

# Philosophy of Topology and Components Selection for Cost and Performance in Automotive Converters.

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**Abstract-** This presentation will show the relationship between power converter topology, for a rating of 2kW or more, and their cost in contemporary environmental and practical situations and propose how to achieve a robust and cost effective design for automotive industry. The discussion involves a comparison of different topologies and major power stage components and focuses on the application of the converter in hybrid and other vehicles. All this will be based on the author’s 30 years of international development experience in the automotive industry.

## I. INTRODUCTION

The goal of this presentation is to draw the attention of power electronics design engineers who work, or are going to work, for the automotive industry. The general main requirements of electronics equipments for the automotive industry are **Cost**, **Reliability**, and **Electromagnetic Compatibility** (EMI). Obviously, this subject is too big for the format of a conference paper so we will stick to the basic points. Let’s look with a narrow focus.

Power electronics is an engineering application of physics. Engineering is a tool that a company can use to make profit. When engineering is done well – the company can make a good profit, on the other hand, if engineering is not done well – then there can be problems, ranging from a lack of reliability, all the way to an engineering disaster. Therefore the total cost of a product and its development are the main focus of engineering (including after sale costs). Power electronics design starts with the selection of topology and power components that will be used.

The requirements for the automotive industry are specific and are different from industrial and commercial ones. They are much closer to military requirements but the cost must be significantly lower. Some of these requirements and conditions are common with general requirements for power supplies: some are exclusive to the automotive industry, such as reverse polarity protection, load dump over voltage from alternator, peak current up to 2900A, water resistance, and vibration. Table 1 shows the main requirement and conditions of electronic equipment for the automotive industry. Before we start to discuss real topologies, let’s see a general relationship between cost and efficiency for power converters. Fig.1

According to this curve, we need to stay in the minimum cost area. When we go too close to 100% efficiency, cost will be

TABLE I

1	Sources: battery and alternator
2	Load Dump Over voltage from alternator
3	Reverse polarity protection
4	Jump start stresses
5	High efficiency under light load and low consumption at idle and key off.
6	Peak currents up to 2900A at 12V
7	Over voltage spikes to 800V
8	Electromagnetic Compatibility
9	CAN-bus communication capability
10	Life time, reliability
11	Mechanical challenges: Water resistance and vibration
12	Operational temperature -40C to +110C
13	Development cycle time pressures

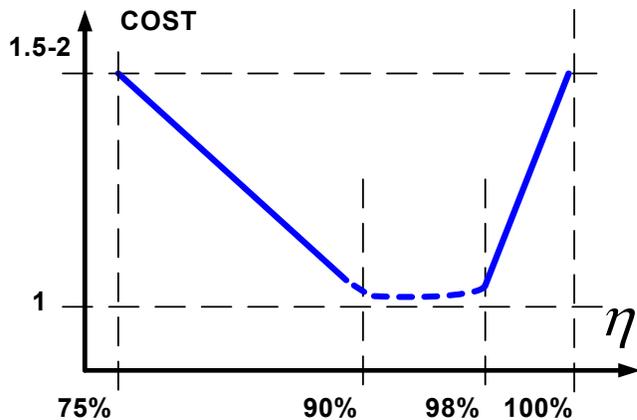


Fig.1 Relationship between cost and efficiency

extremely high. The cost effective design needs to stay between 90 to 98%, but at the same time we need to remember that efficiency itself is not the target, rather the low cost and superior performance is the target. This level efficiency can be provided only by SMPS. The switch itself can be hard-switching or soft-switching. Hard-switching itself is simple but it has a major disadvantage: high stress on the semiconductor at the time of switching. That requires the use of more powerful semiconductors in order to stay in the SOA. Hard-switching has a collateral effect of high level of EMI. Soft-switching is more complicated but it has very small switching losses and significant reduction in the level of EMI. Also soft-switching

helps packaging of control together with power stage, by significantly reducing interference. Finally: General design which uses soft-switch technology will have a cost reduction compared to hard-switch technology. That's way we use soft-switch technology.

II. ALTERNATOR AND THE DYNAMIC INVERTER

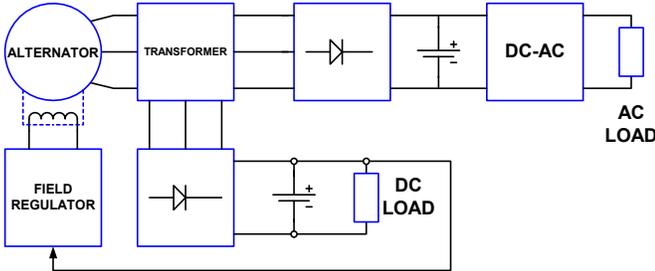


Fig.2 A block diagram of a dynamic inverter

One characteristic of the automotive industry is that the alternator of a vehicle is the source of energy. This source has a slow response time that creates many problems when we use an alternator as a source for the dynamic inverter. Fig.2 shows a block diagram of a dynamic inverter. This inverter needs to provide power for many kinds of load, preferably with fast response time. Vanner Inc. manufactures two dynamic inverters based on the same topology: an old traditional design and a modification of that, which is relatively new.

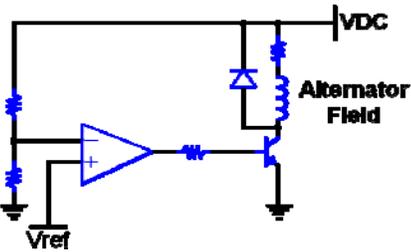


Fig.3 A simplified regulator for a traditional inverter

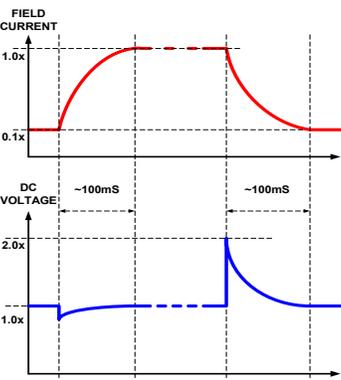


Fig.4 A response time and voltage of traditional field regulator

The traditional design has a 6kW inverter and a large alternator. The modified design has a 3kW inverter and a small alternator, but can provide start and running for a more powerful load and it costs less than the traditional one. The cost

of the modified inverter is 17% lower relative to the cost of the traditional inverter. We use a different topology in modified inverter for alternator field excitations than in the traditional design. Fig.3 shows a simplified field regulator for a traditional inverter.

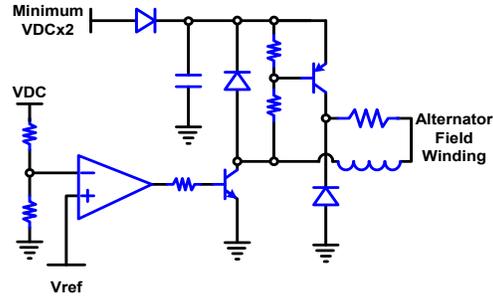


Fig.5 A simplified new topology for a field regulator

In this case, a response time is up to 100ms and there is a big voltage overshoot (Fig.4) when heavy load is disconnected. Fig.5 shows simplified new topology for a field regulator of alternator. [1] With this topology, we have a faster response time and a significant reduction in overshoot voltage on the DC

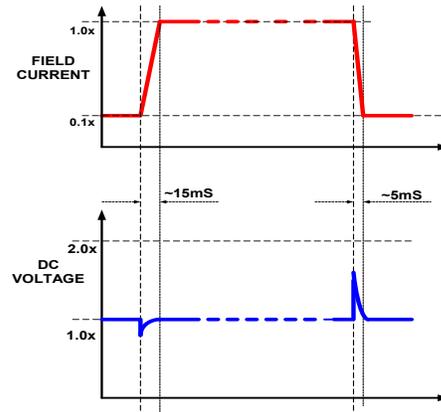


Fig.6 A response time and voltage of Modified field regulator

link that reduces stress for other components. In other words, this increases the reliability of the whole system of the vehicle. Finally we have reduced electrical stress, improved response. DC-AC inverter of the modified design has ZCS turn-on technology. This way, efficiency improves and there is a cost reduction of the package and EMI filter. The overall result is a reduced cost for the customer.

III. DC-AC INVERTER

New DC-AC (Fig.7) inverter has complete soft-switch technology and higher efficiency, around 97% with commutation frequency of 40kHz. [2,3] Soft-switch technology

helps us to reach higher commutation frequency which reduces the size of the filter, and finally we get a cost reduction. Now the next question: which soft-switch technology can we use in this case? Let's see a comparison between our new DC-AC inverter and DC-AC inverter with an auxiliary resonant commutated pole Fig.8 We decided to make this comparison

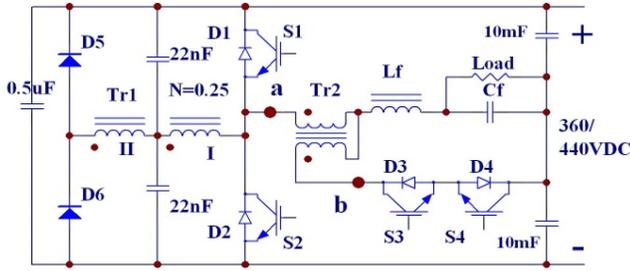


Fig.7 New DC-AC inverter

because both inverters have the same main electrical performance: efficiency, electromagnetic emissions, and commutation frequency. But the inverter with an auxiliary resonant commutated pole has a higher cost around 2-3%, and reduced reliability. This is because the inverter with an auxiliary resonant commutated pole has additional active switches which require more complicated control and additional gate drivers. Designs with the auxiliary resonant commutated pole were developed for inverters which use SCRs. At the present time for this purpose they use IGBT.

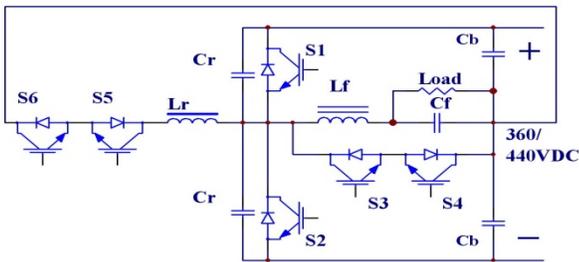


Fig.8 DC-AC inverter with ARCP

That's why a design engineer needs to have a good justification to use an auxiliary resonant commutated pole. The new components require the use of new techniques and this is important for the automotive industry where a long product lifetime is expected and obsolescence will create problems. One more point is about a DC-AC converter which is used for motor drive in hybrid and electrical vehicles. When DC-AC converter is used without a filter, cables which provide connections between a converter and motor can be sources of EMI. Longer cable will have higher level of EMI. For EMI reduction we need to use a special shielding of cables. Cost of this shielding can reach 30% of the converter price. Cost of filters can be up to 10% of the converter price. All this shows

how we need carefully to choose a configuration of the power stage and particularly in this case pay attention that the converter itself cannot be alone. The converter and motor should be looked at as one integrated power stage. We need to see the whole picture from the start to the end. Only this way can we get a good cost with optimal performance.

#### IV. DC-DC CONVERTER

Now let's speak about an isolated DC-DC converter which is more popular now on hybrid vehicles. Table2 shows the basic specifications of a new product from Vanner Inc. a bi-directional DC-DC converter. While developing this converter, we decided to reduce efficiency by 2%. This reduction helped us to reduce cost by 15%. This was done by changing components and packaging. In this converter, we use our proprietary topology Fig.9.[4,5,6,7,,9]

TABLE II

The basic specifications of DC-DC converter

High voltage side: 500VDC-800VDC
Low voltage side: 20VDC-30VDC @300A
Operational temperature: -40C to +70C @ full power
Efficiency 94% excluding reverse polarity protection and pre-charge (93% with)
Efficiency 84% @ 5% load
Consumption @ idle 60W
Life time minimum 7 years
Cost for customer equivalent to conventional alternator

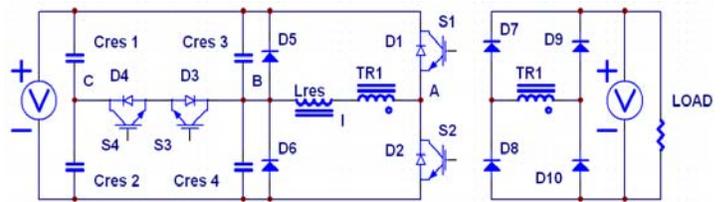


Fig.9 The topology of new DC-DC converter

We made a comparison between our topology and phase-shift topology Table 3. We made this comparison with the assumption that all topologies have the same efficiency, output power 4kW and input and output voltage, with output current above 100A. The main advantages which help us achieve cost reduction are the following: the power transformer works in optimal conditions, approximately a trapezoidal waveform with roughly constant RMS voltage regardless of the input voltage. The current carried by the winding is almost sinusoidal with a duty cycle of 90% and does not change with the input voltage. This is an advantage when considering transformer losses, and along with the fact that the new topology can reach higher

TABLE III

Comparisons Phase-shift topology and New topology

Parameters	Phase-Sh	New
Max. com. freq.	1x	2x
Load range	Limited	Unlimited
Commutation	ZVS	ZVS,ZCS
Rectifier recovery	Recovery losses	Optimal
Transformer	Not optimal	Optimal
DC-bias	Yes	No
Control	Standard	Special
Idle Losses	1.5%	0.15%
COST	Basis	Basis minus 10%

commutation frequency, significantly helps to reduce the size of the transformer, decreases price, and increases the transformer's efficiency. The rectifier works with ZCS commutation and without an inductor and with a duty cycle of 90%. When we have an output current of 100A and more, the output rectifier with an inductive filter is not a good solution because the inductor itself is not cheap. There will be hard switching of rectifier diodes which will increase energy losses and EMI, and, as a result, increase cost. In this case resonant topologies with ZCS are preferable. The next very important point is what power magnetic components we need to use. During the last 15 years, we can see how the cost of power semiconductors went down and the cost of copper went up. This trend will continue. Therefore any topologies which use the transformer inefficiently (like push-pull) or with two or more power transformers, will not be considered, (although they could be viable if there are special requirements such as a space application, etcetera.) This is the first point: to use a topology where the transformer works under optimal conditions. For our converter, we developed a power transformer which is a physical part of the power stage which also uses SMA with a maximum constant current of 300ADC.[8] Full integration of a power transformer into the power stage has very strong benefits when we have a current of 100A and more. We made a comparison of our transformer with a planar transformer with the same conditions (110kHz 280A output). The planar transformer has a price which is 20% higher than our transformer and 2% lower efficiency. Efficiency is reduced because the planar transformer has not enough contact area for 280A. If the contact of the area increases, the cost will increase too. This is a second point: the transformer itself cannot be useful alone. It can be used only as part of the whole power stage. That's why when you make a package design you need to see the whole picture.

## V. SEMICONDUCTORS

At the heart of a power converter are the power semiconductors. Clearly, the main types of power

semiconductors used in the automotive industry are MOSFETs, IGBTs and Bipolar transistors. For automotive applications it is preferable to use semiconductors with a gate threshold voltage of 2-4V or higher. With a lower gate threshold, semiconductor reliability will be reduced or the cost of the gate drive will increase significantly. That is why we do not consider semiconductors with logic level threshold or GaN type devices. GaN has the additional penalty of high cost. This raises the question: what semiconductor can we use and how can we use them? For low voltage, below 200V, obviously a MOSFET is straightforward to use. For high voltage we have a choice: MOSFETs, IGBTs, Bipolar transistors, or a combination thereof. In this case there are many options, but we would like to examine one option and make a comparison. For high voltage (1200V or higher) and high current, it is very reasonable to use an Emitter Switched Bipolar Transistor (ESBT), see Fig.10. [10,11,12]



Fig.10 ESBT symbol and equivalent circuit, cascade connection

This configuration has many advantages: it has very low conduction and switching losses, it is useful for high commutation frequency (up to 150kHz) and has a very reasonable cost. A disadvantage is that it is not simple to drive. Let us make a comparison of an ESBT and SiC transistor. An SiC Half-Bridge module (CAS100H12AM1) costs \$360. A Half-Bridge using an ESBT (STE70IE120) has similar specifications to the CAS100H12AM1 but costs \$120 (cost includes 4 transistors, 2 anti-parallel diodes and 2 current transformers). Unfortunately the STE70IE120 is obsolete. ST has explained that there was a very low demand from design engineers. We show here only one way how a design engineer may use cost effective semiconductors and not raise hopes that there might be a magic semiconductor.

## VI. EMI and RELIABILITY

During the last 15 years the EMI requirements for electronic units for automotive applications has become more stringent, from CISPR25 class 2 to class 4. The main reason is the demand for compatibility. A contemporary vehicle has many electronics units on board and the tendency is for these numbers to grow. In other words each unit need to operate without interfering with other units on the vehicle. I would like to remind you, that, soft-switching significantly reduces the level of EMI and, as a result, there will be a reduction in the cost of the EMI filter. Therefore we discuss only soft-switch

technology. The next point about EMI is the slew rate of voltage. This slew rate shouldn't be higher than 2500V/uS, and it's better when it is 1500V/uS or less. In this case, EMI will be reduced, reliability will be increased, and the cost of the EMI filter itself and shielding will be reduced. Also we need to pay attention to reliability. Troubleshooting is included in the cost of the product. If the product is more reliable, it results in a cost reduction of the product for the customer. In the automotive industry this requirement is much stronger because of the price of troubleshooting is much higher than in the industrial and commercial markets. That's why more reliable design is preferable. For example: resonant topologies with clamp diodes provide passive power limiting. In other words, they will be more reliable during transient conditions. The cost of a converter rises rapidly depending on the number of active switches. Control gets more complicated and reliability goes down, so a multi level configuration, series connections of semiconductors are acceptable only when the source voltage is high, above 1000VDC. We can say almost the same about switching capacitors and multi-phase topologies for DC-AC and DC-DC converters.

## VII. SUMMARIZE

Now we can summarize the rules of the Vanner engineering department in establishing the norms for new product development in order to keep a cost effective design:

- Efficiency target: 92-98% The efficiency itself is not the target, rather the low cost and superior performance
  - Use soft-switch technology
  - Minimum of active components
  - Reduced quantity, and simply constructed, magnetic components
  - Use integrated magnetic components
  - Use SMA where possible
  - Simple assembly for low labor content
  - Minimize interconnections
- Use strategies to minimize system transients
  - When rectifier current is higher than 100A use only ZCS commutation, without an inductive filter
  - Use multi-level topology only when voltage is above 1000VDC
  - Limit slew rate to 2500V/uS
  - Use standard surface mount components to optimize assembly
  - Keep operating frequency high to minimize the filter
  - Maximize board mounting, minimize chassis mounting  
In other words packaging is key to realizing the benefits of the topology

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