Intelligent Power Semiconductors for Future Automotive Electrical Systems

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1. Introduction

National and international programs to reduce fuel consumption (the three liter per 100 km or 80 miles per gallon car) and cut CO_2 emissions are up against increasing demand for electrical power.

When translated into terms of fuel consumption - every extra 50 kg of weight or extra 100 W of electrical power increases fuel consumption by 0.2 liters per 100 km - it is clear that these objectives can only be achieved through a significant improvement in efficiency, which in turn means replacing conventional mechanical solutions with electromechanical technology (e.g. the water pump). Increased demand for electrical power is being driven by the need to comply with anti-emission legislation (preheating of catalytic converters), to optimize combustion (electromagnetic valves) and to provide greater driver safety and comfort (e.g. heated windshields) and navigation systems.

Present-day automotive electrical systems have reached the limit of their efficiency. Hence the need for a radical rethink of the entire automotive electronics system. This will involve reviewing every component so automotive component manufacturers, equipment suppliers and semiconductor manufacturers have come together in consortia to exploit this opportunity:

- MIT/Industry Consortium working group on Advanced Architectures for Automotive Electrical Systems[1)] (part of the US Partnership for a New Generation Vehicle: PNGV),
- Forum on Automotive Electrical System Architecture in the Year 2005[2)]

A key aspect of these programs is to provide cost-effective power electronics or to define the relevant criteria for achieving this objective.

2. The need for a new electrical system

The typical 14 V electrical system in a mid-range or luxury car today is rated at approximately 800 W - 1500 W continuous load; this is equivalent to a continuous current rating of 60 A - 110 A. The average annual consumption is around 550 W, with maximum static loads of 2500 W (180 A) being quite feasible. If all the electrical loads were to be activated simultaneously, this would represent a power demand of the order of 10 kW[3)] even today.

When we consider that the maximum static currents which can safely be handled by today's cables, batteries and generators are of the order of 150 A - 200 A, it soon becomes obvious that the automotive electrical system in its present form has reached the limit of its capacity.

At the same time however, the automotive industry already needs even more electrical power. Reasons for this include the emergence of new features such as heated windshields and preheating of catalytic converters, as well as financial reasons such as reducing gasoline consumption and cutting emissions. A beneficial development here is the replacement of today's mechanical solutions by electromechanical ones, as is happening with, for example, the mechanical water pump and power steering[4)] . Accompanying this development, there can then be a move from applications with purely digital switching to regulated applications matched to actual power requirements. Electrical load regulation or control can be achieved e.g. by pulse width modulation (PWM).

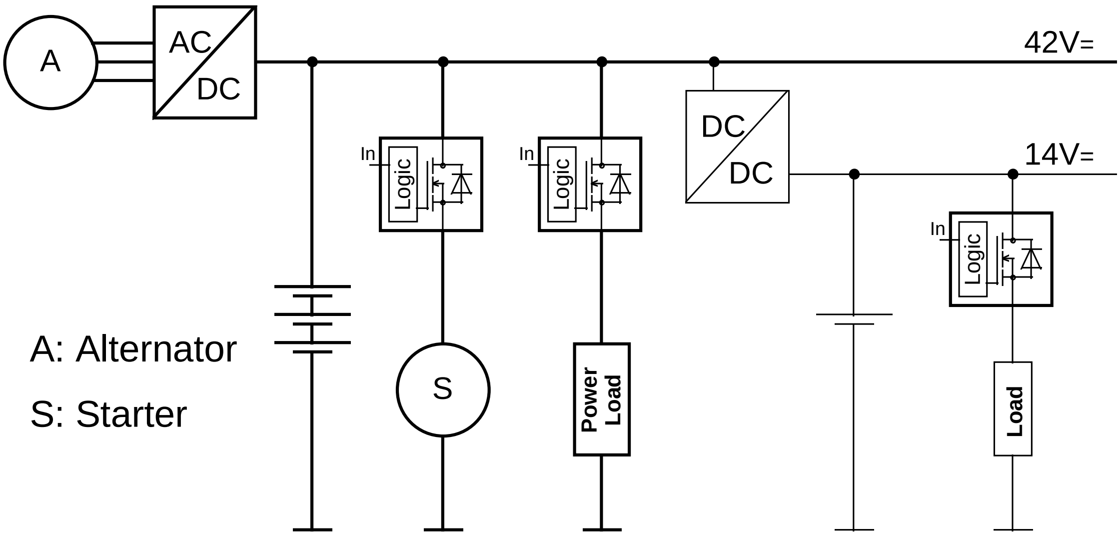

Fig. 1: Simplified automotive electrical system for the future with 14 V and 42 V dc supply

The continuous electrical power which will be needed in the year 2005 is estimated to be in the range 3000 W - 7000 W, with an annual average of around 1700 W. The dynamic aggregate electrical power demand will then be at least 30 - 40 kW.

Given this scenario, it is clear that today's 14 V electrical system is not fit to enable the change taking place in the automotive industry. Hence the need to investigate a new higher-voltage system. All the discussions currently taking place on this subject are pointing to a 14 V electrical system modified to include a 42 V dc supply (Fig. 1). The 14 V system is to be retained to avoid having to change all existing applications; also, a 14 V supply is more suitable than 42 V for some loads such as lamps and small motors or valves. The new 42 V system, on the other hand, is designed for power-hungry loads such as engine cooling fans and electromagnetic valve actuators.

3. Advantages of a new electrical system

We have already touched on the advantages of a new electrical system. The main benefit of higher voltage is reduced current. Tripling the voltage reduces the current needed by a factor of three. If the switch, cable and connector infrastructure is left unchanged, the losses incurred from these sources can be reduced by a factor of nine. Reducing cable and switch losses is a way of achieving the increased levels of efficiency essential if the 3 liter/100 km car is to become a reality. Another objective may be to leave losses unchanged and to increase the on-state resistances of switches and cables by a factor of nine. It would then be possible to reduce cable cross-sections and plug-in contacts, but the main cost savings would be in semiconductor power switches as a result of reduced chip areas.

The introduction of a new electrical system would also be an opportunity to rethink features which add cost today, such as dynamic overvoltages, necessary in the event of a load dump (could be replaced, for example, by central or active load dump protection) and to eliminate static overvoltages, caused by jump starting. As a result, switches and loads would not have to be rated for unnecessarily high overvoltages, instead they could be rated essentially for nominal voltage. The concept shown in Figure 1 is one of many options under discussion. Here, the 14 V voltage is generated by a DC/DC converter from the 42 V system and stored by a battery. The 14 V supply is thus regulated and should be free of load dump and other, static, overvoltages. Nor should there be any voltage dips down to 6 V, such as occur today on start-up. Present day applications have to be rated for these low voltages which means that at 14 V these applications are always being operated at a higher voltage, thus increasing power consumption and unnecessarily degrading efficiency. The higher currents when operating with overvoltage means that today’s switches have to be rated for lower resistance than is actually necessary.

4. Implications for power semiconductors

The move from simple switching functions to regulated or controlled electrical loads requires the use of semiconductor power switches. The question then is what is the optimum operating voltage for high-capacity semiconductor switches.

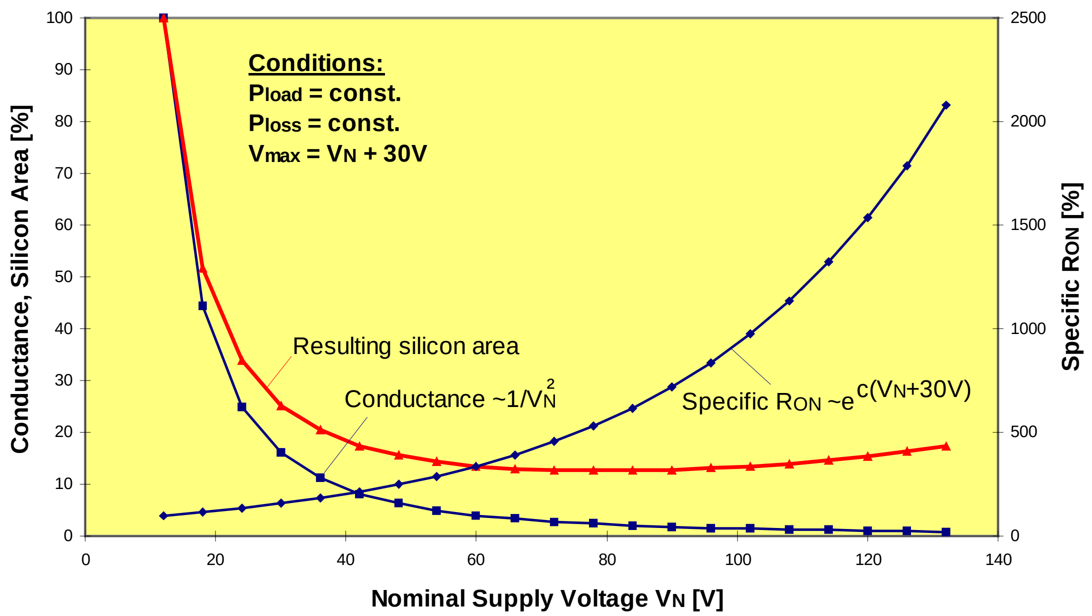

Fig. 2: Necessary silicon area for the vertical power semiconductor switch as a funktion of nominal supply voltage

In Figure 2 the conductance of a semiconductor switch needed to switch a given load with constant power loss is plotted over the nominal supply voltage V_N. The curve -1/V²N shows a dramatic fall in the necessary conductance above 14 V (≡100%).

On the other hand, the specific on-state resistance of a power switch increases exponentially with the maximum voltage occurring at the switch $V_{max} = V_N + V_{add}$. Here, V_{add}, the difference between the maximum static operating voltage V_{max} and the nominal supply voltage V_N, is taken to be 30 V and relates to power semiconductors in use today, where $V_{max} = V_N + V_{add} \approx 14\ V + 30\ V$ (≡ 100%).

Together, these two facts yield the silicon area necessary for the power part of a semiconductor switch as a function of nominal supply voltage. A higher nominal supply voltage drastically reduces the silicon area, assumed to be 100% at 14 V, to values around 15 - 20%, with no clear minimum being apparent.

If we consider only this element of the equation, then we can state that as regards the power semiconductor, a nominal voltage anywhere in the range 40 V to 120 V would be equally appropriate for the future. In order to identify the optimum nominal voltage, this information needs to be correlated with other information, e.g. electrical motor manufacturers' data on efficiency and manufacturing costs or data from cable and connector manufacturers on cable cross-sections, corrosion and protection against accidental shock. Nor should we neglect the effect which necessary technology developments have on semiconductor manufacturing costs. We will examine this question more closely later.

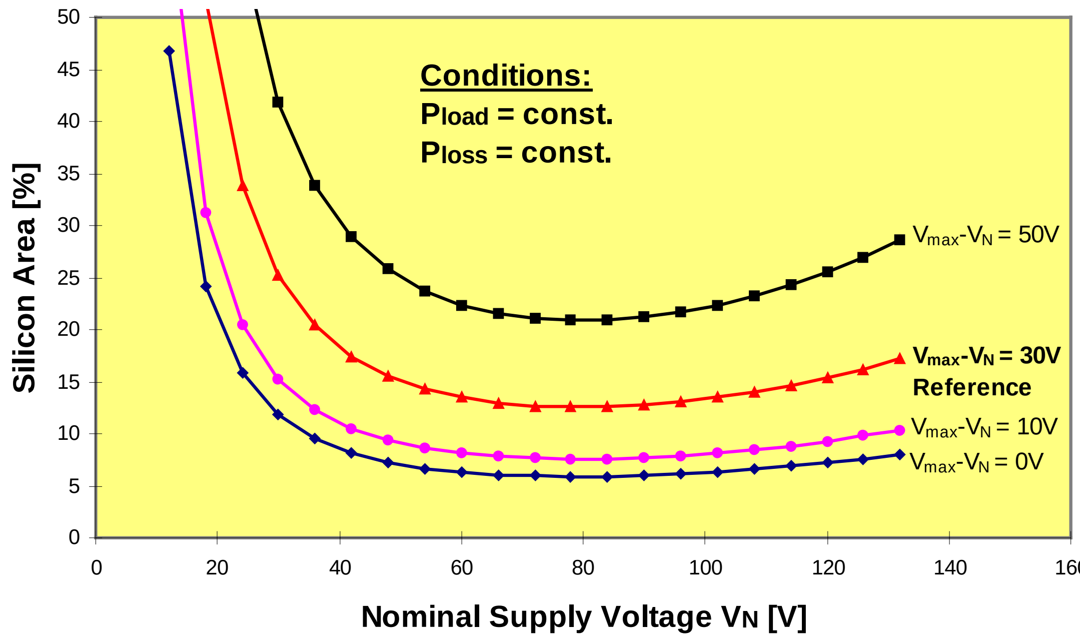

Fig. 3: Effect of the additional required withstand voltage V_{add} on the resulting power chip area as a function of the nominal supply voltage

Figure 3 shows the effect which the additional withstand voltage required, V_{add}, has on the resulting silicon area, using the reference curve $V_{add} = V_{max} - V_N = 30$ V from Figure 2.

If modern techniques such as central or active load dump protection on the generator succeed in limiting static and high-energy overvoltages to a theoretical value of 0 V, then for certain ranges of nominal voltage a further halving of the silicon area to less than 10% compared with switches in use today, can be achieved. Thus, by selectively reducing overvoltages, vehicle manufacturers can decisively influence semiconductor switch costs. It should be possible to achieve a value of $V_{add} \approx 10...20$ V in actual automotive electrical systems.

Investment in semiconductor technology has a decisive effect on costs of power semiconductors. For this reason, it would obviously be desirable to implement future power switches using existing technologies. The most advanced technologies currently used by Siemens, e.g. S-Smart, have a minimum withstand voltage of 60 V. Delivering a component with $V_{max} = V_N + V_{add} = 42$ V + 20 V requires only a slight technology adjustment, which can be achieved within a short timeframe. In any event, this step can be taken with the introduction of a new more powerful technology (technology shrink). The cost situation for future power switches clearly points to a nominal voltage of 42 V with minimum permissible overvoltages of the order of around 15 V.

On the 14 V side, where switches with $V_{max} \approx 45$ V are used today, the same approach can be taken. By eliminating unnecessary overvoltages, switches with $V_{max} \approx 20$ V can be used in the long term, employing a semiconductor technology with breakdown voltages of 25 - 30 V. Thus, in the long term, there is potential in the 14 V electrical system too for achieving savings through reduced silicon areas. In all these calculations, we should not forget of course that the effect on component costs of reducing silicon areas is not a linear one. Package costs, test costs and logistic costs are not affected.

Reducing the size of chip areas does have one disadvantage which should be mentioned here. The thermal resistance of a power switch is in inverse proportion to its chip area, as a result the thermal properties of the switches are impaired at 42 V. On the plus side however, modern applications tend to avoid generating heat ("silicon instead of heatsink") and thus the thermal resistance of a power switch is often not of prime importance. The same is true of the maximum energy which a switch can absorb when shutting down inductive loads, or when dynamic, high-energy overvoltages occur. This too decreases with a smaller chip area, but is still sufficient to be able to switch all actual inductances without suffering damage.

For a number of years now Siemens has been supplying power semiconductors with maximum permitted static operating voltages of around 60 V in its TEMPFET family (BTS120 at 100 V), HITFET family (BTS149 at 60 V or TLE5216G at 65 V) and PROFET family (BTS307 at 65 V, BTS442x2 at 60 V and BTS550P at 63 V). The idea of a 42 V automotive electrical system has already been explored from the angle of power semiconductors and is not new territory for Siemens. Switches are already available to enable users to build applications today and thus gain experience.

5. Implications for the logic part of power semiconductors

Modern power semiconductors often have an integral logic part for protection and diagnostic functions. This logic part usually has an internal stabilized voltage supply and does not therefore depend primarily on the nominal voltage of the vehicle electrical system. The provision of the

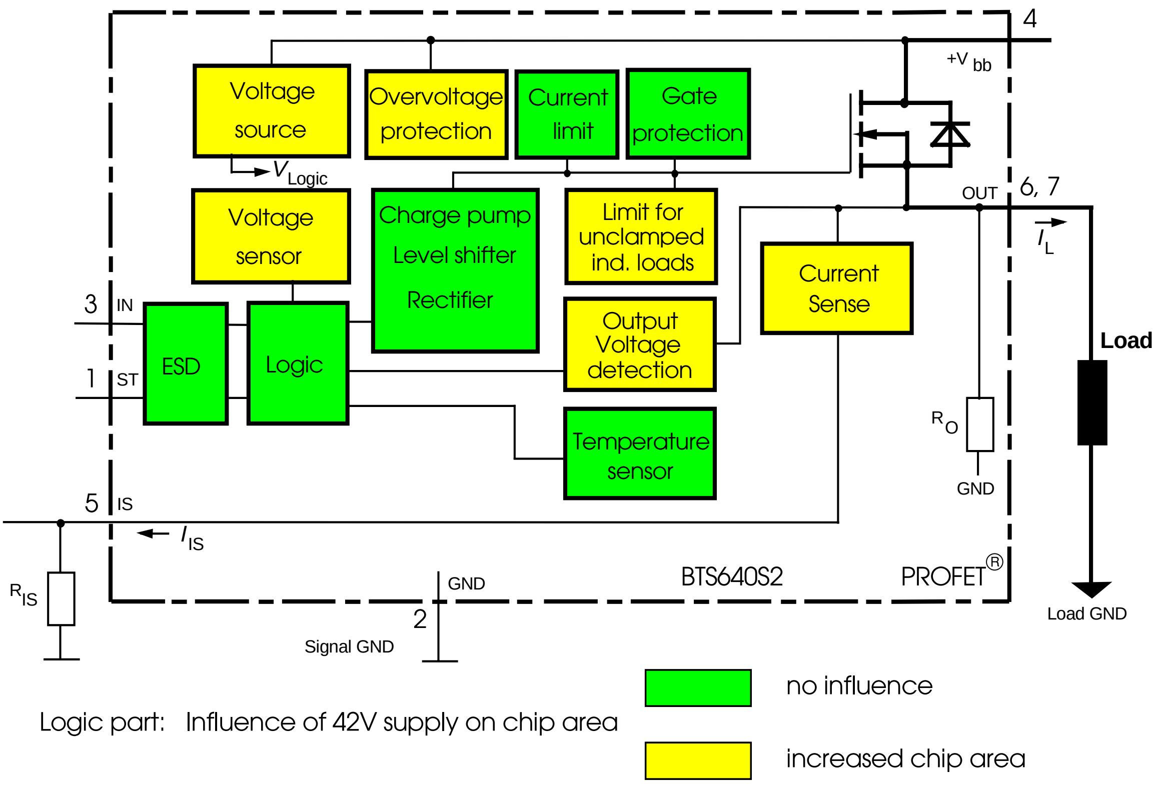

Fig. 4: Effect of higher supply voltage on the integral logic part of a smart power switch such as the Sense PROFET BTS640S2

internal operating voltage and of some functions, e.g. detection of overvoltage and low voltage, do of course depend on the maximum on-board voltage and have an adverse effect on the silicon area.

Figure 4 is a block diagram of a smart high-side power switch. In this diagram, those parts which result in a larger chip area because of higher on-board voltage are highlighted. If we assume that the logic part of such a switch represents around 25% of the area, then an estimated 3 - 5% of this is affected.

To summarize, increasing the nominal voltage will increase the area of the logic part but the effect on overall costs will be negligible.

6. Implications for packages and assembly

With a higher nominal voltage, greater loads can of course be switched for the same on-state resistance of the switch or the same power loss. Figure 5 shows the switchable loads as a function of on-state resistance, where the silicon temperature is assumed to be 100°C.

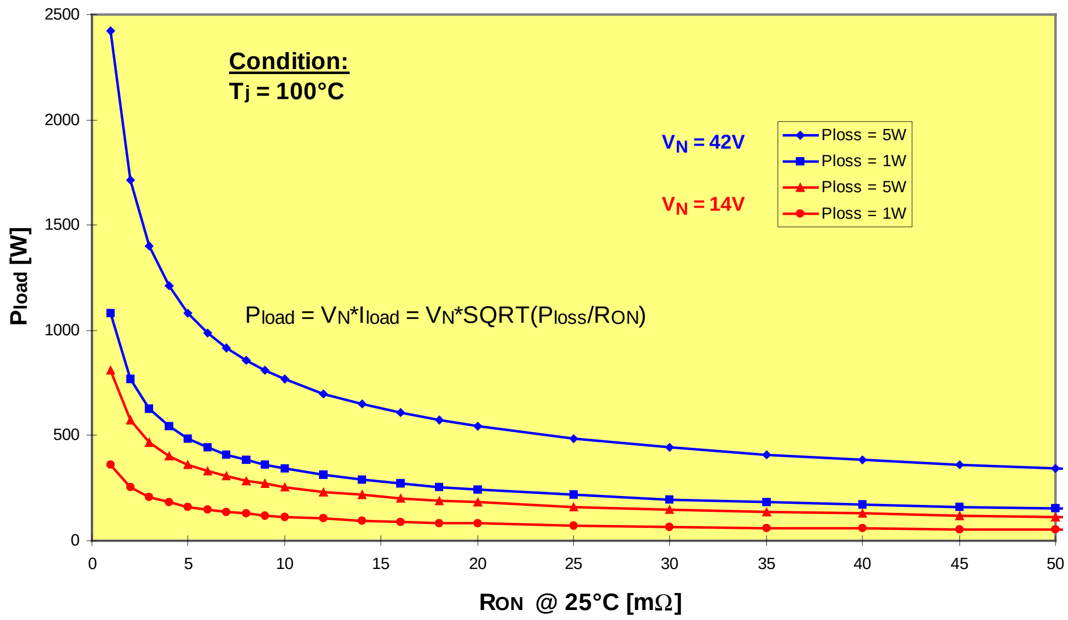

Fig. 5: Switchable continuous load as a function of on-state resistance for 14 V and 42 V power supplies

The different parameters used were a power loss in the switch of 1 W and 5 W with a nominal supply voltage of 14 V and 42 V.

Using current assembly techniques, Siemens is able to supply components rated at less than 5 mΩ (smart high-side switch BTS 550 P at 25°C). This assembly technique is suitable for components with an on-state resistance as low as 3 mΩ at 25°C. According to Figure 5, with an operating voltage of 14 V, a 3 mΩ switch like this can switch loads of 200 W - 500 W continuous, with a power loss of 1 W or 5 W, assuming a chip temperature of 100°C and an associated 50% increase in on-state resistance.

Under the same conditions, with a nominal supply voltage of 42 V, the switchable load increases to 600 - 1400 W continuous. This means that in a 42 V system, switches using this assembly technology are able to switch the maximum conceivable loads, approx. 1500 W continuous and transient peaks of between 3000 - 4000 W. To sum up, switches with 1 mΩ on-state resistance and the new assembly technology this entails are not absolutely essential in a 42 V automotive electrical system. Present-day assembly technologies are adequate for producing power switches for the year 2005.

7. Voltage definition of future power semiconductors in 42 V and 14 V systems

After discussing the advantages and the implications of introducing a new automotive electrical system in general terms, we now need to address the specific question of how future power semiconductors are actually to be defined if they are to meet the new voltage requirements. The basis for this is the "Draft Specification of a Dual Voltage Vehicle Electrical Power System 42 V/14 V" produced by Mercedes-Benz and BMW and presented at the Consortium of Advanced Automotive Electrical/Electronic Components and Systems[5)] in Boston.

According to the concept presented, the overvoltages and voltage dips occurring in the new electrical system will be much more narrowly specified than in today's systems. For the 42 V system with a nominal voltage of 43 V with the engine running, an upper limit of 52 V for static overvoltages will be permitted. High-energy dynamic overvoltages, e.g. in a load dump, are limited to a maximum of 55 V by active or passive measures (see Fig. 6). Voltage may drop to min. 33 V as a result of load peaks or when the engine is off, to a min. of 25 V on starting. The specification quoted above does not make any reference to the permitted temperature range. In the following, we will assume a range of -40°C to 150°C, the normal convention in the automotive sector.

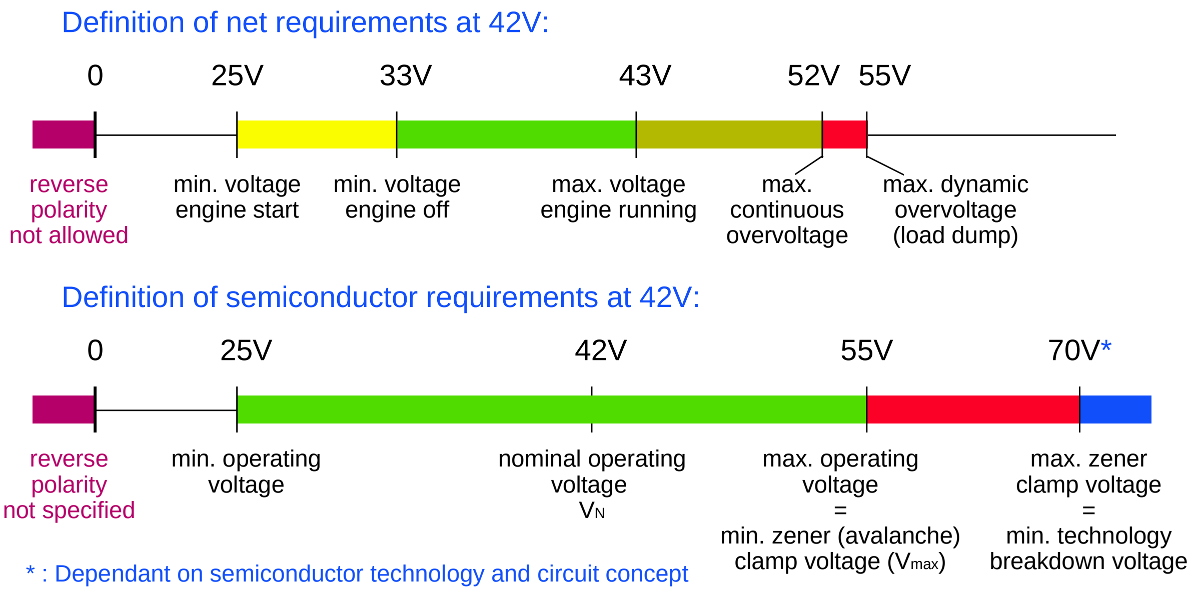

Fig. 6: Voltage definition of future power switches for the 42 V system

From the requirements given in the specification for the vehicle electrical system we can ascertain the voltage requirements to be satisfied by future power semiconductors. It is desirable for a power switch to be able to operate over the full range of operating voltages without any malfunction. Hence the proposal that 25 V to 55 V be chosen as the range of operating voltages for these switches; this is technically feasible. Above 55 V, the self-protection measures of the switch for low-energy dynamic overvoltages (such as occur when switching inductances) come into play. For standard FET switches operated in the avalanche range, this yields a minimum technology-dependent breakdown voltage of 55 V to 60 V. In smart switches with active zener clamping, a minimum technology breakdown voltage of approx. 70 V can be derived for the whole temperature range. Switches for today's automotive electrical systems are often produced with technology breakdown voltages of approx. 60 V. As mentioned earlier, upgrading from 60 V to 70 V is feasible at any time and can be done when new technologies are introduced. It is quite clear, however, that today's technology voltage is capable of producing tomorrow's switches, with enormous potential for achieving savings as a result of the reduced currents.

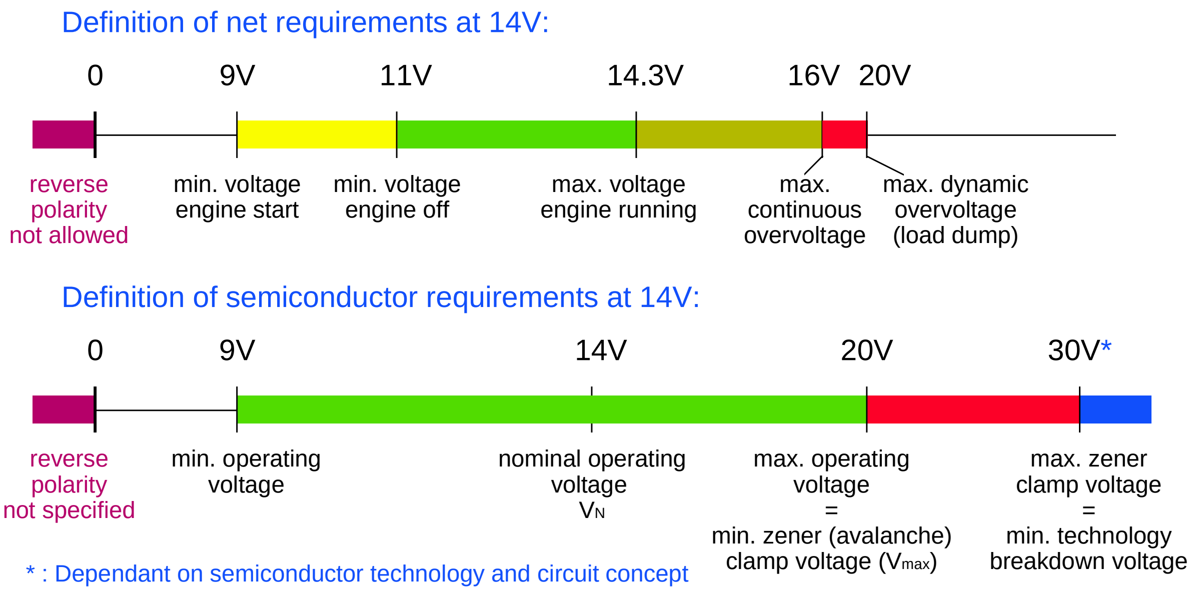

Fig. 7: Voltage definition of future power switches for the 14 V system

The implications are the same for the 14 V electrical system (cf. Figure 7). The required voltage range in the new 14 V system has been significantly narrowed by the elimination both of voltage dips on starting and overvoltages which occur in classic load dump situations. The static voltage range is specified as 9 V to 16 V. Dynamic, high-energy overvoltages are specified as 20 V max. For power components designed specifically for this system, the desirable operating voltage range is therefore 9 V to 20 V, with the switches' self-protection features being triggered above 20 V. For standard FET switches operated in avalanche range, the minimum technology-dependent breakdown voltage is again in the range 20 V to 25 V. For smart switches with active zener clamping, a minimum technology breakdown voltage of around 30 V can be derived. Here too, moving from today's 60 V technology voltage to 30 V may yield further potential savings.

So far, the question of reverse polarity has not been considered at all. The need for reverse polarity protection in power switches in present 14 V automotive electrical systems imposes significant additional costs because of the current flow through the parasitic inverse diode on polarity reversal and the associated temperature rise without overtemperature protection. Efforts to eliminate polarity reversal in future automotive electrical systems by design measures are seen by semiconductor manufacturers as essential if new high-current applications are to be implemented as cost-effectively as possible. Particularly in high-current applications, and in bridge circuits, this is an aspect which determines costs.

According to the Draft Specification, the voltage ranges quoted above for automotive electrical systems of the future relate to ambient temperatures of -40°C to 85°C, for the voltage requirements of power switches a range of -40°C to 150°C was assumed for the silicon temperature.

8. Effect on conducted electromagnetic emissiom

The pulse width modulation (PWM) technique is increasingly used for controlling and regulating electrical power. PWM will play a key role, particularly with the power-hungry loads envisaged in the 42 V automotive electrical system, where optimum use of energy is another requirement. As soon as electrical loads cease to be switched on and off statically and instead are operated at a particular PWM frequency, the question of possible electromagnetic emission arises and with it the question of the possible effect on other systems. The present 14 V system can cope with PWM frequencies up to 200 Hz using comparatively simple means, but frequencies up to around 20 kHz call for more sophisticated suppression measures. However, the lower the level of disturbance, the simpler and cheaper the filter elements.

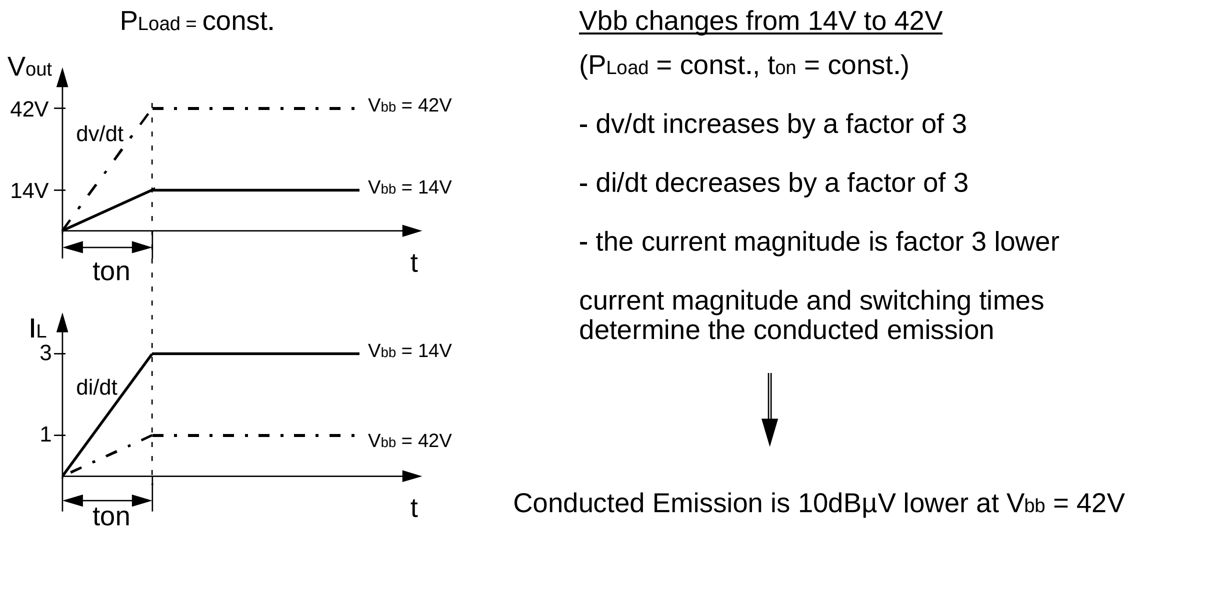

Fig. 8: Illustration of turn-on slopes for voltage and current achieving the same turn-on time with a 42 V or with a 14 V supply

In fact, changing from 14 V to 42 V, with the same power demand and the same on/off switching times, reduces conducted electromagnetic emission by approx. 10 dB. Figure 8 illustrates the correlations using the turn-on slopes for voltage and current. In order to achieve the same turn-on time with a 42 V supply as with 14 V, the rate of voltage rise has to be increased by a factor of three. In spite of this increase however, the rate of current rise decreases by a factor of three. The current amplitude is also lower by a factor of three.

The rate of current rise and current amplitude are the key factors which determine the spectrum of conducted electromagnetic interference, hence the reduction of around 10 dB in the 42 V system already noted. By analogy, the same holds true for the turn-off times and the turn-off slopes.

If we were to assume a constant rate of current rise, the switch would turn on with a rate of voltage rise nine times higher and a turn-on time three times shorter, without having any significant effect on the electromagnetic spectrum. This would be an advantage, for example, in keeping the turn-on and turn-off losses in the switch as low as possible.

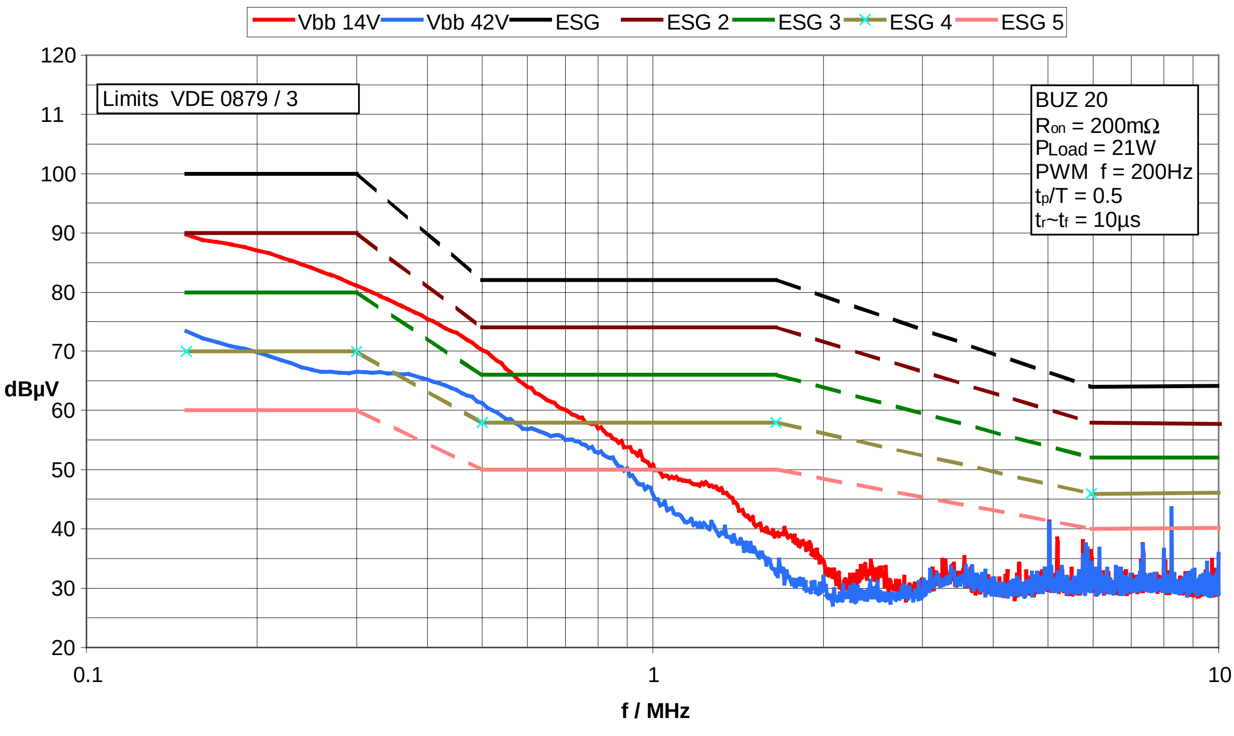

Fig. 9: Different spectra of conducted electromagnetic emission on the positive supply voltage conductor at 14 V and at 42 V supply and 200 Hz PWM frequency

Figure 9 shows the spectrum of conducted interference on the positive supply voltage conductor (V_{bb}) of a test circuit with a BUZ 20 power switch and using an ohmic load and a PWM frequency of 200 Hz with a pulse control factor of 50%. The power loss in the load was taken to be constant, P_{Load} = 21 W, for both the 14 V and the 42 V system. In both operating points, the switching times were set at 10 µs. The vehicle electrical system was replaced by a standard artificial mains network (5 µH // 50 Ω). The curve for the spectrum is quite clearly lower for the 42 V supply.

Lower switching losses or a reduction in conducted electromagnetic emissions are thus welcome secondary benefits of changing from a 14 V to a 42 V electrical system.

9. Conclusion

The introduction of an additional 42 V electrical system as discussed will open up new opportunities for the automotive industry and create an optimum environment for the use of power semiconductors. A nominal supply voltage of 42 V lies within the optimum voltage range in terms of total costs of power semiconductors, including technology, and has the effect of dramatically reducing silicon areas. With a carefully designed system, the vehicle manufacturer is in a position to minimize semiconductor costs by reducing the overvoltage requirement for the semiconductors. Thorough analysis shows that there are distinct advantages to using semiconductor switches in the future 42V system and in the new 14V system. There is no compelling need for new assembly technologies or packages, even for the most power-hungry loads in the 42 V electrical system.

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