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Journal of Power Sources 127 (2004) 16–26
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

Systems for 42 V mass-market automobiles

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Abstract

With the introduction of the Toyota Crown Royal Saloon in August, 2001, 42 V automotive electrical systems made the transition from a technology for the future to present-day production. Nevertheless, there is widespread malaise in the 42 V technical community, stemming from a slower than expected introduction to the marketplace. This paper discusses some of the reasons for the slow adoption of this technology, and indicates a possible way forward. This paper looks beyond the initial uses of 42 V in limited-volume, high-end cars and light trucks, and discusses the prospects for 42 V in mass-market vehicles, given what is presently known about the technology. It is concluded that a case can be made for 42 V, even at some increment in cost. The motivation is improved fuel economy. The cost targets necessary for this benefit to be achieved are discussed, and new components being widely discussed as part of future electrical systems are evaluated for mass-market applications. New developments with higher potential are suggested.

Keywords: 42 V; Automotive electric systems

1. Introduction

Throughout the history of the automobile, there has been a continuing trend toward the use of more and more electrical power on each new vehicle design. Within the past decade, long-range thinkers within the auto industry have accelerated discussions of the changes that should occur in automotive electrical systems to accommodate this trend. The most visible manifestation of these discussions is the decision to develop 42 V dc generation and distribution systems for future automobiles.

By 1998, the industry had largely decided that 42 V was the next step for conventional automobiles. (Hybrids and electric cars need higher voltage.) Interest was high, both among automakers and among their suppliers. The prevailing vision was that 42 V would be introduced first in elaborately equipped luxury vehicles, followed by a rapid spread across the industry product line. Initial systems would be dual-voltage systems, with new features at the new voltage, but with many present 14 V parts continuing to be used. The automakers in particular viewed the dual-voltage system as undesirably complex and expensive. While they for the most part accepted the necessity of the dual-voltage system as a transitional device, their vision was of a rapid transition to a single-voltage, 42 V system.

About this same time, the view was widely held that adoption of 42 V would lead to cost and weight savings (before accounting for the costs of added features), due to the savings in wire harnesses and in power MOSFETs to control present electronic controlled loads. The primary motive for choosing a higher working voltage was and is the ability to make, or to make more economically, electrically driven features which do not exist on automobiles today, but the thought that these features could be achieved at a savings (after non-recurring expenses had been recovered) was a valuable additional enticement.

In the intervening years, a number of technical challenges have become evident to developers of 42 V systems. The cumulative effect of these challenges has been to delay the introduction of 42 V parts and systems, as the parts suppliers work out the problems. The solutions that are being developed introduce another element of cost. This additional cost covers solely the cost of using the higher voltage. It is quite possible that the incremental cost exceeds the savings associated with a smaller wire harness and lower MOSFET costs. It now appears that in order to introduce new electric features requiring a higher voltage, the carmaker must first incur an increase in the net cost per vehicle, before the cost of the feature itself is considered.

While such an increment in cost is highly undesirable, it might be tolerated in a limited-production, high-margin luxury vehicle, the reputation and sales of which depend on leadership in the provision of new luxury and/or performance features. But, the pathway forward to mass-market

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0378-7753/$ – see front matter © 2003 Published by Elsevier B.V.
doi:10.1016/j.jpowsour.2003.09.004

cars is no longer evident. When it was thought that there would be net savings with 42 V generation and distribution, the way was clear. As soon as 42 V parts dropped low enough in price, the new system would be used on mass-market cars for the cost savings to be gained. But, if there is a cost to be incurred, 42 V will be adopted on a mass-market car only if the car will use enough new electric features, and save enough cost on those new features as a result of 42 V, to be less expensive overall.

It is possible to envision a set of 42 V enabled features which will enhance the value of a mass-market car by enough to justify an increase in cost. But, there will be a relatively restrictive limit on the allowable cost increase. It can be reasonably inferred from the allowable cost increase that many of the features presently being developed for luxury automobiles will not be adopted for the mass market. Other features not presently under development for luxury cars do offer potential when evaluated in comparison to requirements for mass-market cars.

2. Benefits of 42 V in advanced automobiles

The principal benefits of a 42 V electrical system relative to today's (on the same basis 14 V) electrical system arise from the reduced current required to supply any stated level of power. The lower current means that electrical conductors in the wire harness can be smaller, lighter, and less expensive. It also allows a given electrical power to be switched by solid-state elements that are smaller and less expensive. These benefits accrue to all elements of the electrical system. The benefit of reduced wire size is important, but probably not sufficient to result in selection of a new operating voltage. The reduction in the cost of solid-state switching is more important. The reduction in silicon area per watt of load can be between 67 and 89%, depending on how switch losses are allowed to vary [1]. Since silicon area is a major determinant of semiconductor cost, this difference can be great enough to make the difference between feasibility and impracticality of a proposed new electric feature.

3. Technical obstacles to 42 V

As the world contemplated the acceptance of a new operating voltage for automotive electrical systems, activities began in many places to evaluate existing commercial auto parts for use at the new voltage, and to consider the design of new components. Although it cannot be proven, it is reasonable to assume that every supplier then selling electrical parts to the auto industry either knew from prior experience how his parts would work at the new voltage, or set out to find out. Of those who set out to find out, not all were forthcoming with their findings.

Over time, a number of technical challenges were identified. While none of these challenges is significant enough to prevent the application of 42 V systems, each of them has required study and investigation by a large part of the 42 V community, and each of them has required new product development by at least some elements of the community. All this work has lead to delay, relative to original expectations. Some of the new 42 V capable products have features which will make them more expensive, even on a per-watt basis, than 12 V products for similar functions.

In the following paragraphs, a few of these technical challenges will be discussed.

3.1. 42–14 V faults

One of the more vexing classes of problems arising from the adoption of dual-voltage cars is the matter of inadvertent short circuits between conductors at the two voltages. In a system with a single supply voltage, the only possible short circuit is between the supply and the return. In automobiles, the return is the body of the car. In such an event, a large current flows. It is a straightforward matter to specify a fuse for each circuit which will reliably pass current in the absence of a short circuit and reliably blow out in the event of a short circuit. When there are two supply voltages, the short of a single supply voltage to ground remains the most probable short circuit event, so fuses for each system should continue to be selected by the same criteria.

When considering the possibility of a short circuit between different voltages, some unpleasant possibilities are quickly recognized. In every reasonable case, the circuits which are shorted together are each protected by a fuse. In all but the most exceptional cases, one fuse will act initially. But, what happens after that can be quite different, depending on the location of the short, the impedances of the circuits, and the current rating of the remaining fuse.

In some cases, the second fuse will also blow, and the affected circuits are safely de-energized. In other cases, the second fuse will not blow. If the short circuit remains, the system will remain in an abnormal but energized state. In some cases (for example, 14 V applied to a non-critical 42 V component), no hazard exists, and the abnormal state may be permitted to continue until it is repaired. In other cases, the abnormal state may result in 14 V components experiencing a long-term overvoltage and/or critical 42 V components experiencing a long-term undervoltage.

At the least, the existence of two supply voltages adds a significant additional step to the process of fault analysis for the system. Additionally, it will probably be necessary in some cases to monitor for hazardous abnormal conditions and to take action to insure appropriate corrections. This additional function is not difficult to specify, nor is it necessarily expensive to implement. But, it does represent one more feature which must be incorporated into the system.

3.2. Electrical arcs

Possibly the most important difference between 14 and 42 V electrical systems is the difference in behavior of electrical arcs. At 14 V, an arc is inherently unstable. An arc can form as the result of a transient, but as soon as the voltage across the arc falls to or below the supply voltage, it begins to collapse. In the absence of an inductance to maintain arc voltage above 14 V, arcs in 14 V systems are insignificant occurrences.

At 42 V, an electrical arc is stable, provided that the separation of the contact points between which the arc exists remains below a threshold value. While an electrical arc exists, it is possible to transfer electrical power from the system power source to the arc. As a result, arc energies in 42 V systems tend to be many times greater than in 14 V systems. A single arc event at modest current can easily render a part unsuitable for further use.

While these effects have long been known, they were initially unappreciated by the automotive electrical systems community. The widespread recognition of the importance of electrical arcs, about the summer of the year 2000, coincided with the beginning of a general acceptance that 42 V distribution was not going to be less expensive, per watt, than 14 V.

The dramatic difference in arc behavior implies that any component which uses electrical arcs in its normal function will need to be redesigned for 42 V. In automobiles, the affected components are principally switches and relays. As a practical matter, wire connectors are also strong candidates for redesign. Formally, these parts are not designed to interrupt load current. But, because the consequences in the 12 V case are benign, auto repairers have widely adopted the practice of using connectors for this function.

One of the keys to design for 42 V is implicit in the description of the difference in arc behavior. A 42 V arc is unstable, provided that the arc is longer than a threshold length. So, a design which quickly develops spacing between the contacts is indicated. In some cases, it is effective to put multiple gaps in series. In this respect, the designers of electrical connectors have the most difficult problem. In switches and relays, the designer has control over the rate at which the contacts part. In a connector, unless the designer is exceptionally resourceful, the rate of parting is determined by the repair technician.

Since the importance of electrical arcs came to be widely understood, many auto parts suppliers have been diligently and visibly working to develop product lines suitable for 42 V. The 42 V switches and relays are available. In the case of connectors, there is still some talk of altering the service industry practice, and avoiding the use of connectors to interrupt load current. But connector makers have been especially creative in response to this new challenge. It will not be a big surprise if they are able to offer cost-competitive solutions that tolerate disconnection under load.

Ultimately, it appears that electrical arcs will not be a show-stopper issue for 42 V. But the need for all new parts, most of which will be more expensive than their predecessors, will remain a source of additional cost.

3.3. Electrochemical corrosion and surface tracking

Electrochemical corrosion and surface tracking are two distinct phenomena, which have in common that they involve the flow of electrical currents and are aided by the presence of electrolytic solutions. As is the case with electrical arcs, these phenomena are not new, and there is substantial expertise and knowledge outside the automobile industry. Within the auto industry, significant understanding of these phenomena does exist, but it is non-uniformly distributed.

Although the phenomena are distinct, they are discussed together in this section, in part because of their similarities, and in part because many in the automotive community are presently using one or the other name (most commonly corrosion) to refer to both phenomena.

At present, concern about corrosion and tracking are high, principally because understanding of these phenomena is not universal. Even among those who understand the phenomena, the methods to design and to qualify components with adequate performance at the new voltage level are imperfectly known. It should be expected that over the coming months, progress and the beginnings of order should come to be visible relative to these phenomena and 42 V automotive systems.

3.4. Idle-stop air conditioning

Idle-stop operation is widely perceived as being the additional automotive function which justifies the application of 42 V. Once the application has been justified, there are many more functions which can benefit from use of the new voltage. So the existence of any obstacle which threatens to interfere with the widespread adoption of idle-stop operation has the potential to significantly slow the adoption of 42 V. The challenge of equipping an idle-stop vehicle with adequate air conditioning has the potential to be such an obstacle.

The challenge of combining idle-stop and air conditioning is important to the initial adoption of 42 V in luxury cars, which are universally equipped with air conditioning. It may be less a concern in the mass market, although in parts of the world, air conditioning is common even in low-end new cars, and the acceptance rate is rising in all car classes and all markets in which penetration is not yet 100%.

It might seem that the most practical solution is simply to turn off the air conditioning during the idle-stop interval. For short stops, the change in cabin temperature will be small compared to the change in cabin temperature experienced during other transients. But auto companies are virtually unanimous that air conditioning must operate during the idle-stop interval. This requirement often seems to be based more on the perception of a responsible individual that this is how things should be than on the results of any hard market-survey findings.

But, the question remains for longer stop intervals: what should be done to provide air conditioning during idle-stop intervals? The obvious first answer is to disable the idle-stop function when the air conditioning is being operated. This solution is definitely simple and effective, but it has one very undesirable attribute: it obviates the benefits of idle-stop capability for part of the year in most of the world, and for all of the year in part of the world. The benefit of idle-stop capability, on a worldwide basis, is reduced by a substantial fraction, perhaps half.

The obvious second answer is electric air conditioning. During the idle-stop interval, the air conditioner can be driven be the battery, and the required electrical energy can be restored during the subsequent driving interval.

This obvious solution has several less-obvious disadvantages. Most arise from the equipment cost and efficiency consequences of multiple energy conversion steps, first from fuel to mechanical energy in the engine, then from mechanical to electrical energy in the generator, from electrical to chemical and then back to electrical energy in the battery, from electrical to mechanical energy in the air conditioner motor, and finally from mechanical to thermal energy in the air conditioner. Just the act of listing the necessary conversions helps to explain the disadvantage of this solution. Many of these disadvantages are mitigated by the solution employed in the Toyota Crown vehicle [2]. In this clever embodiment, the air-conditioner compressor is driven conventionally (directly from the engine by means of a drive belt), whenever the engine is running. It is driven by an electric motor only when the engine is unavailable. Further, the electric motor which drives the air conditioner is the same motor which starts the engine and which acts as a generator when the motor is running.

But, even if the Toyota solution is adopted, one important disadvantage remains. The vehicle battery will be severely challenged to provide air conditioning during idle-stop intervals. Consider a typical scenario. The air conditioner draws 3 kW net, from the electrical energy supply. Drawing 3 kW from a 36 V battery is likely to reduce the output voltage to 24 V (let's neglect for a moment that operating at this voltage violates the proposed 42 V operating range limits). At 24 V, 125 A are required to provide 3 kW. One minute of operation (certainly not an unreasonable city traffic-light delay interval) requires, therefore, just over 2 Ah or just over 8% depth of discharge on a 25 Ah battery.

Reference to Fig. 1 shows that such a modern flooded lead–acid battery is capable of 2000 such discharges. To put 2000 discharges in perspective, consider that if one assumes a round-trip commute with 10 1 min stops each way, the battery will be consumed in 20 five-day weeks of commuting. A battery life of well <1 year is a likely prospect. Adoption of an AGM battery is a productive step for more battery life, but the life is not likely to be extended to 2 years under the scenario above, according to Fig. 1. Given today's cost premium for AGM batteries, this choice is unlikely to be superior to flooded lead–acid for operating cost.

The quick let's-assume and let's-pretend analysis of the previous two paragraphs does not constitute a proof that electric air conditioning cannot be used to provide idle-stop air conditioning. Any of the assumptions can be challenged. By turning down the operating point, certainly some useful air conditioning can be done with <3 kW. On the other hand, no other electrical loads were considered. A lower-impedance battery may not pull down as far as 24 V, but this analysis made no provision for increased impedance as the battery ages.

What is clear from the analysis above is that idle-stop duty is an important challenge for the battery, and selection of a satisfactory system solution will require a challenging effort, with no assurance of a solution. There are design directions which can assure a technical resolution which will assure adequate battery life, but all have drawbacks which will in all probability preclude their selection. A substantial (i.e., a factor of two or more) increase in battery capacity will substantially increase battery life. But, such a solution is unlikely to

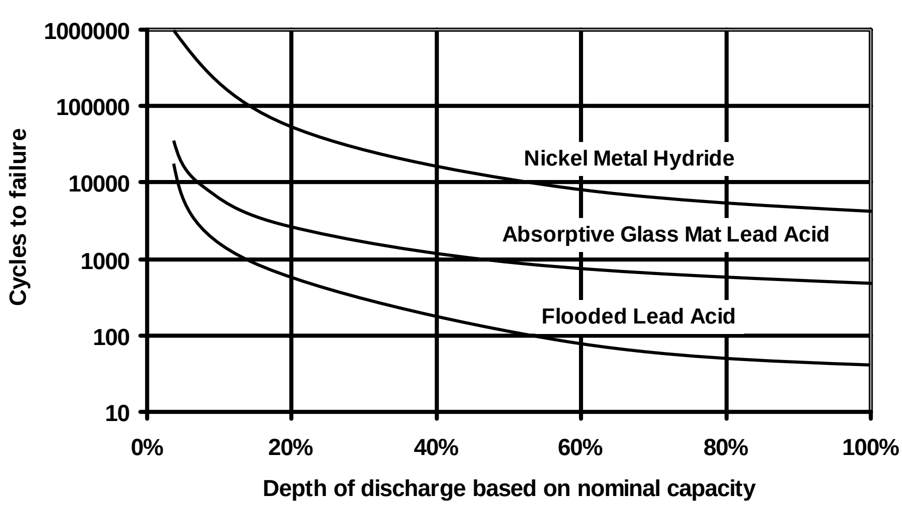

Fig. 1. Effect of depth of discharge on battery life for NiMH and lead–acid chemistries (from [3]).

be acceptable. Addition of a kilogram of non-structural mass (such as battery mass) has the consequence of requiring a substantial fraction of a kilogram of structural, suspension, running gear, and drivetrain mass. So, even without talking about cost, the doubling or more of battery mass is unlikely to be an acceptable alternative. An alternative battery chemistry (most likely nickel metal hydride) can provide a fully satisfactory battery life, but for mass-market automobiles, this is unlikely to be an economically acceptable choice.

After the first obvious alternative, the most promising design directions to resolve the idle-stop air conditioning dilemma are not the obvious ones. One attractive possibility is the possibility of an on-board electricity source that is not driven by the propulsion engine. A large number of alternatives can potentially go directly from fuel to electricity or from heat to electricity. The electricity can then be used to drive the air conditioner.

A fuel-to-electricity converter has the advantage of providing not just air conditioning, but all the electrical load during the idle-stop interval. The requirements on the battery might then be reduced, not only with respect to an idle-stop vehicle without direct fuel to electricity, but also compared to today's vehicles. The battery might actually be lighter and less expensive. Fuel to electricity systems include fuel cells, and separate, non-propulsion engines, driving generators. The challenges of the former approach are well known from recent widespread publicity. The challenges of an auxiliary engine are also reasonably well understood. It should be remarked that an engine for this application can conceivably be adapted for optimum operation at a single speed and load, and then operated, if at all, at that optimum speed and load. It should also be remarked that a full automotive exhaust clean-up system can be presumed to be available to the auxiliary engine at no incremental cost, and there may even be a benefit for keeping the catalytic converter heated into the operating range.

A heat-to-electricity converter is of course a fuel-to-electricity converter if the heat comes from a burner. An attractive alternative is a dual-mode converter, which converts engine waste heat (either from the exhaust stream or from the water jacket), when such heat is available, and uses a burner when electricity is required and waste heat is not available.

A second solution is heat-driven air conditioning. This technology is quite feasible, with economically viable applications many decades ago in commercial and residential air conditioning and refrigeration. Its application to motor vehicles has not been extensively investigated, but preliminary assessments are encouraging [4].

4. 42 V and mass-market cars

All of the considerations discussed above suggest that there should be no obstacle to prevent a visionary vehicle development manager from applying 42 V to a high end vehicle. The Toyota Crown stands as evidence that this speculation is in fact true. Other 42 V luxury and specialty cars, therefore, should not be a surprise.

But, the bigger question about the future of 42 V systems turns on their ultimate acceptance in mass-market cars. The balance of this paper will be centered on a possible course for 42 V to succeed in this application, and on the conditions for this success. Future development directions are suggested.

Mass-market cars will always succeed by offering superior value for money. Luxury features may be purchased for subjective reasons, but this phenomenon cannot be readily exploited by sellers of mass-market cars. In this marketplace, the large number of cost-sensitive buyers will drive the market to an economic frontier at which for every price point a high and approximately equal value will be available. In short, a seller can get a premium in the mass market, but only by delivering an increase in value which is worth every cent of the premium.

Why would an automaker participating in this marketplace choose to offer a 42 V car? Such a decision makes good economic sense, if 42 V allows the inclusion of enough features to justify the cost of the new technology. Market success requires that the new features be priced at the point defined by market.

This paper offers the premise that the new value which can be offered by 42 V to the mass market is improved fuel economy. It is an observable fact that improved fuel economy brings a cost premium in the mass market. It is also reasonably universally accepted that 42 V offers a potential for improved fuel economy.

It is beyond the scope of this paper to exhaustively evaluate the technologies which have the potential to improve fuel economy. Instead, we will postulate that a 42 V mass-market vehicle may incorporate several fuel-economy-enhancing technologies, including idle-stop operation, electric power steering, electric front-end accessory drive, and electric turbocharger boost, with associated engine downsizing. We further postulate that the fuel economy improvement from these changes is of the order of 15–25%. Note that only the latter postulate really matters in the subsequent discussion. If the new technology enables the postulated savings, the conclusions follow, independent of the particular technical changes which produce the savings.

This new feature, an increase in fuel economy, can be exploited for economic advantage in all markets of the world. In Europe and in Asia, improved fuel efficiency earns an increased price at the point of sale. In today's United States marketplace, the customer is seldom willing to directly pay more for fuel economy, but the fact that each automaker's fleet must meet CAFE requirements provides an incentive to the automaker to adopt a more fuel efficient technology, up to a certain price point. The automaker can then readjust his product line to feature more high-profit vehicles without paying CAFE penalties.

5. The value of 42 V as a fuel economy technology

One pervasive difficulty in assessing the prospects of a new technology is the challenge of defining the market for a capability which does not presently exist. In the automobile industry, costs and market demand are well understood by those inside the industry. But, a near-universal refusal to speak about these costs and demands openly and frankly makes it difficult for those not closely associated with any development to know these factors. However, in the present case, if we accept the premise that the value of 42 V in mass-market automobiles is limited to its contribution to reduced fuel consumption, then there is a way forward to assessing what may be the allowable cost for this new technology.

The information we seek can be derived from Fig. 2, taken from [5]. In this figure, the horizontal axis is the authors' estimate of the cost of a new technology, divided by the percent fuel economy benefit which the new technology provides. The vertical axis represents the percent fuel economy achievable from a given technology.

The authors' intent in developing Fig. 2 is that the benefit under discussion is a generalized one, with 1% representing either a percent improvement in fuel economy or a percent improvement in output power, or, presumably, a linear combination of the two. As engine improved output power can be used to reduce engine displacement, which then produces fuel economy benefits, these two effects are roughly and approximately substitutable one for the other. The limitations of this approximation, along with the size of the ellipses representing various technologies in Fig. 2, give the reader an idea of the precision of this analysis. For the purposes of this paper, we will interpret percent benefit in Fig. 2 to mean percent fuel economy improvement.

The cost axis in Fig. 2 is normalized on a per cylinder basis. Since we are discussing mass-market cars, we will presume a four-cylinder car, and the cost numbers from Fig. 2 may be multiplied by four.

Various candidate technologies for improving fuel economy are indicated on Fig. 2. Each technology is indicated by an ellipse, the dimensions of the ellipse presumably reflecting the authors' uncertainty about the cost and/or benefit of the technology. The benefits and costs are in every case incremental over a baseline of two valves per cylinder, overhead cam, fixed valve timing.

An automaker wanting to increase the fuel economy of a planned vehicle will consider the information contained in Fig. 2. He will be driven to choose the least expensive way to achieve the fuel economy he needs. His thought process will be the conceptual equivalent of scanning Fig. 2 (from left to right), selecting the first technology or technologies that are not already on his vehicle.

The order of the technologies, along with a knowledge of what systems are being implemented on new platforms today, can give us a desirable insight into what a carmaker must pay to obtain increased fuel economy in a new vehicle. Starting at the left, we see technologies like four valves per cylinder, which is virtually a standard feature on any new engine today. Few carmakers are going to be able to improve fuel economy by adopting this technology; for the most part that option has already been exercised.

Looking farther to the right we see options like five-speed (automatic) transmissions and cylinder disabling. These technologies are being announced now on new vehicles for availability soon. It appears that this region of the graph represents the location of the market today. If we look farther still to the right, the technologies which appear, for example, the Miller cycle or two-stroke operation, are being adopted only rarely or not at all. They are beyond the economic threshold; automakers have less expensive options which they will choose in preference to these technologies.

It would appear, therefore, that the market for fuel economy stops at about US$ 3 per cylinder per percent, or at US$ 12 per percent for a four-cylinder car. With this number, we can readily establish that the fuel economy value of 42 V is US$ 180–300 per vehicle, assuming fuel economy

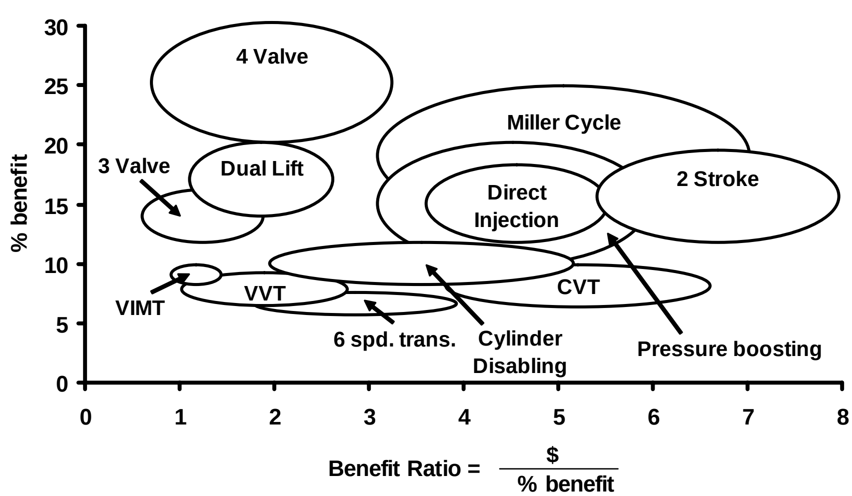

Fig. 2. Percent benefit vs. normalized cost for fuel efficiency technologies.

benefits of 15–25% as above. Note that this value reflects what the automaker may be willing to pay to adopt the new technology *and to incorporate the novel features which deliver the fuel economy*. This number is of course a net value; the cost analysis should take into account a credit for the conventional parts replaced in the new system.

Note that this threshold value represents the difference between widespread adoption of the technology and limited or no adoption. If 42 V is the least expensive way to improve fuel economy, most vehicles needing improved fuel economy will adopt it. If some other (mechanical) technology is less expensive and not presently implemented, no vehicles will choose 42 V for fuel efficiency.

The uncertainties in the preceding analysis should be apparent to the discerning reader, but so should be the underlying validity. It is certain that there is a maximum cost which will justify 42 V for fuel economy. It may neither be the number suggested here, but it is unlikely to be twice as much, nor less than half as much. For brevity, only this one analysis is presented here, but other writings by people in positions to know seem to confirm that some threshold does exist similar to the one presented here.

Parenthetically, the analysis above does not accurately reflect the decision process of any particular vehicle program manager. The costs which are presented in Fig. 2, and the hypothetical costs for the 42 V system contemplated here, are mature selling costs, assuming that the technologies under consideration are all being applied at large enough volume so that development costs have been amortized and that capital assets (plant and tooling) been accounted for in a way that recovers the cost over the full life of the assets.

A real-world vehicle program manager will be faced not with such minimized costs, but with real-world cost quotes from suppliers, who may want to recover development and/or capital costs more quickly, based on the uncertainties inherent in innovation. Despite this, it remains a useful exercise to think about how decisions would be made in the absence of these costs. Every technical innovation requires development expense and capital expense, and the auto industry always seems to find a way to fund these expenses for innovations which improve the breed over the long haul, so in the course of using cost to forecast the future of technology, it is reasonable to neglect these costs unless they are exceptionally large or unless the goal is to forecast what will happen in the context of a particular program, rather than what will inevitably happen.

6. Selection of features for 42 V mass-market vehicles

A vision of what a 42 V system has to accomplish and what it must sell for is very helpful in visualizing what a 42 V mass-market car may include. While it is widely accepted that 42 V parts will cost more than 14 V parts, for reasons outlined above, it is apparent from this analysis that the cost increment had better be small. The author has no inside track to OEM prices for car parts, so no detailed projection will be made as to the cost increment or decrement from any individual choice.

It does seem probable that the larger portion of the budget available to produce our intended mass-market car should be devoted to the features which give it added functionality. So, of US$ 180, perhaps 2/3 or US$ 120, may be devoted to new features. This leaves perhaps US$ 60 for expenses solely related to including the new voltage on the car. This budget includes the incremental expense of providing electric power at a second voltage (including the incremental expense, if any, of a second battery) as well as any expense associated with making the electrical system safe against hazards, such as a 42–14 V short, which do not exist in the absence of the second voltage.

It follows that the vision of the electrical architecture of the 42 V mass-market car is likely to be quite different from the widely held picture. Considering Fig. 3, the

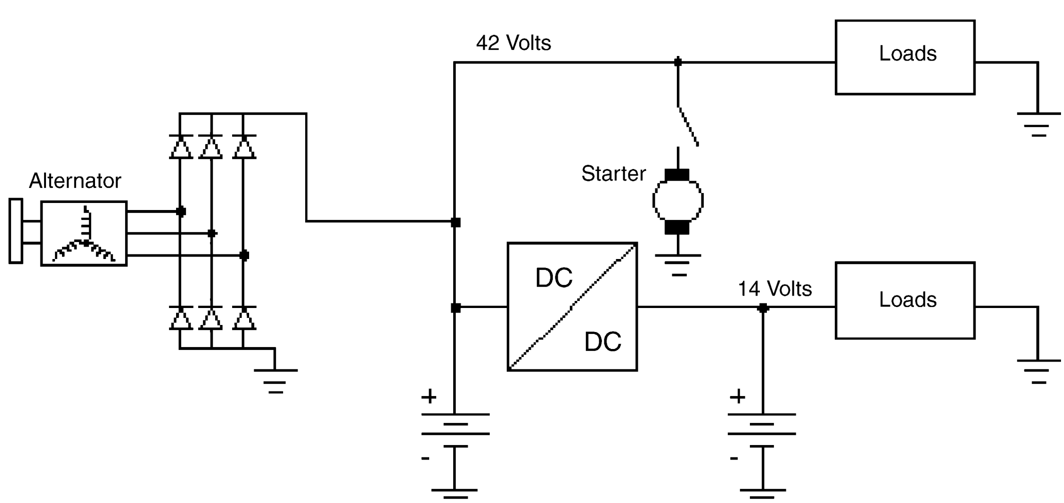

Fig. 3. Archetypal dual-voltage system.

overwhelming majority of magazine and journal articles that have been published concerning 42 V automobiles include a figure which is the topological equivalent of Fig. 3. Electrical power is presumed to be generated at the new voltage. The 42 V system consists of a battery and loads. The starter is presumed to work from this new voltage (frequently the starter and the generator are envisioned as one machine, working in two modes). A 14 V system, consisting of a battery and loads, also is shown. Power to the 14 V bus is provided from the 42 V bus via a dc-to-dc converter.

Until a very large production volume of 42 V cars is developed, a 14 V system is likely to be a necessary part of a 42 V car. The sheer number of electrical parts on a modern car makes it prohibitively expensive to develop 42 V variants of all of them at the outset. It has been shown that a battery on the 14 V bus of a dual-voltage car is a less expensive alternative to no battery. With a battery, the dc-to-dc converter can be sized to handle the average load on the 14 V bus, rather than the peak. The savings pays for the battery.

But for a mass-market car, there is a significant problem with Fig. 3. Prevailing wisdom suggests that a dc-to-dc converter will cost US$ 0.1 W^{-1}, and the required rating is anticipated to be 500–1000 W. With a total budget of US$ 60, it is not likely to be possible to use a dc-to-dc converter. Alternatively, low-cost dc-to-dc converters may be developed and/or the required rating of the converter can be substantially reduced. There are some indications that these alternatives may be possible.

6.1. *Alternatives to dc-to-dc converters*

Perreault and Caliskan [6] have developed a circuit which allows generation of power at two voltages and has the potential to offer very low cost. Fig. 4 presents a schematic of the circuit. The alternator is envisioned to be a conventional automotive alternator, although a variant of the circuit works well with an integrated starter-generator. The bridge rectifier in the lower right replaces a similar bridge rectifier which is already part of a present-day automotive alternator. In this bridge, MOSFET's have been substituted for the diodes in the lower legs. These MOSFET's can provide several valuable functions, including transient overvoltage protection and improvement of output power and efficiency of the alternator. The output of the bridge is the 42 V output. A second output at a lower voltage is readily obtained by the addition of three more rectifying elements shown in the upper right.

It has been shown that the circuit of Fig. 4 is capable of directing the full output capability to either the 14 or 42 V bus, and also capable of splitting that output between the buses at any proportion between. Further, the ability of the MOSFET's to extract additional power from the generator makes it possible to redesign the generator, reducing the cost of the iron and copper parts of the machine enough to pay for some of the additional silicon. We anticipate that all the circuit elements in Fig. 4 can be mechanically packaged within the alternator housing, as is done today with the rectifier bridge and voltage regulator.

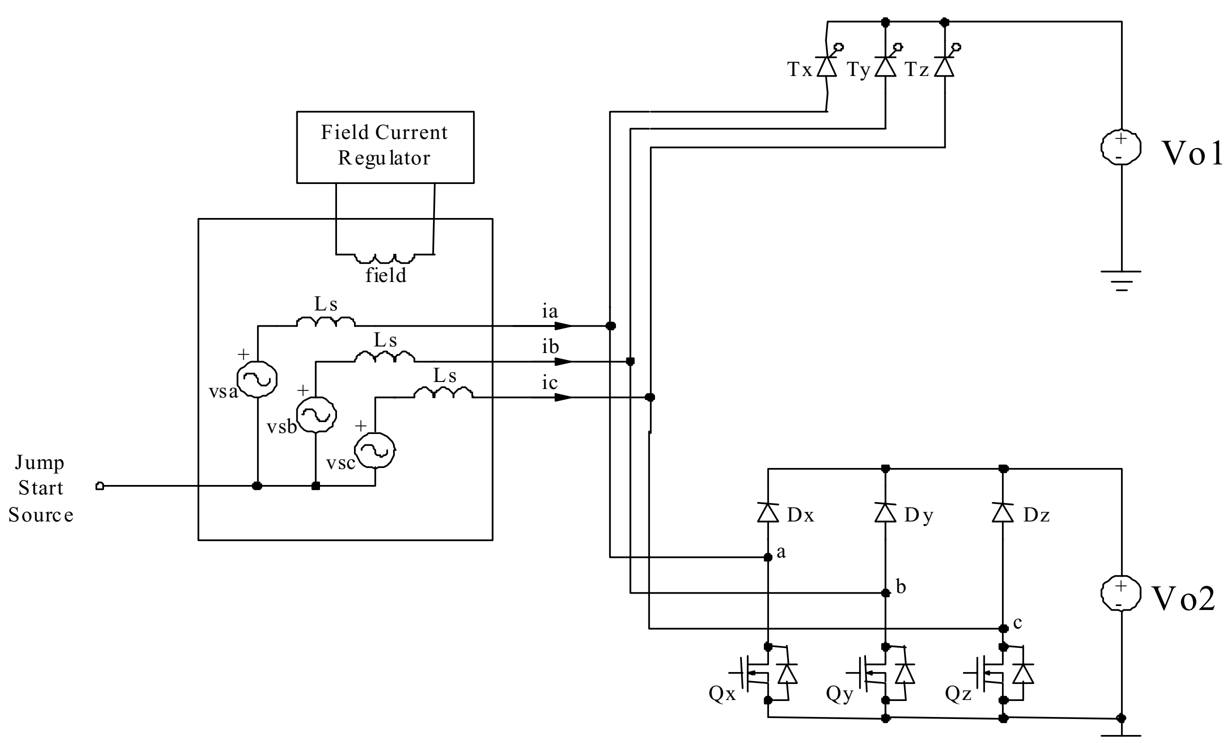

Fig. 4. Dual-output alternator incorporating switched-mode rectifier.

We project that dual-voltage capability can be added using the technology of Fig. 4 for a recurring cost of less than US$ 10 per automobile. We expect this solution to be dominant over the dc-to-dc converter architecture of Fig. 3. This leaves US$ 50 per vehicle for the remaining costs of adopting 42 V.

Several of the technical advances which give rise to improved fuel economy from 42 V adoption are arguably defensible even in light of the cold analysis of this paper. Electric power steering and electric engine accessories all require introduction of new parts, but in every case the new parts are not inevitably more expensive than the parts they replace.

6.2. Electrically assisted turbochargers

An electric turbocharger will be more expensive than a conventional turbocharger, and even a conventional turbocharger is not standard equipment on today's mass market gasoline car. One of the reasons why turbocharging is not more widely practiced is turbo lag following a call for a step in torque. Electrically boosted turbocharging provides improved driving characteristics compared to conventional turbocharging and may make the whole concept of turbocharging more acceptable.

The cost of an electrically boosted turbocharger will be a large part of the entire budget which we are allocating to performance-improving parts. But, the downsized engine which the turbocharger enables should cost less than the baseline engine, and the reduced engine mass should have beneficial effects on the mass and cost of the body, suspension, and drivetrain parts. This latter savings is best implemented in a vehicle designed from the start for the smaller engine. If the smaller engine is one of several engine options, it will be more difficult to realize the benefits made possible by reduced powerplant mass.

It is beyond the scope of this paper to investigate the extent of savings, either in the engine itself or in the rest of the vehicle, from downsizing the engine. But, it is reasonable to postulate that the savings might largely offset the cost of the electric turbocharger. It is even possible that the net result might be a saving.

6.3. Electric power steering

The adoption of electric power steering in our postulated future automobile is easy to justify from a cost viewpoint. Already electric power steering (at 14 V) is accumulating an increasing market share in small vehicles. For a given duty, a 42 V electric power steering unit should be less expensive than a 14 V unit.

6.4. Idle-stop systems

Unfortunately, the cost projections for the remaining new technology, an idle-stop capable motor-generator, exceed the entire budget for new parts. Projections vary, but numbers on the order of US$ 500 are not uncommon. Not even possible savings on a revised engine with boosted turbo and on electric power steering can offset this cost penalty. This presents a substantial challenge to the whole premise that 42 V can be used on mass-market cars for fuel economy. In congested driving conditions, idle-stop can make a substantial contribution to fuel economy. But more importantly, idle-stop operation represents most people's defining feature when future vehicle electric systems are discussed. It is the one capability which defines the proposed automobile as new and more advanced. It is the attribute which can persuade decision makers to adopt 42 V.

6.5. Alternative means to implement idle-stop

One possible solution is to achieve idle-stop restarts by means of an impulse starter [7]. An impulse start is achieved by first spinning a flywheel to some speed and then coupling the flywheel to the engine with a clutch. Fig. 5, from [7], shows results of a simulation of an impulse start. At first, the flywheel speed ramps up. Then, as the clutch is engaged, the flywheel slows and the engine speeds up, ultimately coming to the same speed. Two cases are shown, the first for a warm engine, the second for an extremely cold engine. In the simulation, the warm engine starts immediately. (The subsequent ripples in speed are the effect of the individual power strokes on the idling engine.) The cold engine, despite a substantially greater initial energy, fails to start.

For idle-stop operation, the impulse start operation has much to commend it. Idle-stop will be performed only with a warm engine, so any problem with cold start is not a barrier, provided of course that cold start is solved another way. The real merit of impulse start is that the required large torque for a short time is provided by a mechanical clutch, which is a well-developed, inexpensive component well suited for this function.

The flywheel can be a very modest mechanical device. The energy requirement is small enough that it can weigh 5 kg or less, and this is assuming that it is designed using

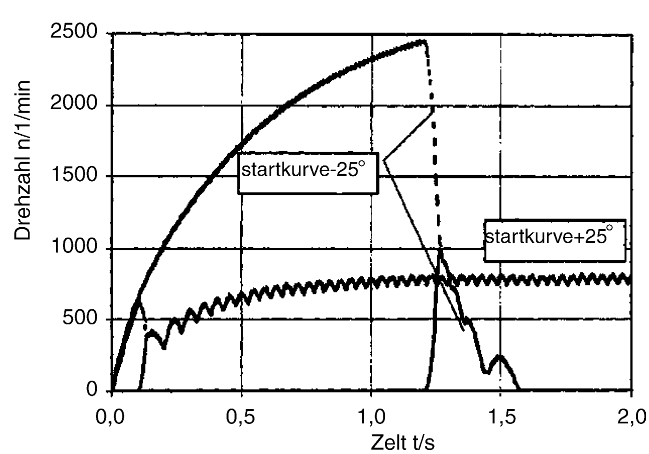

Fig. 5. Simulation results for impulse start—cold and warm examples.

inexpensive steel at very conservative stress levels, so that the risk of flywheel burst is entirely negligible. The duty on the clutch is much less than that required to start an automobile, so the clutch size and cost can be much less than for the primary clutch. The flywheel can be spun to speed over several seconds, using a much smaller electric motor than the one required for direct starting. This smaller motor will be much less expensive than a direct-start motor, and will require much less expensive drive electronics. One can readily imagine that the starter flywheel can be fitted to an auxiliary shaft on the main transmission, where it might run at a multiple of engine speed. The flywheel will want to be disengaged from the drivetrain for general driving in any event, so transmission mounting can facilitate that feature. Also, attached to an auxiliary shaft, the part could be made removable for service without disrupting the main drive train. In an era where existing manual transmissions are being automated, and new transmissions all incorporate more sophisticated control, one might imagine that some means could be found to spin the flywheel to speed using regenerated vehicle kinetic energy from the end of the stopping sequence.

All of this structure can implement a compact, efficient, idle-stop restarter, for much less than the cost presently being quoted for crankshaft starter-alternators.

Cold start can be performed as it is today, using a conventional electric starter. The inability to remove this part presents a cost and mass disadvantage, but the existence of an independent starting system makes failure to restart a double-contingency event, much rarer than a failure to start in today's cars.

7. An alternative view

Not all of the assumptions which have been made nor all of the conditions which have been postulated are rigorously defended here. If an important underlying fact is wrong, it is probable that some of the conclusions are wrong, too. For example, the British company Ricardo Plc. have produced an impressive prototype "€ 5" emissions vehicle, which achieves substantial advances in fuel efficiency by applying 42 V technology [8]. This vehicle is a retrofit of an existing mass-market product. It applies many of the technologies and meets many of the goals outlined in this paper. Ricardo's cost projections appear to show that this approach will require a cost premium that this paper would consider reasonable. But, it does so by applying an integrated starter-alternator and an advanced-chemistry battery, two technologies judged here to be too costly.

8. Conclusions

This paper presents an idiosyncratic view of the way forward for 42 V; a way forward that includes neither dc-to-dc converters nor integrated starter-alternators, nor advanced automotive batteries. Everyone in the automotive world recognizes the prime importance of cost in technology decisions. Yet very often, discussions of technology proceed as if cost were not a concern. The premise is advanced that 42 V cannot be introduced as a cost saving technology at today's level of functionality. But in advanced vehicles, which perform at a level beyond today's cars, for example, in fuel efficiency, it is possible to assemble a suite of features which use 42 V and which are cost effective. To do so, we have chosen to look critically at the cost of each component, relative to the improvement in functionality which it provides, and not all of the elements which most planners have included in their visions of future electrical systems make the grade. Conversely, a need is projected for new automotive systems which are not under widespread development today.

But even with this singular perspective, it does appear that the long-term future of the automobile does include 42 V electrical systems, although it may be prudent to keep an open mind about just what features will be found on such future automobiles.

The Ricardo findings can be read as a refutation of the fundamental conclusions of this paper. Or, they can be read as a confirmation that, by assembling a number of advanced features, it is possible to use advanced automotive electrical systems in conjunction with other changes to the vehicle architecture to produce a cost-effective advanced-performance automobiles with improved fuel economy and mass-market costs.

No matter whether one of these views prevails, or if yet another combination of components proves to be most favorable, the electrical systems of future automobiles will deliver added value that fully justifies their added cost, and they will do so more effectively than alternative means to achieve the same objectives.

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