditioning in the passenger compartment. With air conditioning these loads combined are on the order of 3-5 kW, which is impractical to supply from the present 12 V, or future 36 V, battery. For this reason, the ideal idle stop system incorporates an electric power supply alternative to the current alternator, and this topic is discussed later.

Electromechanical Engine Valves

In an electromechanical valve train (EMV) the valving of each cylinder is controlled independently and with complete variability with respect to crank position. This allows valve timing to be optimized with respect to fuel economy and emissions at all engine speeds, with anticipated improvements in fuel efficiency of 20% or more, and emissions reductions of about 20% for HC, 25% for NOx, and 10-20% for CO [11, 12]. Disabling of cylinders for additional fuel economy improvements, reduced starting torque requirements, and "static" starting (no starter motor) are additional potential benefits.

A schematic representation of a popular actuator design is shown in Fig. 4. The natural response of the spring/mass system is augmented by the electromagnets to overcome losses and gas forces, and to provide holding at the extreme ends of the stroke. While conceptually simple, this design has several difficult challenges and remains the subject of aggressive development by several companies.

While the average power requirement of an EMV system is approximately 100 W/cylinder, the peak power requirement is substantially higher, on the order of 1 kW/cylinder.

Steer-by-Wire

A steer-by-wire system eliminates any mechanical link between the driver and the front wheels of the car. Advantages are numerous, including the future integration of an intelligent highway vehicle system (IHVS) and the elimination of the steering column which is a principal hazard in front-end collisions. The challenge for the electronics industry is to demonstrate that safety is not compromised by the elimination of the mechanical link to steering that now exists. Two issues must be addressed here – reliability of the electronics, and reliability of the power supply.

Brake-by-Wire

Power electronics is already extensively employed in the ABS that is now standard on most cars. However, the actual braking is still done hydraulically – only valving is controlled electrically. In a brake-by-wire system pad motion is controlled by an electrical actuator. Like steer-by-wire, the issue of reliability is paramount.

Advanced Semiconductor Devices

Wide-bandgap semiconductors represent an important means of achieving high-temperature power devices. Based on a number of figures of merit, Diamond and Silicon Carbide (SiC) are the most promising materials for high-temperature power semiconductor devices [13], of which SiC is closer to commercial viability [14, 15]. Benefits of SiC include a wide operating temperature range, a high critical breakdown field, high saturated electron drift velocity, and high thermal conductivity. Electrical and material parameters for the most important SiC polytypes for power devices along with other semiconductors are illustrated in Table 2 [16].

The most important benefit of SiC power semiconductors in automotive applications is the potential for high-temperature operation; while Si devices can achieve derated operation at temperatures up to 200 °C, SiC devices have the potential for operation up to 600 °C or more [17]. Experimental SiC MOSFETs with operating temperatures up to 650 °C have been demonstrated, as have SiC Op-Amps, gate drivers, and logic devices with operating temperatures in excess of 300 °C [18-21]. High-voltage SiC Schottky Diodes have also recently become commercially available, albeit with junction temperature ratings of only up to 175 °C [22]. A second benefit of SiC power semiconductors is the potential for substantial device size reduction for high blocking voltages (100's – 1000's of volts), due to the high critical breakdown field of the material. With the exception of a few specific applications in automobiles (such as ignitions, HID lamp drivers, and other high-voltage drive circuits) this is not likely to be a major factor in automotive applications due to the relatively low-voltage requirements.

	Si	GaAs	6H-SiC	4H-SiC
Bandgap (eV)	1.11	1.43	2.9	3.2
Dielectric Const (•$_r$)	11.8	12.8	9.7	9.7
Breakdown E (V/cm) (at $N_d = 1\times10^{17}$ cm^{-3})	6×10^5	6.5×10^5	35×10^5	35×10^5
Saturated Velocity (cm/s)	1×10^7	1×10^7	2×10^7	2×10^7
Electron Mobility (cm^2/V-s)	1350	6000	380 ⊥ to c axis	800 ⊥ to c axis
Hole Mobility (cm^2/V-s)	450	330	95	120
Thermal Cond. (W/cm-K)	1.5	0.46	4.9	4.9

Table 2 Properties of Si, GaAs, and SiC as drawn from [16].

To achieve affordable SiC devices for automobiles, some critical problems need to be solved. The defect density of SiC must be reduced to allow higher yields and larger devices to become practical; manufacturing techniques suited to the material need to be fully developed; and packaging techniques suitable for very wide temperature range operation must be developed to ensure acceptable device operating lifetimes. Meeting these challenges is important for continued development of high-performance automotive power electronics.

Electrical Power Generation

The ISA described earlier is a radical and expensive departure from the conventional automotive alternator. An innovative electronic modification to the present alternator has been proposed as an economical and efficient means of generating 42 V [23, 24]. The power circuit utilized with this approach is shown in Fig. 5. Fig. 6 shows a comparison between the performance of the new system and the same machine operating as a conventional 14 V alternator/diode rectifier supply. Not only does this new system produce more than twice the power of a similarly sized 14 V machine, but it does so at substantially improved efficiency so the thermal design of the machine need not be modified. The electronics comprises a switched mode rectifier which permits the machine's capability increase with speed to be exploited. In the conventional system the power available from the machine is constrained by its output voltage being regulated to 14 V. The switched mode rectifier permits the machine voltage, and hence its power, to increase with speed while maintaining a constant 42 V dc output.

The development of an alternative to the engine driven electrical power supply has only recently become an issue as idle-stop operation is seen as practical and desirable. General Motors has recently announced the introduction of a solid oxide fuel cell as an auxiliary power unit (APU) to replace the alternator [25, 26]. Another interesting option is a thermophotovoltaic system. In this system fuel is burned to create light whose spectrum is then converted to match an

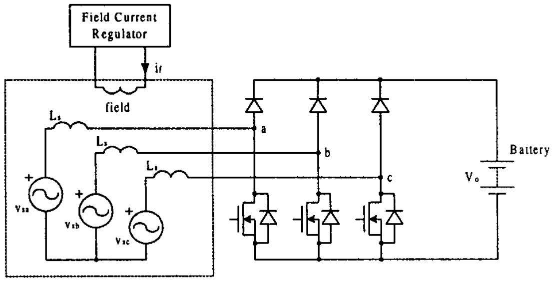

Fig. 5 A conventional Lundell (claw-pole) automotive alternator modified by the addition of a switched-mode rectifier to provide a 42 V output.

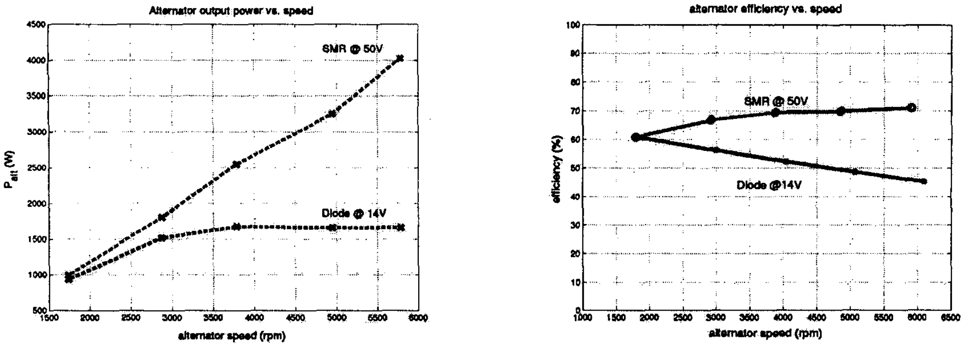

Fig. 6 Output power and efficiency vs. speed for the alternator/SMR compared to the same machine operating as a conventional 14 V automotive alternator/rectifier.

array of surrounding photocells. Both of these schemes require substantial electronic control and conversion.

Conclusions

The imminent commercialization of 42 V automotive electrical systems will provide a new and very large market for power devices. But in order for this opportunity to be realized the cost of the new electronic systems must be competitive with conventional alternatives. Since the electrical system of a car is invisible to the consumer, new system introductions must be motivated by improvements in safety, comfort, fuel economy or emissions. While not yet economically attractive, SiC devices are ideally suited to the harsh automotive environment.

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