ABSTRACT

A few years ago, the automobile industry agreed to adopt standards for a new voltage for the production and use of electrical power. The perception was near universal that 14 Volts was at the limits of its capability, and that 42 Volts would be adopted in a rush. The universal perception was wrong. Since then, much of the auto industry has encountered hard financial times. In a totally separate development, parts suppliers introduced innovations at 14 Volts, some of which a few years ago were thought to require 42 Volts. Today, there are 42-Volt cars and trucks for sale, but only at numbers far lower than necessary to begin to achieve economies of scale. But the factor which caused the industry to develop the 42 Volt standard, the growth of electricity use on motor vehicles, continues with no sign of letup. Further, the true technical obstacles to adoption of 42 Volts have been discovered and at least provisionally solved. The way forward to cost-effective solutions for advanced automobiles is clearer today than it was in the past.

INTRODUCTION

Throughout the history of the automobile, the average load on the electrical system has been increasing, model year upon model year. The principal drivers of this trend have been the increasing use of electric power to perform secondary vehicle functions which in earlier automobiles were performed by alternate means, and the increasing level of equipment on the average automobile. Electric windshield wipers and electric radiator cooling fans are examples of the former class, and the near-universal use of electric rear window defoggers is an example of the latter class. There is no reason to expect that this trend will not continue into the future.

For the most part, this evolution has been gradual, and the industry has responded by installing more powerful electric generators and larger batteries to service the gradually increasing load. In the 1950's, there occurred a conversion from 6-Volt to 12-Volt electrical systems, which made it possible to accommodate the larger load more economically. At that time, the automotive electrical system was much simpler than today, and this transition took place quickly, and without much, if any, increase in expense.

For well over a decade, visionaries within the industry have been questioning whether continued use of today’s 14-Volt system will be the most economical way to provide electric power in the future. Even before 1990, SAE had organized a committee on Dual/Higher Voltage Electrical Systems [1]. By 1994, a series of workshops had begun at MIT, to address the possible future of automotive electrical distribution [2]. The successor to the workshops is the MIT/Industry Consortium on Advanced Automotive Electrical/Electronic Components and Systems (the MIT Consortium) [3]. One early product was the proposal of 42 Volts as a standard for automotive generation and distribution [4].

Implicit in this search for a new distribution system was the search for a cost-effective solution. The principal reason that the industry chose to come together to propose a standard was the belief that by agreeing to a standard, parts complying with the standard would be produced in large volume (compared to the results for a company-specific, or proprietary, standard), and that the large volume would encourage parts suppliers and produce low component costs.

The case was made that future electrical components, processing higher levels of power and using semiconductors to control the primary component power flow, could be produced more economically, if they were designed to operate at a higher voltage [5].

Some argued that at the new voltage, power could be generated and distributed at a lower cost. Certainly, savings were expected in the wire harness. And savings could be projected for the generator, too.

Less expensive power generation and distribution to less expensive loads could result in a lower cost power system. Of course, this outcome depends on the projected savings being realized in both the pre-existing components being converted in voltage and in the new components. It also requires that little or no new equipment (components or functions not present in the present system) be required for the new system.
Although some projected that the new voltage would be a cost saving, the mainstream vision was never that the electrical system for a current production model would be made less expensive by adopting the new voltage. Rather, the goal was to make it possible for a future automobile, with a higher installed electrical load, to be made at lower cost than if the new voltage were not available.

But whether the vision was a cost saving, or simply a cost-effective way forward, auto companies and parts companies from all over the world endorsed the new standard. Many established substantial internal development programs to produce parts for the anticipated new systems. A positive-feedback instability developed. As each successive company announced a 42-Volt development program, other companies would reconsider their plans, and frequently increase their commitment. Expectations grew very high. The vision for the industry was of a cost-effective technology upgrade. But for each individual company, 42 Volts became an opportunity for new profitable product lines, an imminent threat to existing products, or both.

But in late 2004, adoption of 42 Volts for most manufacturers is viewed as a contingent possibility, rather than as a firm plan. Most of the internally funded development programs have been stopped. The possibility exists that automotive electrical systems will continue their evolution without widespread adoption of 42 Volts. At the very least, the introduction of 42 Volts will be far slower than was anticipated only a few years ago.

This paper explores the reasons for this change of mind, and discusses the way forward from here.

Some of the potential obstacles to adoption of a new distribution voltage were apparent even as the proposal was being developed. Still others became evident as work progressed to develop the components of the planned new systems.

THE DUAL-VOLTAGE DILEMMA

One of the most important differences between changing distribution voltage now at the change of the millennium, compared to the 6-Volt to 12-Volt transition at mid-century, is the relative complexity of today’s auto electrical system. The total number of electrical parts on a modern automobile, and the fraction of the total vehicle cost which they represent, bears no comparison to the first 12-Volt cars. Setting aside for the moment questions of technical feasibility, the act of developing a new part to functionally replace every electrical part on a modern automobile, even if the only difference in the new part is the input voltage, represents a monumental undertaking. It is far from clear that the non-recurring design and qualification expense could be economically recovered over the production life of a single vehicle platform.

To avoid this massive conversion expense, most parties considering a new distribution voltage have proposed dual-voltage systems. In these systems, the new loads which require or benefit from the new voltage, are provided power at that voltage, while a second 12/14 Volt system provides power to legacy loads.

The adoption of a dual-voltage system quickly leads to a number of other system choices. Clearly, if there are loads at two voltages, there must be a power source at each voltage. Prime choices are a dual-output alternator and a DC/DC converter operating between the two voltage buses. Because the cost of each power source depends on its peak power, one is quickly lead to conclude that a dual-voltage system should use a battery at each voltage, to allow the power source to be sized only for the average power at that voltage.

Vehicle designers look at the resulting system, with two batteries and dual power sources, and conclude that this represents an unsatisfactory solution, certainly for the long run. Some manufacturers have at times suggested that they would not build dual-voltage systems, but in most cases, the dual-voltage solution has been accepted at least as a short-term solution, while most makers planning or producing 42-Volt dual-voltage autos envision going to a single-voltage solution at some point in the future.

With more detailed analysis, this seemingly understandable goal is not as clearly desirable as it may seem. Some loads (incandescent filament lamps prime among them) do not scale well to higher voltages. A designer charged with eliminating all lower voltage loads must either do without incandescent lamps, or, alternatively, arrange to operate lamps in series strings, probably with some burnout protection circuit. It has been demonstrated that lamps can be successfully operated from 42 Volts using a relatively simple PWM control circuit. The cost, weight, and inefficiency of the potentially numerous PWM lamp controls must be weighed against the cost and weight of a potentially small battery and a voltage source, which itself probably comprises some form of a PWM circuit, most probably more complicated than the simple lamp driver.

The need to use dual voltage is thus seen as a necessary cost penalty for 42 Volts, at least in the short term, and probably for a very long time.

TECHNICAL CHALLENGES FOR 42 VOLTS

In the years since the possible need for a higher distribution voltage has been established, investigators have identified a number of ways in which 42-Volt or dual-voltage systems are qualitatively different from 14-Volt systems. Each of these differences requires consideration at the system engineering level, and most require some additional features in the new bus architecture, which add to cost but not to end-user function. So cost-effective solutions to these technical
challenges are required for 42-Volt or dual-voltage systems to succeed.

ELECTRIC ARCS – By far the most pervasive difference between 14 Volts and 42 Volts is the behavior of electric arcs. At 14 Volts, with all common materials of construction for automobiles, arcs are inherently unstable. If a circuit is interrupted, for example by a relay or switch, an arc will occur, but it will persist only as long as an inductive \( L \frac{di}{dt} \) voltage exists to sustain it. When the voltage across the arc falls to or below 14 volts, it self-extinguishes.

At any voltage much above 14 Volts, certainly at 42 Volts, an arc between two electrodes separated by a small gap is stable; it can theoretically burn indefinitely. There is an exception to this statement; for very small currents, arcs exhibit unstable, self-extinguishing behavior at 42 Volts. In practice, arcs do not burn indefinitely. Most often, the process which caused the electrodes to be separated does not stop, causing the electrode gap to increase with time. At a long enough gap, the arc becomes unstable and self-extinguishes. In extreme cases, the melting of the electrode is the process which lengthens the gap until extinction occurs.

This difference in behavior can, in unfavorable cases, result in dissipation in electric arcs which is much greater at 42 Volts than is possible at 14 Volts.

Although this problem had been recognized by several companies, it was not widely discussed in public until it was brought to the attention of the MIT Consortium by Yazaki in 1999. The subsequent public investigation quickly defined and bounded the problem.

The Videos - The issues of electric arcs at 42 Volts has been dramatized by the existence and frequent showing of a number of very dramatic videos. Some of these videos make arc welding look tame by comparison, and truly remarkable component damage is sometimes shown. These videos have been responsibly prepared and presented within the automotive electrical systems community, but their adverse impact on the larger automotive community may have improperly damaged the image of 42 Volts. Almost without exception, these videos present the consequences of failing to consider arcs in the design of 42 Volt systems. They are examples of bad design, and in extreme cases negligently bad design. There are far fewer videos and before-and-after photos of the consequences of good and responsible design.

The fact is that the possibility of arcs must be considered in the design of 42 Volt systems, and the possibility of arcs limits the applicability of 14 Volt parts at the new voltage. But the possibility of arcs does not make it impossible to design safe and cost-effective 42-Volt systems.

Fuses – One of the earliest findings in the investigation of 42 Volts was that existing automotive fuses could not be used. At 42 Volts, 14-Volt fuses fail dramatically, with an arc persisting for some time within the fuse body before eventually extinguishing, and frequently with the fuse body bursting into flame. Much to their credit, the automotive fuse industry, despite being very small and lightly capitalized by industry standards, rolled up their sleeves and developed new designs which did work satisfactorily [6]. These new fuses are compatible with present production practice, and samples quickly became widely available. The apparent ease with which the industry dealt with the 42 Volt fuse problem may have set expectations which suppliers of other parts could not so quickly meet.

Switches and Relays - The problem of 42-Volt arcs is not so severe in switches and relays. The designers of these components have control over how fast their contacts separate, and they have the option of putting more than one set of contacts in series. So it is fairly straightforward to design a switch or relay for 42 Volts. Of course, switches and relays designed for 14 Volts are unlikely to be satisfactory at the new voltage, unless they are switching loads below the threshold current for unstable arcs.

Connectors - Connectors are another matter. Most connectors are not intended to be mated and unmated under load. But at 14 Volts, the practice has no practical adverse consequences, so it has become widespread in the repair industry. But at 42 Volts, the consequences can be significant. Even a single disconnection under load can render a connector unsuitable for further service. With few exceptions, the connector designer cannot control the rate at which the contacts separate; that is generally determined by the service technician. So the principal design remedy available for switches and relays does not apply to connectors.

The industry has not selected a standardized response to the need for 42-Volt connectors. In part, this is due to there being no single clearly superior choice, but in part it is also due to a diverse range of reasonable choices. A strong case can be made for abandonment of the practice of mating or unmating connectors under load. The provision of a single, accessible master switch could make this change easily acceptable.

Alternatively, selective application of special connectors could be used. Many loads at 42 volts can be connected or disconnected under power with no more consequence than at 14 Volts, because their currents fall below the threshold. Only a few loads may need special treatment, and for these, the industry has demonstrated a range of practical choices. A sense pin can break before the power pins on disconnection, and the sense pin break can drive a relay which disconnects the circuit. Some connectors introduce a resistance in series with the load before the final contact parts. And in one case, a very promising contact alloy selection reportedly offers damage free mating and unmating under a range of conditions covering many practical loads [7]. Few if any of these technologies are in parts
catalogs today, but the way forward to cost-effective, arc-insensitive connectors seems to be open.

Parallel Arcs - In addition to switches, relays, and connectors, the difference in arc behavior at the two voltages requires consideration of the consequences of arcs at locations where no arcs are anticipated. The first class of such arcs occurs as a result of faults to ground. Such a fault can occur when an energized wire breaks and falls against the auto body, or when a portion of the body or frame cuts through wire insulation. These arcs are called parallel arcs, because they exist in parallel to the load.

Parallel arcs tend to be high current events. The source voltage is divided between the arc voltage, and voltage across the impedance in series with the arc (including the source impedance). Most commonly at 42 Volts, a substantial portion of the source voltage appears across the series impedance. For this to happen, the circuit current must be many times the design current, and the most common consequence is that a fuse blows, extinguishing the arc.

It is not uncommon for arc currents to be intermittent, even with nominally dc power supplies, and in the event of an intermittent arc, it is formally possible to dissipate much power in the arc for a long period of time, without blowing the fuse. We investigated this eventuality at MIT, and our observation was that this subclass, parallel arcs which do not blow fuses, was a relatively small threat. The duty ratio of the intermittent current must be very low to prevent fuse blowing, so low that this event will represent only a very small fraction of cases. And, with acceptable duty ratios and reasonable series impedances (values representative of an automotive wire harness), the resulting arc is not very energetic. In our experiments, we commonly saw melting of wire insulation and whiffs of smoke, but only in the immediate vicinity of the arc. We did not see open flame [8].

Series Arcs - The other class of unintentional arcs is series arcs. Here the arc occurs in a path which is in series with the load. Connector arcs are series arcs. Because the load is in series, the arc current cannot exceed the load current, and fuses will not act. The most common place for a series arc is at a connector, if not a connector being deliberately opened, then one which has been improperly mated.

A series arc can be viewed as a member of a class of failures, all of which comprise an unintended high impedance in series with the load. Corroded connectors and partially but not totally severed wires are other members of this class. Any of these failures can cause a local dissipation of energy intense enough to overheat and even to ignite the failure site. These failure modes exist in today's automobile fleet, and there is no protection against such failures in today's automobiles. It is far from apparent that the possibility of a stable series arc changes very much the overall risk to a vehicle from this class of faults, taken as a whole.

Finally, it is possible to develop active circuitry which detects an electric arc and disconnects the failed branch. Arc detection is sufficiently cost-effective that it is used in the ac service in new residences in many countries [9]. It is also now being marketed for electric power systems in transport category aircraft. These both represent AC applications, but some of the the same suppliers indicate that DC arc detection can be performed, as well [10].

Electric Arc Summary - Arc behavior is demonstrably different at 42 Volts than at 14 Volts. This difference can be used to make very dramatic videos. But the videos show cases which cannot exist or should not be permitted to exist in a practical automobile. When a detailed circuit-by-circuit, failure-by-failure analysis is made, it is probable that the risk of damage by arc is negligible or acceptable in the vast majority of cases. For a few circuits and/or failure modes, new technology may be required. For these cases, a range of cost-effective solutions exists. In short, arcs are a new technical challenge for the designer, but they do not pose an insurmountable obstacle to using 42 Volts in automobiles.

BUS-TO-BUS FAULTS – The dual-voltage automobile has a new failure mode, that of a short between the high-voltage and the low-voltage buses. This problem of course cannot exist without two voltages, but in a dual-voltage automobile, it can be imagined to be relatively common, as designers expect to feed some loads with both voltages, and to mix voltages within bundles of the wire harness.

A "hard" (low-resistance) short between the two supply voltages will almost certainly blow a fuse. But what happens after that depends on many factors. One cannot control in general which of the two affected fuses will blow first and it can be established that there are many operating cases in which the second fuse does not blow.

In general, the requirement for a safe outcome should be that both affected fuses clear. Some have argued that a final outcome with 14 Volts applied through the short to a 42 Volt load is safe. This is defensible regarding the stress on the 42 Volt component, but there is a hazard in that the short, while being low enough in resistance to allow for fuse clearing, is still a high enough resistance to produce hazardous local heating.

A working group was formed in Europe by the Sci-worx forum (which met originally under the German name Forum Bordnetz, then later used the name Forum Vehicle Electric System Architecture, and is now considering another name change), to make recommendations concerning design for safety in light of the possibility of a bus-to-bus short. Their recommendation comprised a zonal protection concept, in which conductors at different potentials were kept separate [11].
More recently, work supported by the MIT Consortium showed a simple, elegant design methodology which can guarantee clearing of both affected fuses by including simple active elements in the fusebox. The cost to implement this methodology is modest [12].

A similar, less severe, problem occurs when a load is fed from both voltages, using a common ground contact for both circuits. Should the ground contact be lost, the load is placed in an unusual state. In general, this state need not be hazardous to the load or the vehicle, but it is yet another failure mode to be considered during design.

In summary, the bus-to-bus short in dual voltage systems presents a new failure mode. Design methods, either involving vehicle layout or the inclusion of active elements in the fusebox, have been proposed and evaluated. This obstacle has been adequately identified and studied, and suitable countermeasures have been defined.

CORROSION – In 2002, an SAE Toptec included an important session in which the performance of electrical parts, under electrical stress were evaluated as a function of voltage in accelerated life tests in corrosive environments [13]. This session presented the independent, un-coordinated studies by a number of important contributors, but the independent works formed a surprisingly coherent theme. Although the physics of the processes being tested include many processes, including electromigration and surface insulation degradation, the studies were generally referred to as corrosion studies, and that name, although at least partially misleading, is the one used here.

In general, the deterioration of the parts was troubling. And parts tested at 42 Volts deteriorated substantially faster than parts tested at 14 Volts. But other than a general caution that one should be careful when using parts designed for 14 Volts at 42 Volts, it is hard to draw any conclusion from this session, or from any other source which has come to the author’s attention.

Because the investigations were in almost every case accelerated tests, it is difficult to form any firm conclusion about the suitability of any given part for a proposed service, other than service at 14 Volts in an automotive environment. The strength of the accelerating functions is not known, nor is the threshold between acceptable and unacceptable deterioration.

Compared to arcing or bus-to-bus faults, the state of knowledge and readiness of the automotive industry regarding the collective phenomena referred to as corrosion at 42 Volts is not far advanced. In part, this is the case because the system engineers who lead the early efforts understand the threats of arcing and faults, and are comfortable dealing with these problems. The perception has been that corrosion is “just a materials problem” and that suitable solutions can readily be found.

It is the author’s perception that the problem of “corrosion” will not stand in the way of use of 42 Volts in automobiles. Certainly trackless trolleys and streetcars work in exactly the same environment as automobiles, using voltages far above 42 Volts, and with product lifetimes and duty cycles far in excess of the automotive standard. But the present state of uncertainty will prompt early adopters to design more conservatively than the mature economic optimum, willingly incurring a probable penalty in system cost for a reduced risk of a systemic reliability problem. As experience is accumulated with parts working in the field at 42 Volts, unneeded conservatism will gradually be eliminated, and parts reflecting the true economic optimum will emerge.

PRESENT STATUS

The previous paragraphs summarize the remarkable work that the automotive electrical community has done in finding, evaluating, and fixing the obstacles to application of 42 Volts. A number of important, and sometimes fascinating, technical problems have been uncovered. In each case, one or more solution(s) have been found. Despite considerable searching, the industry has not found a showstopper problem which would derail the use of 42 Volts.

Yet the industry is at a standstill regarding this technology. The reason is not technological, it is economic.

There are two economic challenges. The first is the financing of transition costs. This is not a new problem; it occurs with every technological transformation, and the auto industry solves it all the time. The second economic challenge is to identify the value which justifies the expense.

It is apparent that there is a cost required to implement 42 Volts. The source of cost is evident in a dual-voltage car, and even in a pure 42-Volt application, parts which perform functions that are presently being adequately performed at 14 Volts are likely to cost more, at least until volume builds to comprise a substantial fraction of the world’s production.

So the early vision of 42 Volts as a cost reduction has proven to be unrealistic. But there is still the vision of 42 Volts as a cost-effective way to get more electric functions on the vehicle than is possible today.

To be selected on this basis, 42 Volts must be the only way, or the least expensive way, to get the required level of power and function, and the cost must still be low enough so that the vehicle designer does not reconsider the specifications for power and function.

The electric equipment market has changed to make it harder for 42 Volts to meet this selection criterion. Important electric functions including electric power steering and idle-stop operation, have been introduced.
to the market as 14-Volt functions. (There remains some question whether the 14-Volt implementations can be applied to the full range of light car and truck sizes, but prototype idle-stop systems have been demonstrated at 14 Volts even on large American V8 engines.) The output capability of automotive alternators has been increasing. Electromagnetic engine valve actuation (an important electrical load) has faded into the background, as more advanced mechanical valve actuation systems are implemented.

As it becomes possible to do more and more with 14 Volts, the auto companies have strong incentives to put off adoption of 42 Volts. Even if a given function can eventually be implemented less expensively at 42 Volts, the incentives are all negative for the early adopter. Each of the technical obstacles discussed above must be dealt with be any 42-Volt design. With limited experience with this new technology, a design error is more possible for the first/early adopter. Risk of high warranty expense and/or reputation for low reliability and poor quality is high. Then too, the suppliers will look to recover much of their investment in the technology in business dealings with early adopters.

At present, there are few vehicles that need 42 Volts, and there are powerful incentives not to rush to the new technology.

Just as each company to start a 42-Volt development program or to plan a 42-Volt product launch generated a flurry of interest and then activity among other companies, so has it been the case that each company to abandon its plans causes reconsideration at those companies which still have programs. Either out of embarrassment, or in a desire to demonstrate that they have learned from their previous excessive enthusiasm, decision makers may choose for their company to have absolutely no association with 42 Volts.

In late 2002, one manufacturer put the incremental cost of a 42-Volt system, including only an integrated starter-generator, at between 555 and 1130 Euros [14]. The author concludes that these costs are difficult to justify on the basis of increased fuel economy.

Even in the face of such a negative outlook, there are two 42-Volt vehicles in production, and a few more still being developed [15,16]. Evidently the long-term prospect remains attractive, even if the short term is not.

**FUTURE PROSPECTS**

Just as expectations were once unreasonably high, they are now unreasonably low. The fundamental reasons for considering a voltage change are as sound as they ever were. There is no let-up in the growth of electricity use in automobiles. If anything, with increasing adoption of electric power steering and idle-stop operation, the rate of growth is increasing.

The work which has been done in the past several years has identified important differences between 42 Volts and 14 Volts, which require that 42-Volt systems and their components be designed with an awareness of these differences. The good news is that we know that 14-Volt systems cannot be converted directly into 42-Volt systems. However, for each technical difference, we have good ideas how to proceed to design the 42-Volt system.

Based on the work we have seen to date, 42 Volts will require a cost premium, but with sound design, it is easy to imagine that that premium will be 50 or 100 Euros, not ten times that much. None of the technical challenges discussed above require an expensive new direction.

50 Euros is still too much cost, just to have 42 Volts, but so is even one Euro. But at 50 Euros, it is plausible to believe that some new capability may be enabled, for example, electric turbo boost, which produces an overall vehicle benefit which exceeds the cost. It is also plausible that the voltage change will permit cost reductions in other systems which may be specified on future cars, which can be implemented at 14 Volts but are more economical at a higher level.

As both the unrealistic optimism of the past, and the pessimism of the present give way to realism in the future, we will continue to see more electricity use on automobiles. At some point, we may see some of that use migrate to 42 Volts.

**CONCLUSION**

The idea of 42 Volts in auto electric systems has had in interesting and dynamic history. The whole idea is driven by the ongoing growth in electricity use on motor vehicles, a trend which continues and may be accelerating. About the year 2000, a huge bubble of enthusiasm for 42 Volts resulted in activity all over the world. Investigators identified the important technical questions about application of 42 Volts in automobiles, and made major progress toward finding answers. But as automakers planned to implement 42 Volts, two things happened. First, with a few exceptions, they reconsidered their efforts and cancelled their programs. And second, the electric equipment market evolved so that applications which were once thought to require 42 Volts can now be implemented at 14 Volts. (The second event may have contributed to the first.)

The bubble of enthusiasm came to be replaced with a widespread disillusionment. It is ironic, but when no-one knew what it took to implement 42 Volts, everyone was high on the prospect. But now that we know what it takes, and it is not that bad, opinions are nearly uniformly negative.

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