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The resurrection of GTOs and Thyristors as core components in MW-Charger-application and railway/mining refurbishment

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Abstract

Trains and electric infrastructure are precious parts of our transportation network today and have been so in the recent decades. For the upcoming charging infrastructure in the MW-regime, thyristors should be considered as a solution to compete with MOSFETs or IGBTs. After decades in operation, trains as well as infrastructure needs to be refurbished or replaced. Refurbishment is the more sustainable approach but sourcing suitable components like GTOs gets more and more challenging. This work is meant to highlight, that those apparently "old" technologies still must be considered to achieve the best possible result in the dedicated application.

1 High-Power Commercial vehicle charging

Growingly restrictive regulations regarding emissions are driving the development of electric heavy-duty vehicles. In-city or last-mile logistics as well as buses for urban transportation benefit from shorter distances to be covered per day, leading to battery-electric vehicles that can do 200 to 300km per charge. Fleet operators can align operating and charging hours, so that recharging can be done at night, in a time frame that allows charging at power levels similar to those used for passenger cars today.
State-of-the-art charging hardware can support up to 350kW. Such power is sufficient to conduct the often referred 80%-charge of a 300kWh battery in about 40 minutes, resembling the driver's lunch break. As a rule of thumb, heavy-duty vehicles consume about 2kWh per kilometer, so recharging 150km in less than one hour can be achieved.
With the dawn of autonomous vehicles and the demand to use battery-electric trucks in long-haul operation as well, it is foreseeable that operators demand faster options.
To reduce waiting times, charging standards for commercial vehicles were updated to achieve power levels of 2.5MW, optionally opening the path to even achieve 4.5MW.

Fig. 1 depicts the comparison between High-Power Charging (HPC) for passenger cars and High-Power Charging for Commercial Vehicles (HPCCV)

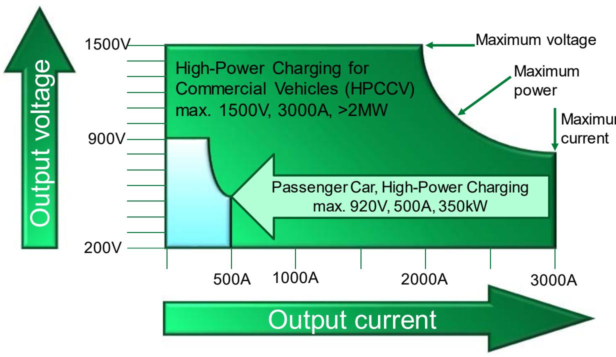

Fig. 1 Comparison of charging parameters for passenger cars and commercial vehicles

1.1 State-of-the-art

Today, increasing the output power levels of a charging infrastructure considers paralleling of modular units. These subunits individually provide power levels of up to 60 kW each.
The classical approach consists of subunits with an input rectifier, followed by a DC-DC-conversion stage that adapts the output voltage to the battery's requirements and control the charging current.

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With SiC-MOSFETs, a Vienna Rectifier as input stage built from 1200 V-devices becomes option. **Fig. *2*** gives an overview of a charger's power stage designed for 60 kW. Even with the two energy conversion stages, the use of silicon carbide (SiC) MOSFETs and SiC-diodes in dedicated parts of the schematic leads to a conversion efficiency of up to 97%, depending on the point of operation.

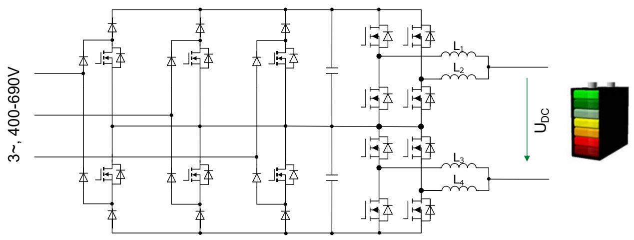
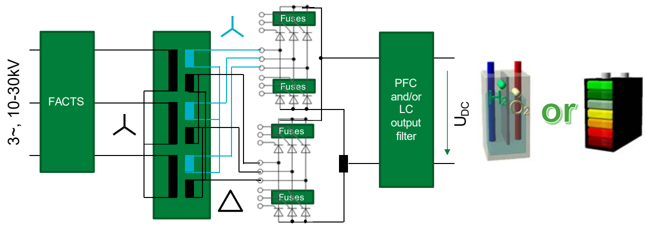


Fig. 2 Classical high-efficiency DC-Charger arrangement based on 1200 V SiC-MOSFETs

To achieve 2.5 MW in such an approach as targeted for HPCCV, 42 subunits of 60 kW each would need to be paralleled.
Most compact designs of such power sections today feature a 19' inch or 483 mm width to be mounted in standard industrial racks. In case of high-performance cold plates, the height can be as low as 2HU or ~90 mm and a length of ~880mm results.
The approach also allows for a high level of redundancy and increases the infrastructure's availability. At the same time, it leads to an inconvenient setup and massive efforts in logistics, control, and potential disassembly in case of maintenance.
It is obvious, that power levels in the MW-domain can only be taken from the medium-voltage grid, making a high-power medium-voltage transformer and grid-sided filters a necessity. This differentiates commercial vehicle charging from passenger car charging where power for a single 350 kW charging station can still be taken from the 400 V-grid directly or can be achieved by stationary buffer-batteries.
Galvanic isolation, preferred by the charging standards, is displaced into the medium-voltage transformer and thus not part of the DC-DC-stage.
Other than in charging passenger cars, the output voltage for commercial vehicle charging is expected to grow up to 1500 V soon, which demands an upgrade of the power semiconductors to the 1700 V-class at least or to change to multi-level designs to cope with the higher DC-voltage requirements. In turn, higher conduction losses within the given setup can be expected.

1.2 Solution based on thyristors

Instead of paralleling a multitude of units to achieve higher power, the well-established B12C-topology based on thyristors as sketched in **Error! Reference source not found.** can be



considered.

Fig. 3 MW-Charger based on B12C-Topology

Beneficially, only two stacks that each form a fully controlled bridge rectifier (B6C) are needed to form a single-stage energy-conversion as currently widely used in electrolysis. As in battery charging, this application demands the fulfillment of similar requirements regarding DC-voltage stability and DC-current control.
Fig. 4 displays the dual-thyristor stack to form the B12C-topology

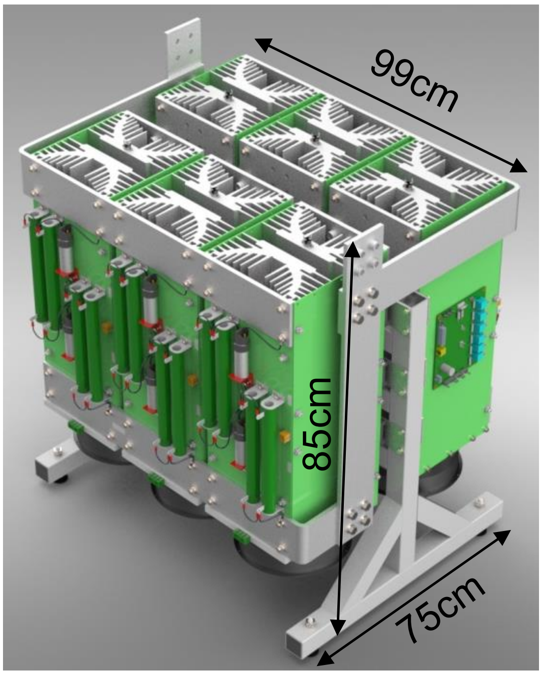


Fig. 4 Fully controlled B12C rectifier stack to support 2.5MW-Charging

The two B6C-units included can be paralleled for higher current or series-connected for higher voltage and are based on Littelfuse's N3620TE360.

In contrast to the 97% efficiency achieved by the SiC-MOSFET-based approach given in **Fig. 2**, this setup can far exceed 99% efficiency, depending on the control scheme in use.
Simulation results based on PLECS substantiate that a design based on an even smaller high-power thyristor type N1718NC200 which is rated 1700 A/2000 V [1] leads to losses of 380 W per switch or 2280 W in each of the B6C-rectifier stacks at an output of 1000 V and 1000 A.
In the combined operation of two stacks, this resembles an output power of 2 MW with only 4560W of losses. This equals into an efficiency of 99.77 % in the conversion stage.
At the same time, the thyristor-based system reduces the amount of resources per kilowatt installed. The picture in Fig. 5 is a comparison of the component sizes, needed to set up a 2.5 MW charging hardware, drawn to scale.

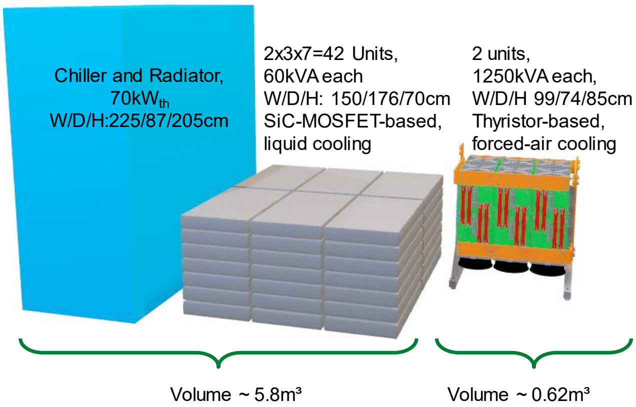


Fig. 5 Comparison of volumes for 2.5 MW charging hardware in different technologies

Furthermore, the lower number of power components, interconnections as well as the absence of a liquid cooling system reduces system complexity and cost for energy in cooling.
In case a liquid cooling system is needed for other parts of the charging station like cables or connectors, using it for the thyristor stacks as well could reduce the size and weight of the stacks and the expanses for cooling further.
Additional advantages arise from the longevity of disk-type devices in regards of cyclic thermal load. Thyristors have a track-record with unprecedented reliability and decades of operation in the field which is a prerequisite in infrastructure.
In contrast to this, SiC-MOSFETs today are even less durable in regards of cyclic thermal loads than IGBT-based power modules [2]. Therefore, fulfilling the restrictive lifetime demands would require further oversizing of the power component in place to reduce the chips' junction temperature swing.

1.3 Scale of the impact

Based on the recently announced project of setting up 1700 high-power chargers [3], an estimation can be done regarding the benefits of the more efficient solution.
If each of the chargers operates 24/7 and handles three vehicles per hour, 10 minutes each to transfer 400kWh, the energy consumption and losses as given in **Table 1** result.

		Liquid Cooling, SiC-MOSFET	Forced-Air cooling Si-Thyristors
Cooling	Power per charger [kW]	22	0.6
	Energy per year per charger [kWh]	95000	2600
	Energy cost per charger [€/year] @ 0.1€/kWh	9500	260
	Money spent, 1700 chargers [€/year]	16.150.000	442.000
Operation	Losses, single charge [kWh]	12.5	1.25
	Energy lost in 1700 chargers per year [kWh]	558.450.000	558.450
	Losses in 1700 chargers per year [€]	55.845.000	5.584.500
	Money saved per year [€]	-	**65.968.500**

Table 1 Comparing SiC-MOSFET and Thyristor-based solutions regarding cost of operation

With SiC-MOSFETs, the efficiency can be boosted by paralleling a larger number of devices which in turn increases the cost as well as the size of the charging hardware, making the approach even less attractive.
In case liquid cooling is available for other components and utilized for the thyristor stack, cost for cooling can be reduced further.

2 Sustainability by refurbishment

In regards of efficient use of money, time, and resources, maintaining the available hardware is the best potential option.

2.1 Refurbishment in railway traction

According to the German Federal Railway Authority [4], several thousand rail cars are in service in Europe today, that demand a continuous supply of reliable semiconductors for refurbishment in the years ahead.
The Bombardier Traxx-Family, for example the E464 in Italy, contributes a large number of railcars with drivetrains based on GTO-technology.
To keep this fleet in operation for the decades ahead, a safe supply of high-performance GTOs is a mandatory requirement. Further fleets currently in operation face the same issue.
With four to five million Euro per piece, railcars that carry the drive train are costly parts in the railway transportation sector. Their mechanical robust construction targets a service lifetime of 20 to 25 years at least which can be extended by regular maintenance.
Besides the mechanical parts, the power electronic components as well suffer from wear. These components as such can't be refurbished and need to be replaced.
Replacement in power electronics often is taken as an opportunity to upgrade the power conversion units. More efficient power semiconductors or more precise control within the application are driving factors in different industries.
In railway traction applications, such a change in the drive train's structure voids the certification of the hardware. In turn, the operating license expires, and a re-qualification and certification becomes mandatory. As this is an expensive and time-consuming procedure, refurbishment of the converter units with components that comply with the ones initially used and qualified is an often-preferred solution.
The remaining challenge for the designer is, that production of components like GTOs or fast-switching thyristors has been discontinued by most of the former manufacturers.
Obsolescence management by storing larger numbers of these components wasn't considered when GTOs had their heyday back in the 1970s and 1980s.
Currently, even re-development of obsolete components by reverse-engineering of remaining parts is an ongoing process to support the railway industry and their OEMs.
The German Railway commissioned the first generation of Inter-City Express trains (ICE1) back in 1991 with an expected service time of 25 years [5]. The GTO-based units in the rail cars, after ongoing refurbishment, will remain in service for at least the next two decades, extending the service-life of these trains to 50 years before decommissioning.

The picture seen in Fig. 6 displays the recently rebuilt power converter for these classes of trains [6].

Fig. 6 Power converter cabinets for the German ICE1 and ICE2, detailing the GTO in use

Similarly, the Swiss Rail still operates a fleet of almost 300 rail cars, type RE420. These were taken into operation starting in 1964 and are expected to remain on duty for further decades.

2.2 Mining Trucks

Other transportation sectors with focus on mobile high-power applications include, cranes, construction machines and heavy-duty mining dumpsters.

Regarding the drive train, mining dump-trucks can be considered rail cars on rubber wheels. Their diesel-electric setup often is a derivate of a rail car's equipment, adapted to the specific needs in mining enterprises. Here too, prolonging the time in service by refurbishment cuts investment, development, and qualification cost.
Fig. 7 is an insight into refurbishing such a truck, showing the diesel-engine and the inverter cabinet.

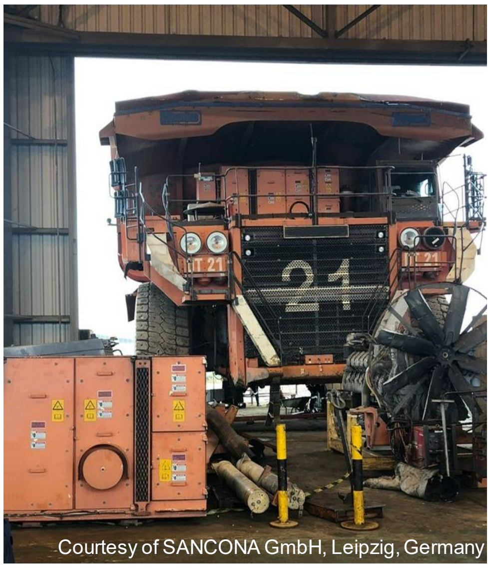


Fig. 7 Mining truck during refurbishment

As the use-case inherently means operation in remote areas, uptime and reliability is of utmost importance. Here, a thyristor or GTO-based solution allows using a converter-structure in a so-called n+1 design. In addition to each semiconductor needed, a redundant one is put in place. Due to the guaranteed short-on-fail-feature, a disc-style device becomes a reliable connection in case of failure [7]. A redundant device instantly replaces the one failed, keeping the truck operational and allows scheduling maintenance within planned idle times.
As disc-devices are hermetically sealed, they tend to be more robust than power modules especially in harsh climatic and environmental situations. Their superior durability in regards of thermal cyclic load adds to the benefits. Therefore, replacing a thyristor- or GTO-based drivetrain using an IGBT-module-based version is not a preferred option in refurbishment.
The picture in **Fig. 8** is a view into a refurbished inverter cabinet, carrying two traction inverters.

Fig. 8 Traction Inverter cabinet after refurbishment

3 Summary

A close look into all details of an application is mandatory to find the most suitable power-electronic solution. Though power electronic is often considered scalable, considering a change in topology and technology instead of doing more-of-the-same can bring unexpected benefits. For high-power chargers in the MW-regime, solutions based on thyristor technology may be superior, even to modern solutions based on wide band gap materials like silicon carbide.
At the same time, for extrinsic reasons, upgrading an existing system to newer technologies, even if technically feasible, is not inherently a desirable option.
Refurbishment, based on the technology used when commissioning the systems, is a highly viable option. This is especially the case in high-power applications with restrictive demands in availability and uptime like infrastructure, railway-traction and the heavy-duty commercial vehicle sector.

4 Acknowledgments

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