Progress report: Literature review
Week 33

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Version 1.0

- **Goal:**

  Aggregated literature review

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- **Notes:**

1. Introduction

This chapter summarizes some aspects of the ongoing debate about the future of the electrical power distribution and the role of the power electronic devices in it. The goal of this chapter is to help to understand what is low voltage DC distribution and what is the role of power electronic devices in it.

This summary of the state of the research in the area is a corner stone for a future research on the components of the low voltage DC distribution.

Royal Geographical Society of the United Kingdom is running a programme of discussions and accompanying resources called 21st Century Challenges. The aim of the program is to inform about and promote the challenges the UK is facing. However, upon quick scan of these challenges, one must realize, that they are of rather global nature. Almost random examples are: Low carbon energy, Climate change, Sustainability, Manufacturing, Economic growth, Energy-water-food stress nexus, Urbanisation, Energy for development[1].

It is evident from almost randomly chosen challenges,that all are in one way or the other connected to the problem of generation and distribution of electrical energy. To illustrate the importance of the electrical energy to the economic growth we can compare the total of global electricity consumption in 2000, which was 15,400 TWh, to a projection of total electricity consumption in 2020 of 27,000 TWh [30]. These projections were made based on the steep rise of energy usage in European Union after 2000. However, the reality is somewhat different and we can see a decrease in the energy use in Fig. 1.

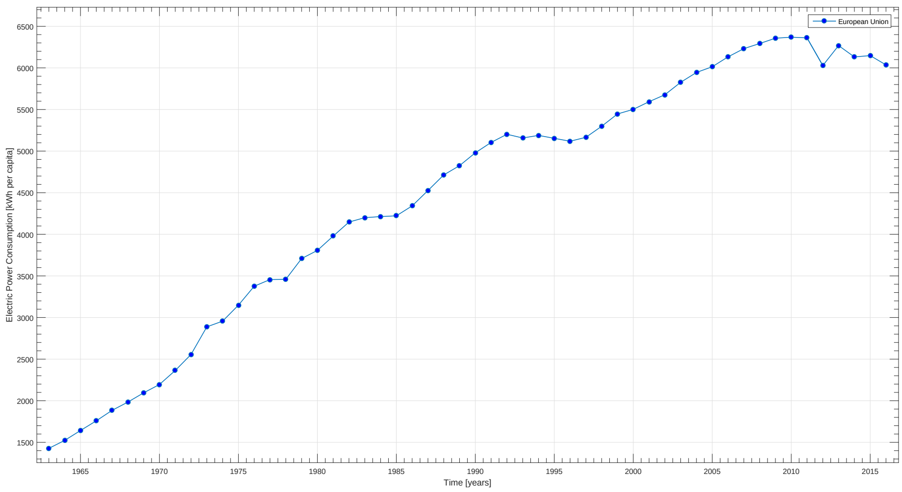


Figure 1: Electric power consumption measures the production of power plants and combined heat and power plants less transmission, distribution, and transformation losses and own use by heat and power plants.Source:

[1]Source:https://21stcenturychallenges.org/discover/

It cannot be concluded whether the decrease in the use of the electrical energy is due to economic situation or simply because more efficient electrical solutions are being used. Considering the fact that the overal trend over past 60 years was increasing and there always were few dips in the energy use for couple of years this might be the case. Thus this short term dip should not comfort us too much.

2. Mega-trends pulling the technology development

The megatrends are large, transformative global forces that define the future by having a far-reaching impact on business, economies, industries,societies and individuals [24]. In this report we are particularly interested in those megatrends that have more or less direct impact on the development of the electrical power distribution system. The main trends that can be identified are growing penetration of renewable energy sources, growing urbanization and decarbonizing the economy.

Producing the electrical energy and not compromise the prospects of the future generation for a decent life in the process requires large penetration of the renewable energy sources(RES). From Fig. 2 it can be concluded that the RES are penetrating to the electrical energy production market relatively fast. However, there is the other side of the coin. That is the nature of the RES. The renewable energy sources are diffuse in nature, which makes them distributed over large geographical areas. Furthermore, the renewable energy sources are also intermittent,meaning that the energy is dispersed over time periods.

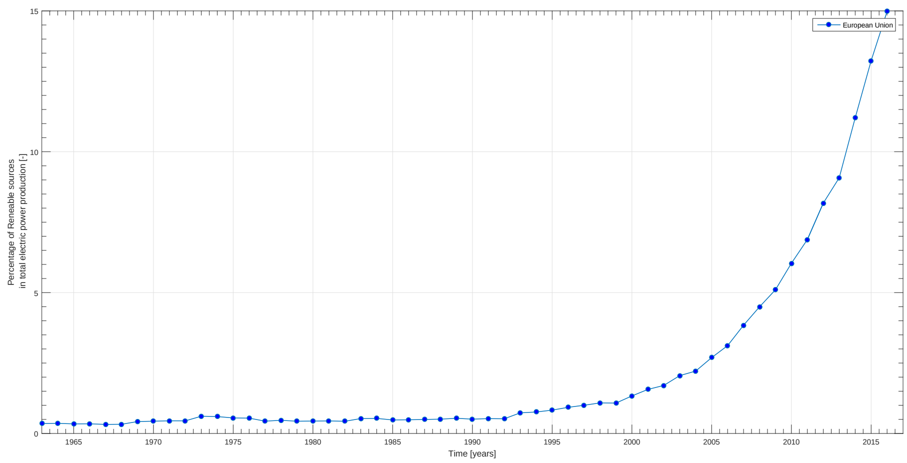


Figure 2: Electricity production from renewable sources, excluding hydroelectric, includes geothermal, solar, tides, wind, biomass, and biofuels.

With higher penetration of renewable energy sources new challenges arise for the power distribution systems. The power systems for electricity distribution were designed to for a situation with strictly defined power flow, and centralized power production. It has been discussed that high penetration of distributed energy sources can lead to overloading of the power distribution systems [30]. Therefore, in order to utilize more of the renewable energy sources the power distribution system needs an upgrade to become more flexible in its topology to allow for multi-directional flow of power both in space and time [19].

Naturally, the energy storage can smooth out the peaks in power production and consumption [59], but it does not influence the reached conclusion about the flexibility of the network. Rather on the other hand, it is already clear that when multiple car chargers are connected, several problems can occur to the grid [97].

The growing urbanization creates further challenges for the society [75]. These challenges are for most part rather unknown to the society. Simply because in 1950 there were only two urban centers with more than 10 million inhabitants in 2015 there were 29 and in 2030 there will be 41 [75]. To have a better grasp of these numbers, in 2015 more than 50% of the popullation lived in the cities, by the 2030 it will be around 75 % [75]. The aglomartions in China will soon hit the milestone of 50 million inhabitants.

The growing number of inhabitants in small area means higher concentration of loads [30]. In combination with the fact that most of the loads installed in the modern cities are of capacitive and non-linear nature [10] a strong need is created for significant over dimensioning of the distribution grid. However, this is contradicting the need for more sustainable society with lower CO_2 emissions. One of the reasons is that the grid is dependent on the use of steel and aluminium [2].

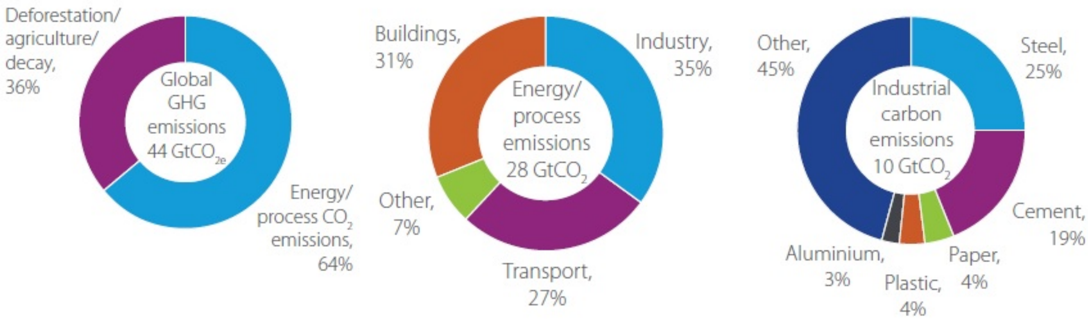


Figure 3: Pie charts showing the sources of global CO_2 emissions.Source: [2].

These trends clearly represent a strong pull for the technology innovation. The future distribution grid is going to work in completely different environment and different context. Thus it is obvious that the time is ripe to rethink the toplevel architecture of the power distribution. The product design for the near future power distribution grid will need to be very compact, scalable, with small footprint [30] which will allow bi-directional flow of power and storage of energy.

3. Microgrids

Definition Microgrids are electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while is landed.[2] [63]

The microgrid is can be used to describe a conceptual solution for the integration of renewable energy sources(RES), energy storage(ES) in such way that it minimizes the architectural changes and operational disruptions to the existing power grid [54]. The concept of the microgrid has several distinguishing features [12]:

- at least a minimal level of local energy generation and/or storage
- interface(s) to the higher level system through bidirectional electronic power converter(s)
- ability to operate in islanded mode, at least during transients
- all energy sources and storage connected through electronic power converters
- most loads connected through electronic power converters
- extensive communication and control capabilities, both internally and externally
- most (possibly all) protection and reconfiguration functions provided by the electronic power converters, with- out the use of thermo-mechanical switchgear
- step-up/down and isolation functions provided by the electronic power converters without the use of low- frequency transformers

The research in microgrid and the fact that the microgrids are decoupled from the main grid, brought up a century old debate-AC vs. DC distribution. The microgrid concept when utilizing AC or DC has some common features:

- net-metering,communication, remote control
- energy sustainable powered by RES

[2]CIGRE C6.22 Working Group, Microgrid Evolution Roadmap.

- heavily dependent on PE

  by good design of PE and proper control the net residential fuel based energy consuptiom can be drastically reduced

- grid tied operation as well as island operation

- demand-response operation and pricing

However, there can be some advanteges of the DC solution like no reactive power, or in some cases lower number of conversion steps. The next subsection will discuss these.

3.1. Why DC ?

There are several reasons why people think that DC grid might be more advantageous than the AC. One of the first reasons that comes to mind is system efficiency. In [22] the authors investigated the feasibility of the DC system for a household. The results show that the efficiency of the system is higher due to lower efficiencies of the converters. Similar comparison was done 6 years later in [72] where the authors compared the DC and AC system for the data centers. The study concludes that the efficiency gain is around 1 %. Yet, it is interesting to compare the quantified results of [72] with for example [66]. In [66] the higher efficiency of the proposed DC solution is claimed however not quantified.

The other argument is cost-effectiveness of the DC. ABB has constructed 380 V_{dc} data center in Zurich[3] in 2012. Performance tests showed that the new power distribution system is 10 percent more efficient than for comparable alternating current (AC) technology. In addition, investment costs for the system were 15 percent lower than for an AC system.

Some researchers make a step higher, and propose to switch even medium voltage(MV) transmission to DC, for example [19]. The main motivation is topology and multi-directional power flow. However, there are also researchers that bring into question the losses in AC transmission [**?**], [21]. Thus it is interesting to investigate 4 from IndexMundi[45]. As is clear from the figure, the losses are decreasing, and from previous discussion it might be concluded, that proving the efficiency might be tricky.

Other comparison of AC and DC solutions for power distribution can be found in [82], [23], [4]. In all of these publications the conclusions are rather indecisive. The common point is that the DC solution is in general more efficient and cost effective when significant amount of power is being supplied from DC sources. As noted in [23], these benefits multiply with the size of the grid.

Furthermore, there are already existing demonstration sites and special cases for DC distribution, where DC performs superior. One of such examples is point-to-point distribution for rural areas in Finland [32]. The solution is depicted in 5.

[3] http://www.abb.com/cawp/seitp202/187b2f29acaea090c1257a0e0029fb1a.aspx

[4] IndexMundi contains detailed country statistics, charts, and maps compiled from multiple sources.

[5] http://www.indexmundi.com/facts/indicators/EG.ELC.LOSS.ZS

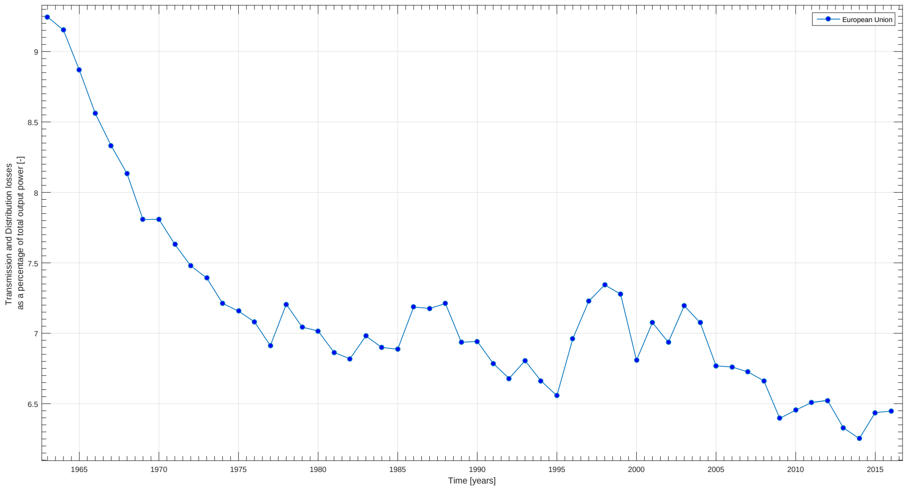


Figure 4: Electric power transmission and distribution losses include losses in transmission between sources of supply and points of distribution and in the distribution to consumers, including pilferage.

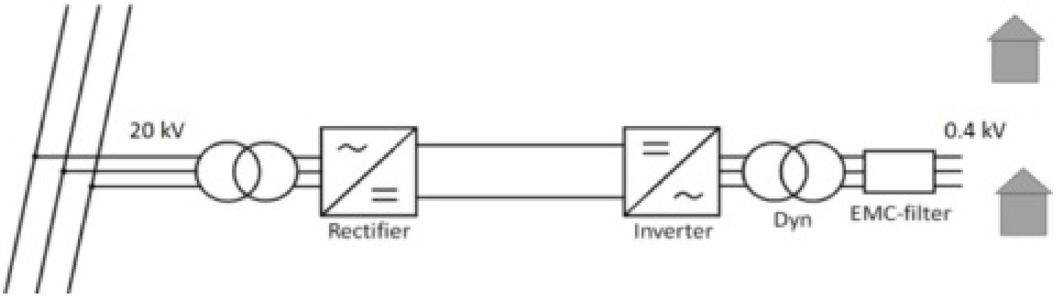


Figure 5: The point-to-point LVDC distribution system PILOT

The efficiency nor life-time are the main arguments for this solution. As it can be argued that the solution with low frequency transformer followed by AC-DC converter is the worst in terms of efficiency and initial costs as explained in [51].

Yet in Finland the DSO are considering of refurbishing the MVAC grid to LVDC grid with 900 Vdc. The reason to switch to LVDC in rural areas in Finland is the *customer outage cost of outage of an hour*. In [33] they have calculated that COC value of an average rural MV feeder when a fault is located in a branch line with a single transformer is **ten** times smaller for LVDC. And in rural Finland bad weather conditions causing outages are quite common.

There are some general advantages of the DC distribution which are transportable [41] :

- smaller cable size for given power level
- no reactive power
- "no" distance limitation in cable systems
- simpler cables

The DC can be a suitable solution for the megatrends that the society is facing now. Most of the renewable energy sources are DC, therefore with their higher penetration to the grid the efficiency gain will be higher [23]. Secondly, as was mentioned the renewables imply multi-directional power flow, for which the DC grid is much better equiped [19].

Furthermore, with the DC grids the argument of smaller amount of components is true, which may not directly reflect to reliability, but inevitably it means less maintenance. Other claim can be made with regards to the material usage. In the DC system it might be possible to use less materials both in cables but definitely in the transformers. However, I did not encounter a persuasive calculation of this influence.

Thus the DC power distribution seems to be as a viable solution, which is worth consideration.

3.2. Microgrid Architecture comparison

The previous comparison was conceptual, and did not look at how the devices are connected physically, what is the architecture of the network. In this report two architectures are omitted:

- direct battery connection- used in telecommunication, results in short battery life, and circulating currents which is unwanted. On the other hand, direct connection of battery increases the capacitance of the network. Which apparently is the only way for example DC.bv. is increasing stability of their networks.
- MultiTerminal DC MG - for very high voltage, mainly for HVDC. Although, it seems that the idea of 'meshed' DC distribution grid [62] comes from the multiterminal HVDC.

OVERVIEW OF HARDWARE TOPOLOGIES FOR DC MGS DC

DC Bus Configuration	Reported Voltage Levels [V]	Standardized Components	Direct ESS Connection	Inherent Stability	Expandibility to multiple buses	Reliability
Single unipolar regulated bus	24, 48, 380	Yes	No	No	Yes	Medium
Bipolar regulated bus	±170,340	No	No	No	Yes	Medium
Multiple regulated buses	48, 380	Yes	No	No	Yes	Medium
SST-enabled MG	380+	No	Possible	If ESS directly connected	Yes	Medium
DC ring bus	24+	No	No	No	Yes	High
Zonal DCMG	380 or higher	Yes	Possible	If ESS directly connected	Possible	High

Table 1: Table caption text

4. Low Voltage DC distribution

In the previous section the microgrids and basic advantages of DC distribution were discussed. Combining the two ideas, we can arrive to an idea of low voltage DC distribution [61]. The LVDC distribution is based on *nanogrid* [62]. The nanogrid can be a house, or some other independent entity such as an office building. An example of such a nanogrid is on Fig. 6.

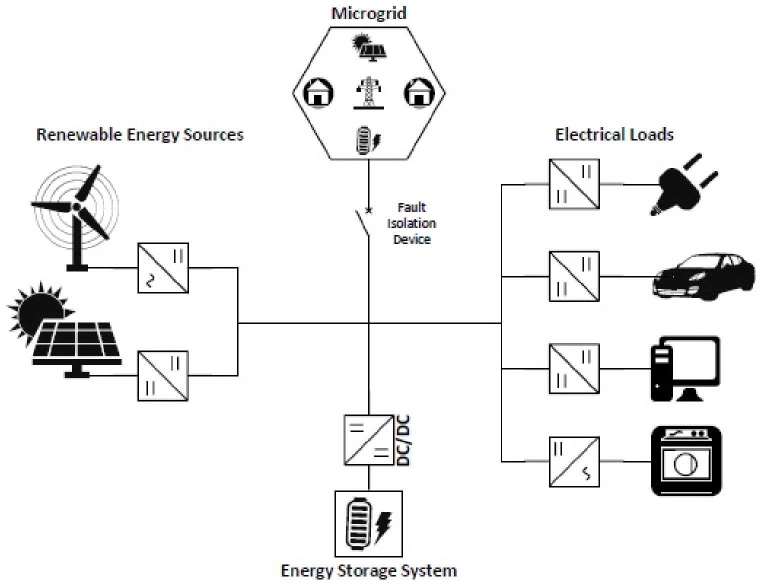


Figure 6: Nanogrid with circuit breaker. Source: Unpublised paper of Nils and Laurens. All credit for drawing belongs to Nils.

As is visible, the nanogrid is connected to the microgrid. The microgrid is an interconnection of nanogrids, generation, consumption,storage, and/or connections to higher level voltage distribution system(s). A microgrids equivalent in today' ac distribution system would be a feeder of substations (which are approximately 500 MW). The microgrid is depicted in Fig. 7.

Finally when we connect the microgrids together, we arrive to a meshed low voltage distribution grid. This macrogrid is an interconnection of microgrids and the integration of the MV and HV grids[6].

[6]The MV and HV grids are not depicted in this picture.

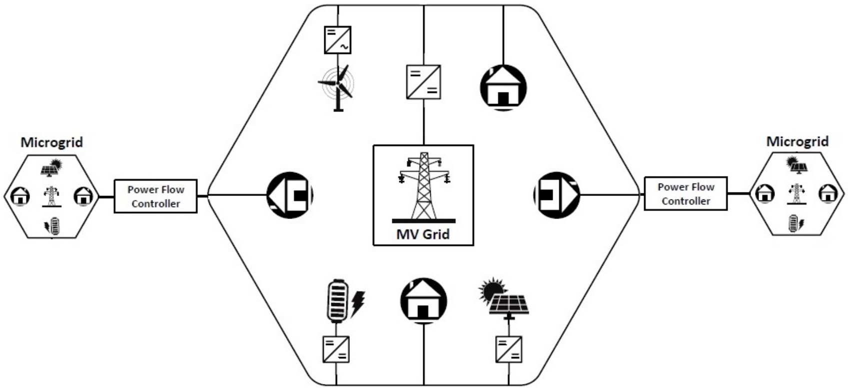


Figure 7: Microgrid. Source: the same

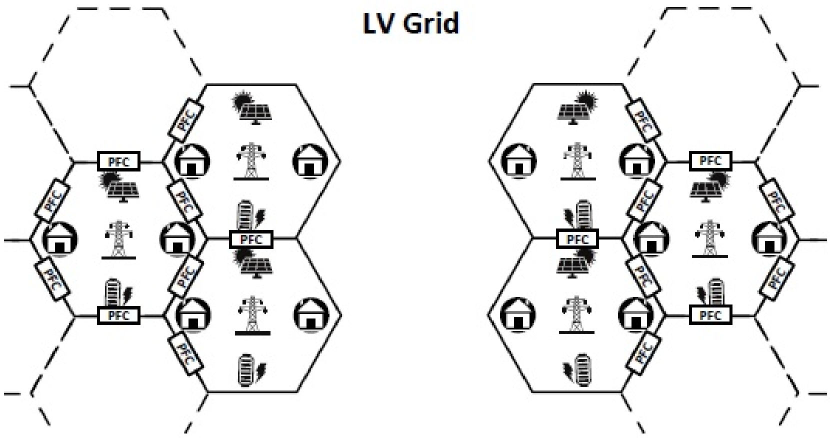


Figure 8: Macrogrid. Source:Nils.

5. Power Electronics

Power electronics always was a multidisciplinary field [84]. The multidisciplinarity of the field comes simply from the various functions the converter must provide. One of the possible representations of the fundamental functions of power converter can be found in [90] or in [86]:

The fundamental functions from Fig. 9, can be easily matched with different research fields. Let's take the *switching function* as an example. The switching function control electromagnetic energy flow/average power [28]. This function is physically implemented via semiconductor device. This device needs to manufactured, and appropriately confined from the surrounding environment. The one fundamental function of the power converter can be readily matched with multiple research fields.

Furthermore, as is noted for example in [49] the power electronics as a research field

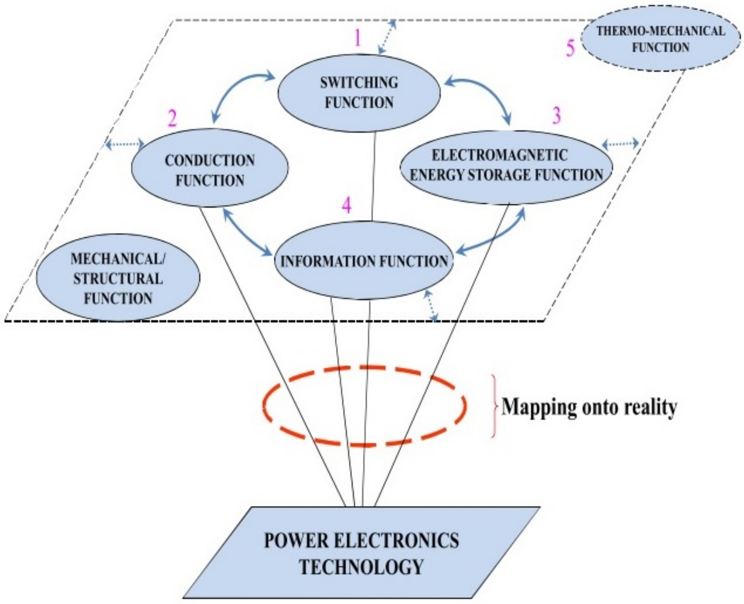


Figure 9: Internal fundamental functions of a power electronic converter. Source: [90].

reached it's maturity. In [86] it is further elaborated that the maturity of the research field is mainly connected to the exhaustion of the internal drivers for research. While the reasoning in [49] and in [90] or [12] is not necessarily the same, the conclusions drawn have a common point. That being that the research in power electronics will be mainly pulled by the applications. This is an interesting point since it add more diversity to already multidisciplinary field.

The previous two paragraphs illustrate a need for a more general approach when compiling a literature review of the state-of-the art in the power electronics. However, the scope of the power electronics is still too large to capture in a simple chapter. Therefore several selected topics will be reviewed which are directly connected to the research on the power electronics in the future distribution of electrical energy.

5.1. Internal Drivers for research

1. **Wide-bandgap devices(WBG):** The WBG promises two major improvements of the operation

$$\textbf{WBG}\begin{cases}\text{High Frequency Operation - reduction of the passives}\\ \text{High Temperature Operation - higher integration levels}\end{cases}$$

There are several challenges for the researches to tackle. First of all for high frequency operation in terms of several MHz it is necessary to improve integration of gate drivers. Furthermore, paralleling of high speed modules is challenge. Obviously, there are many more challenges coming with the high frequency switching, one of witch is the material for the passives and their integration and packaging.

The high temperature operation also brings in several challenges, connected to solder paste, substrates, connections to the environment and others. Especially for the automotive application there are bottlenecks to be tackled.

2. **Multi-Objective Optimization and novel design procedures:** Especially in ETH Zurich the multi-objective optimization method has received a lot of attention. A nice example is [48], where it was shown on PFC converter how the Pareto front and MOO can help to improve the design. With these improved design methods, and quantifying the requirements of the converter, a boundary of the current semiconductor operation can be reached.

   An perhaps interesting trend is to introduce more general design method as for example in [71]. Where the authors proposed a general design procedure for several types of the converters. The idea is based on the fact, that although the converters are used in the grid for different purposes they have enough in common so one general design procedure should be developed.

5.2. Packaging and mopdular design as possible drivers

This section is highly inspired by [73] and [74] and Packaging Tutorial organized in Delft in 2014 namely [7]. From [7]:

> "Winners in assembly and interconnect technologies are always those which enable simple manufacturing and high automation level."

From the quote it follows that for manufacturing process anything that allows for cost-reduction is a clear winner. Furthermore, it collides with what can be found in [85] that ideal is to reduce the complexity of the process : "*...manufacturing system would utilize a single process to transform a single raw material into a single part ...*" and as continues in [85] "*Complexity arises from variety in the inputs, outputs, and transforming process*".

In [73] a very high density DC-DC converter was designed, in the introduction a following figure is found to describe the three corner stones of the converter design:

With regards to the current development and papers describing the future of PE such as [86], [50], [11] I have changed the figure to the following:

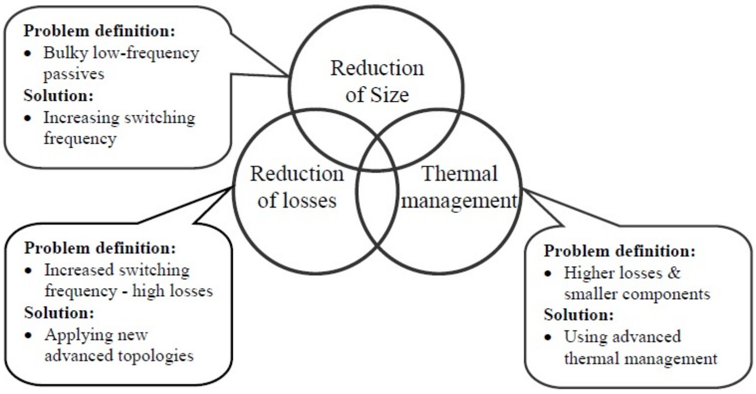


Figure 10: Three cornerstones of the converter design. [73]

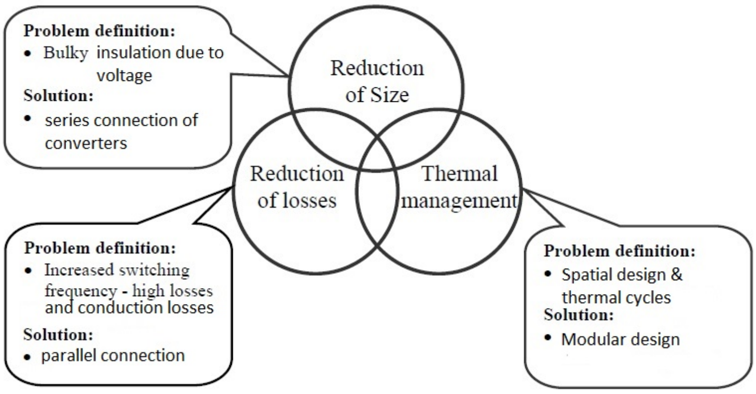


Figure 11: Three cornerstones of the converter design

Of course the figure is highly subjective and made to fit into the project description. Furthermore, the idea to connect converters in series or in parallel is everything but new. However, here the interleaving of converters is connected to the cornerstones of the converter design.

Reasoning behind *reduction of size*, comes for example from [?]. Which is yet unpublished dissertation from Chalmers University. The author was designing a converter for a DC DC converter for high power. As he shows the size reduction is not possible with just frequency under certain point. The same conclusion was drawn for example in [26] or in [94]. Furthermore as is concluded in [34] and [52] there is no fundamental reason why further improvement of power density via minimizing the size of the transformer or capacitor is not possible. However, the insulation materials are evolving slower and can pose a bigger bottleneck.

The claim with reducing the switching losses with paralleling converters comes from [47]. The modular design approach towards reducing thermal stress comes from the hand-outs of Packaging tutorial [25].

In [74] the traditional design of the converter is divided into several parts:

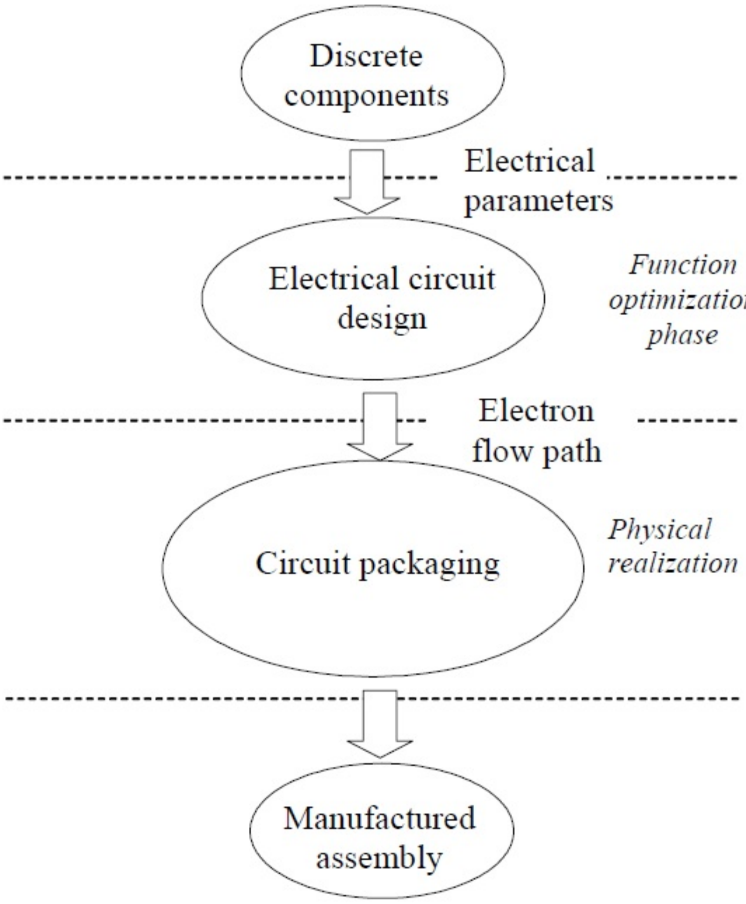


Figure 12: Conventional construction of power electronic converters

In for example [1] the cornerstones of the packaging from the provided definition are:

- electronic circuit
- thermal circuit
- electromagnetic design

5.3. External Drivers for research - Application

Functions:

- enables DC voltage stepping
- DC power or DC voltage regulation
- DC fault isolation

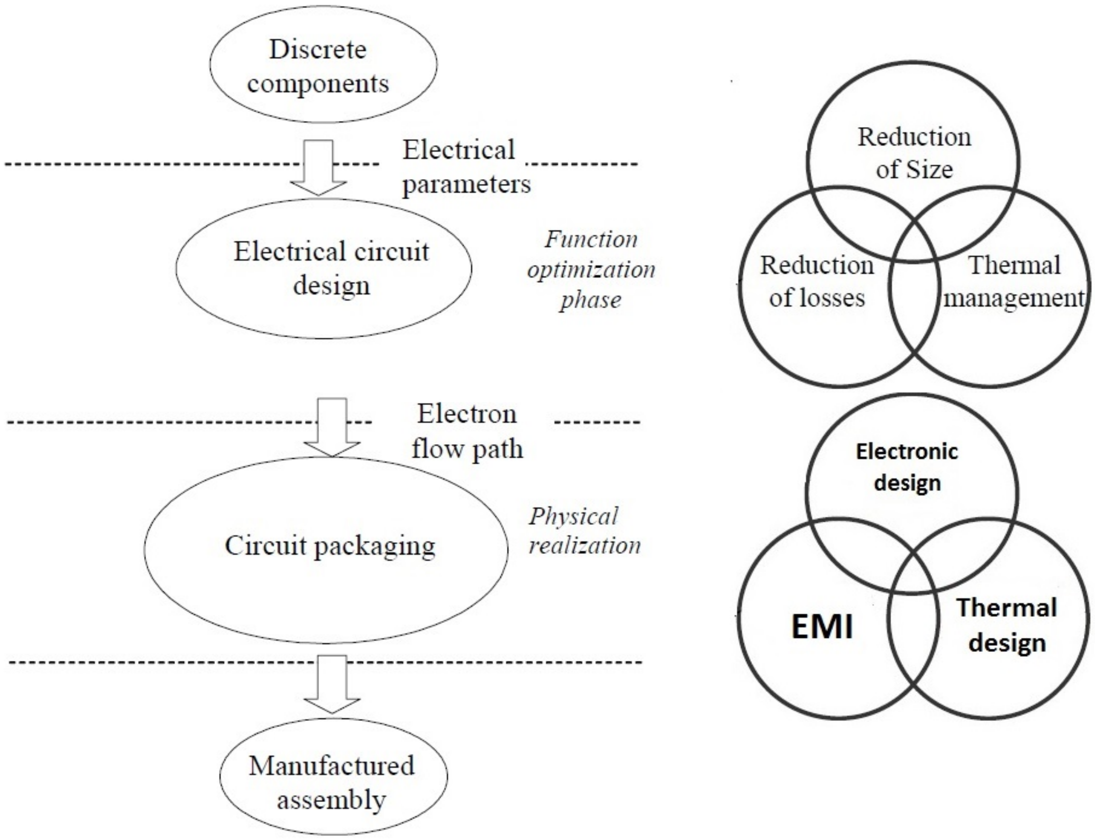


Figure 13: Combinig cornerstones with the traditional design approach

- Interfacing different DC technologies like current source with voltage source DC or monopolar with bipolar DC systems.

Requirements:

- Reduce stand-by losses and efficiency at partial load (very high overall efficiency)
- Long useful life
- high availability - translates to redundancy of the converter
- easy maintenance
- Cheap,cheap and once again cheap
- Environment friendly

In the previous section, I have tried to identify the converters in the DC microgrid. The number and rating of the converters of course depend on the finalized vision. However, it is quite safe to divide the converters into 5 main categories.

1. **RES integration converters** - integrating the renewable resources, such as wind, fuel cells or PV.
2. **Load converters** - not part of the figures, however it is easy to imagine that a whole lighting for a street can be connected to the bus via dedicated converter, which would be a load converter.
3. **Energy Storage** - fast EV charging, or a converter connected to the energy storage to enhance energy savings and stability of the microgrid.
4. **Power flow converters** - or voltage balancers, the converters to improve overall efficiency of the system by active control.
5. **Distribution converters** - Converters to connect to the utility grid and integrate the microgrid to the existing grid, or the converters connecting various parts of the DC network vertically.

5.4. RES integration converter

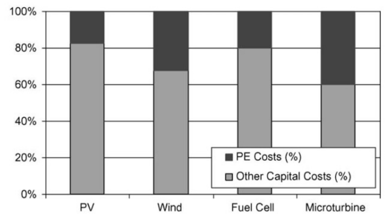


Figure 14: Cost of PE in RES. [15]

The main argument for more RES is mitigating the challenges related to usage of fossil fuels. Furthermore, RES are in general quite small power-wise. For example,the Joseph M. Farley Nuclear Electric Generating plant in rural Alabama has two turbine generators with a combined capacity exceeding 1,700 MW. Each of the 32 generators at Chinas Three Gorges Dam has a 700 MW capacity. In contrast, the largest wind-turbine generators developed are around 6 MW, while the best sellers on the market are still 2-MWwind turbines [56].

The fact that RES are small in power-supply is often an argument why is it good to integrate them also on community level, not only in energy-farms.

As is shown in Fig. 14 the PE comprises a significant part of the total cost of the RES system. From business perspective reducing costs of PE and improving reliability are the key issues. The challenges for PE in integration of RES are [15]:

- Lack of standardization and interoperability among PE components and systems.
- PE devices should be modular and scalable
- Research is not enough concentrated on the system package[7]

It seems that the PEBB or IPEM concepts are heading in the right direction but as is pointed out in many publications, interoperability and interconnections of the modules are still challenge.

5.4.1. Photovoltaic systems and Fuel cells

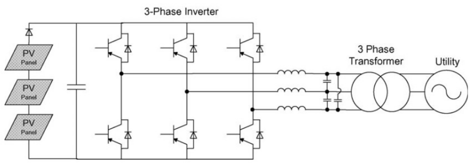
In figure 15 are the two[8] integration concepts for both PV and Fuel cells. The concept on figure 15a used to be applied in the past. It has two main drawbacks, one is that the PV modules not necessarily contribute with the same power, and second that the AC 50 Hz transformer is big and expensive.

The concept on fig. 15b has an advantage of not using bulky 50 Hz transformer, furthermore in the DC-DC converter the MPPT and voltage boost can be applied. Therefore sometimes, the DC-DC transformer is a simple boost.

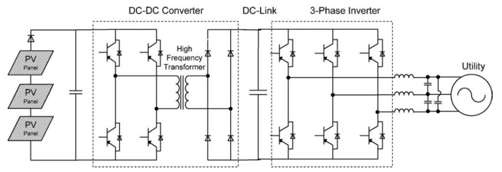
If we assume connection to a DC grid, clearly we save the one conversion step.

[7]Apparently author of [15] didn't hear about our PV integrated modules

[8]There are naturally many more, comprising various topologies or even reconfigurable topologies to incorporate also storage such as [46]



(a) PV system with 3-Φ inverter [15]



(b) PV system with decoupled AC and DC side [15]

Figure 15: PV and Fuel cells integration concepts

5.4.2. Wind energy

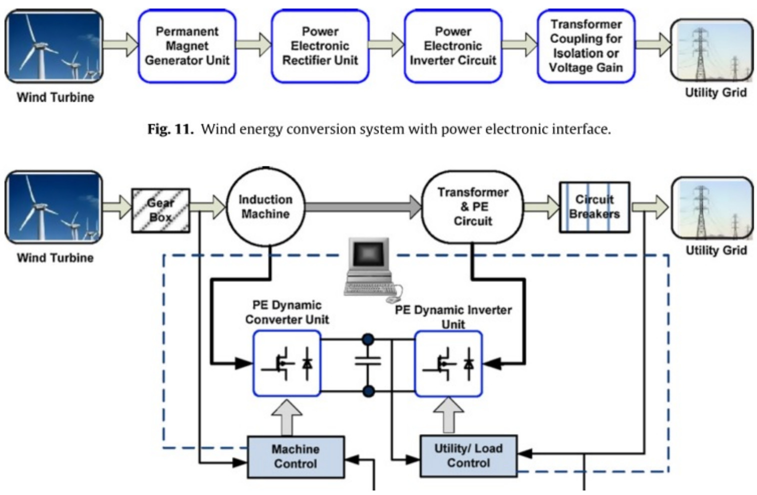


Figure 16: Wind energy integration to the utility grid

The modern system integrating the wind energy to the grid can be categorized to three main groups [84]:

- without power electronics
- power electronics rated to fraction of the wind turbine power
- full-scale power electronics

There are some other RES which will not be named, since they are pretty much the same in topology and also the challenges are quite similar including:

- control - especially for wind turbines, since the wind speed is hard to track
- EMI - How to reduce filtering for connection to the grid
- modularity - how to make interconnections between the modules

5.5. Energy Storage Converters

All chemical batteries produce DC power[9], which leads to the use of PE interface in order to integrate them in the grid. Compared to the previous group of PE for integrating storage it is not necessary to apply some kind of peak power operation. However, these converters need to be bi-directional.

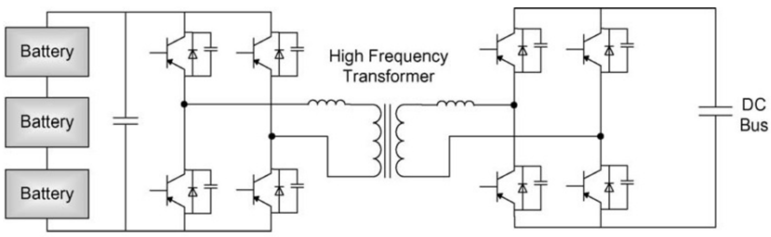


Figure 17: Storage integration for DC network.

The advantage of the system on fig. 17 is that it can step up or down the output voltage thanks to the HF transformer. But, it contains high number of elements.

5.6. Load Converters

In the figure 18 is a schematic structure of a DC house. The appliances are connected to the common DC bus via power electronic interface. In [58] a resonant converter for the inductive cooker was design as case study for the DC house.

[9]As far as I know.

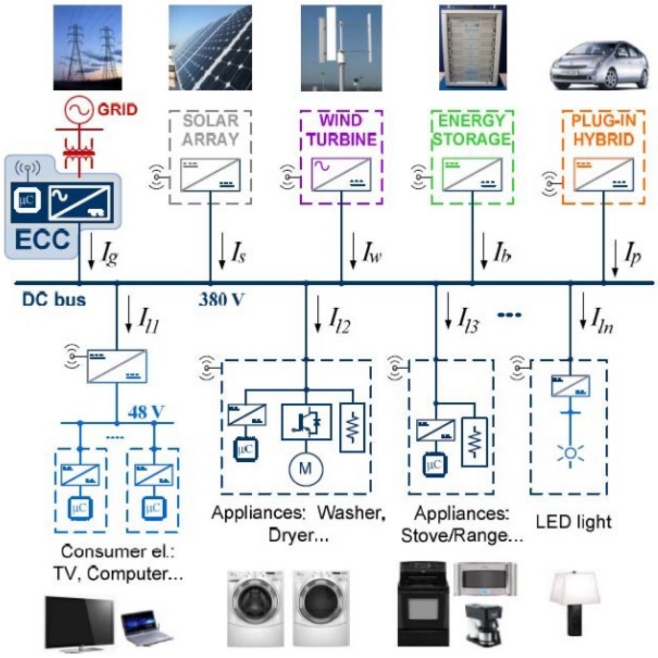
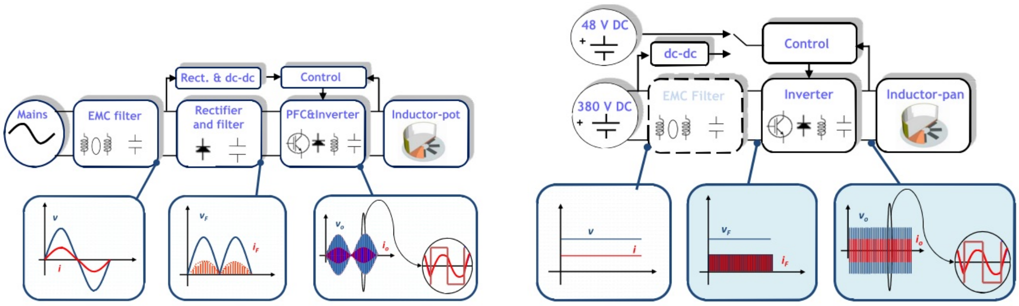


Figure 18: DC house structure. [58]

While the PE interface is a simple half-bridge series resonant inverter an interesting comparison can be made between AC household and DC one.



(a) Inductive heating system - AC house [58]

(b) Inductive heating system - DC house [58]

Figure 19: Comparison of DC and AC household.

As is clear from comparison in fig. 19 in case of a DC house at least one conversion step is missing, the power factor correction.

5.7. Power Flow Converters

The idea of controlling power flow comes from multi-terminal HVDC networks [31]. The reason is that if we have more than one DC line and we cannot fully control the power flow in the lines an overload can occur. In all the works concerning the power flow control it is mentioned that this can be also done by incorporating variable resistors. However, this is hardly economical since efficiency-wise we are not improving the operation of our network.

In HVDC a modular multilevel power flow control converters were proposed [91]. In the same paper it is furthermore realized that the converter should be bi-directional in order to improve the operation. What is interesting about power flow converters is that they do not need to be rated for the full power of the DC grid.

In [60] Laurens proposed a PFC for thee LVDC grid. The reasoning and also the solution is quite similar to the HVDC multi-terminal network. Similar deeds were proposed for example in [68](HVDC) or [65].

In general for LVDC the PFC topic is basically unexplored. Suprisingly even for HVDC the quality of the published work is relatively low, and the topic is not well documented. But my search was a bit brief.

5.8. Distribution Converters

Solid State Transformer is used to describe a converter which is part of the family of flexible ac transmission (FACTs) devices. The SST compared to traditional transformer is supposed to provide more than just voltage step-down and galvanic isolation. The idea is to incorporate advanced control and communication to create a "energy router" [80]. An interesting viewpoint can be found in [19] on FACTs, as is pointed out these devices assume centralize power production on transmission level, therefore they fail to provide the stability necessary for the case when significant amount of power comes from distributes sources.

Using SST makes possible to have multiple output, such as in the figure 20. With such a converter it possible to create a system where both AC and DC are used for what they are best.

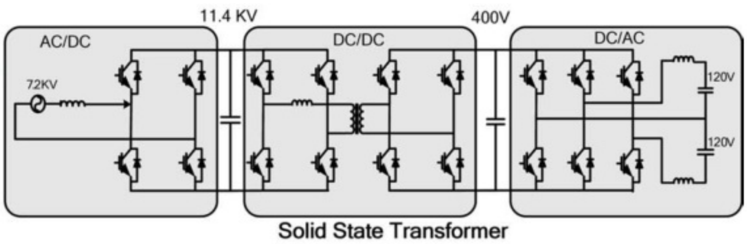


Figure 20: Solid State Transformer

For the era-net project I think it should be possible to decouple the SST into 2 (or 3 parts).

- AC-DC converter connected directly to the grid.
- DC-DC converter with HF transformer to provide beside else galvanic isolation
- DC-AC low voltage inverter

The AC-DC part can be omitted for two reasons basically. First is that a connection to DC grid can be assumed for the sake of the project. But more importantly, during the workshop it was "decided" that AC-DC part is well matured, and already well known, thus should not be investigated. Therefore, it would make sense to consider only the DC-DC part of the SST[10].

The SST can be connected in two places in the 'envisioned' DC microgrid:

- Grid to Distribution Microgrid
- Distribution Microgrid to the House microgrid (alternatively to the zone)

The importance of the distinguishing is clear from the different voltage level. While in the first case there is a need to consider connection to $\approxeq$ 12 to 20 kV in the second case, it is around 1.5 kV.

The second reason for the distinguishign is the different functionality which can be drawn for the two situations. For example in a house we might want to have just one converter to which all the RES are connected, kind of multi-input-multi-output system[11].

A converter interfacing the grid and a single DC house(or nanogrid) was designed in [20]. A 2 stage topology was proposed with rated power of 5 kW.

With the only reason that multilevel makes more sense for higher voltage, I would concentrate on the converter for tying with the grid. This converter should have at lease following features [20] [19]:

1. bidirectional power flow
2. dynamics decoupling of interfaced systems
3. bidirectional fault current interrupt capability
4. smart metering and communication functions

The three main challenges for the SST in distribution are following [37]:

- Efficiency - if the SST are to compete with the traditional transformers then efficiencies around 98% are inevitable
- Thermal Design - The increased switching speeds, and attempts to provide higher power density in order to justify the extra expense compared to traditional transformers are putting the thermal management to the attention

[10] This seems to be a very common practice in many publications. Sometimes it seems that people are almost avoiding work with any AC.

[11] More will be hopefully in the next section.

- Costs- Distribution transformers are pretty cheap, since it is a standarized technology. The cost should not be too high.

In order to construct a converter which is suitable to interconnect ac grid with the dc microgrid. Two options are basically available:

- 2 or 3-level converter
- modular structure

The problem with the first option is t that high power devices which can switch reasonably fast are not really available. Although SiC IGBTs could fill in the gap.

The second option is of interest for this project. The challenges then include besides else a higher cost, but also inevitably lower power density. The most common topology is input-series-connected and output-parallel-connected [26], [89]. The selection of this connection intuitevely makes sense, since on the output is much higher voltage than on the output.

The challenge is first of all to achieve a comparable efficiency to the traditional transformers, because of the cascaded structure. It seems to be common practice to either concentrate on the control of the whole M2C without actually building it, or to build only one module and than test it alone [26].

One of the main challenges in connecting the modules is to cope with relatively large inductance of the interconnections which are causing large circulating currents, causing high losses. The interconnection inductance is also limiting the switching frequency of the modules.

Further challenges inside the modules are achieving ZVS over large range of the load, since both dual-active bridge and half-bridge have ZVS switching only in a limited range. To increase the ZVS region it is possible to include a third leg such in [5]. Furthermore to improve the ZVS switching also the transformer ratio and configuration needs to be considered [6].

The transformer attracts quite some attention as is shown in [37]. Not only the configuration of winding but also the structure are very important for the design. Based on the switching frequency the material should be selected. One of the possible demands might be to avoid the ferrite cores. Because these might be just too big due to their low saturation flux density.

From the point of view of the semiconductor technology used in these transformers an interesting and quite soundly argumented prediction was made in [37]:

- SiC Mosfets will be used in applications with voltage $<$ 15 kV
- SiC IGBT's for 15-20 kV
- SiC GTO's for higher voltages

In the mentioned paper the GaN switches were disregarded. I assumed it was due to 2 reasons:

- price - due to gallium it seems that the lowest price threshold of these devices will remain inevitably a bit higher compared to SiC
- blocking capabilities - the sustained voltage of these switches is still a bit low compared to Si or SiC

However, the GaN switches are an interesting option for power flow control converters.

Based on these very brief overview the main challenges to design the M2C for dc microgrid connection are:

- **High efficiency** - very high efficiency modules to enable high efficiency cascaded structure. This basically includes also the challenges connected to the design of the transformer, switch selection, topology considerations etc.
- **Packaging** - how to reduce the interconnection inductance to reasonable levels
- **Control** - how to control multiple modules connected in series/parallel

5.9. Conclusion

Since this section was a little bit longer, I think it deserves a few closing remarks.

- **RES converters** - The renewable sources integration is studied in many papers. These topics are also well covered in our group. Furthermore, as was discussed before a general design approach for a group of converters might be an interesting topic. An interesting publication regarding general design approach for RES integration is [71]. The topic of integration of RES via PE intergaces is quite vivid, however I would not embark to it since to me it seems that it is a bit out of the scope of the project.
- **Load Converters** - An example study was [58]. The load converters to me do not seem to be an interesting topic. Due to 2 reasons, in case we are not on house level there are not so many loads, and these converters are I think quite well understood in industry. Furthermore, isn't Fraunhofer doing something similar ?
- **Energy Storage Integration** - done by TU/e
- **Power Flow Converters** - This seems to me as quite an uncharted territory. In almost every sense from control to the topology selection and power ratings.. This makes an interesting research topic. On the other hand, since it seems that these converters do not need to be rated for the full power of the system, the M2C structure does not seem to be necessary. More importantly, the microgrid can work without it. And PFC is not the 'missing link'.
- **Distribution converter** - This group of converters I consider as the most interesting. In most of the papers it is assumed that the interconnection between the microgrid and the utility grid can be done in an efficient way and such that the

interfacing PE is able to provide many auxiliary services. However, many research groups such as in Aalborg are basically uninterested in the PE components and only assume that when they need it the PE will be there. Which in most cases is true, but the interface with utility grid can be quite a challenge for the PE.

The choice of this interface makes also sense from the point of view of the era-net. First of all, this converter is truly enabling technology for the microgrid concept. Furthermore, at these voltage levels M2C structure makes sense. And for the higher voltage rating and relatively high switching frequencies there are many challenges to be solved.

On the other hand, apparently many phd projects started with the goal to build and test complete M2C and didn't quite get to the test phase. This makes it even more attractive, but also an interesting opportunity to learn from others mistakes.

5.10. DC transformer

> "Like the left-handed monkey wrench, the concept of a dc transformer has always been something of an inside joke among engineers. However by utilizing superconductors a device has now been created in which a direct current actually can be transformed" [3]

From the previous it is quite safe to conclude that if the DC grids are to be installed, a component is needed that will be able to interconnect multiple parts of the same DC grid. Or multiple DC grids into a mashed DC grid. This converter should be able to at least have these three functions [27], [41]:

- enables DC voltage stepping
- DC power or DC voltage regulation
- DC fault isolation
- Interfacing different DC technologies like current source with voltage source DC or monopolar with bipolar DC systems.
- Reduce stand-by losses and efficiency at partial load

The DC-DC converter is almost equivalent to the transformer in the AC grid. As is almost every where noted the biggest difference between the two is the fact that the converter cannot be overloaded and the time constants are much smaller.

Since it has been many years since electronic transformer(1968) has been proposed, there is already quite some research done in the area. Some researchers thought that solid-state transformers could replace the low frequency counterparts in the AC network, today however it seems that consensus is that SST will be used only in places where the DC link is necessary [51]. Most commonly studied SST is 3 stages converter - AC-DC,DC-DC,DC-AC.

Since the DC-DC part is also interesting for LVDC it appears to make sense to review this part of the SST research. At first a few interesting things, prof. Kolar vision of the research on SST:

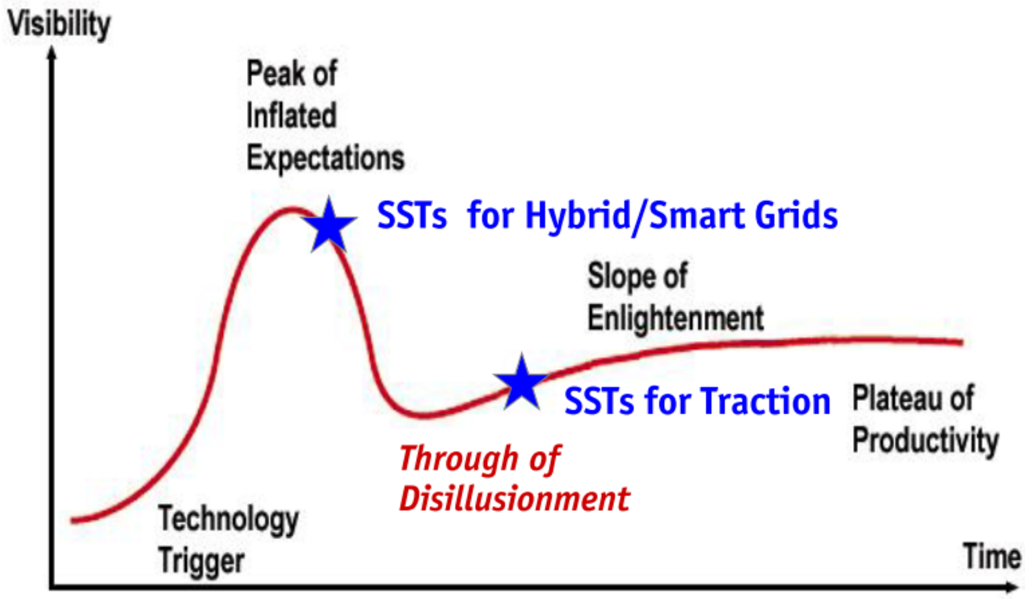


Figure 21: SST hype cycle.

I am not exactly sure how big is the gradient of the curve at Smart Grid point, but I expect it is big enough. Which is a perhaps good point to start to explore only the important things for the application.

The second vision from prof. Kolar is in the next figure:

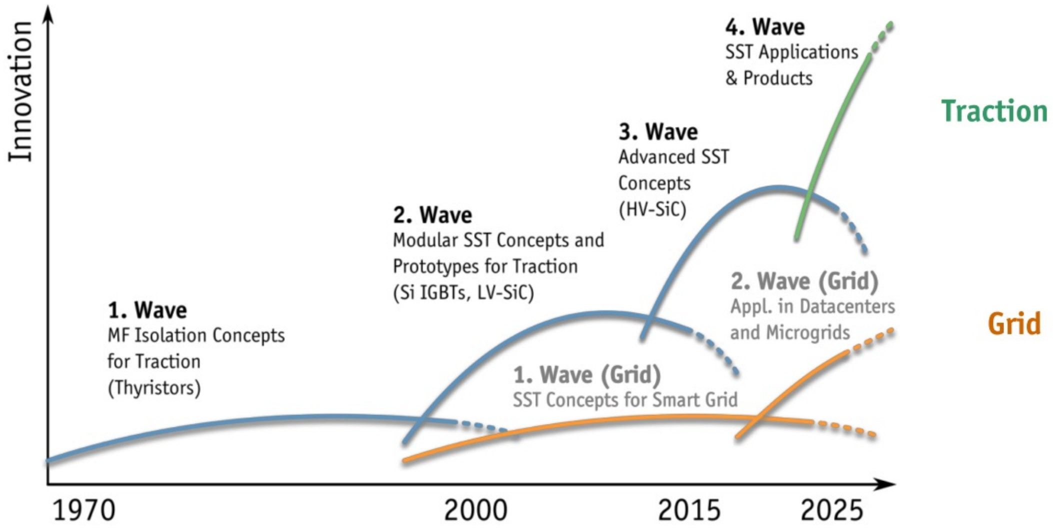


Figure 22: Development Cycle.

The reason why I have included these two figures is, that I think the situation for "modular converter for LVDC distribution" is very similar to the SST for Microgrids. The fundamental questions are relatively well answered, but the converters are far from being used in the practice.

As a part of the FREEDM project a company *GridBridge* tried to create an SST. Product which is now commercially available is not exactly an SST. It is a converter that helps with dynamic regulation of the voltage and reactive power near the feeder. Yet, the GridBridge receive a lot of attention both from industry and government. It is quite strange because there is similar product from a bigger company Verantec. This product seems to be important for the US market where the availability of the electrical power is low compared to Europe.

5.11. Limitations and opportunities

The general problems of the SST technology for the applications are:

- Efficiency - is still considered as a major problem. The reason is very high efficiency of low frequency tf efficiency. Even though, it is recognized as for example in project SPEED[12] that the lower efficiency can be acceptable if it is outweighed by other benefits.
- limited space reduction
- design of HF magnetics for high power
- high costs
- reliability (failure rate & useful life)
- High currents on LV side and High voltages on HV side ? (prof. Liserre)

In the following text I will try to go by each limitation, explain it and link with what has been done in the field.

5.11.1. Efficiency & Reliability & Modularity

For the SST the efficiencies vary widely based on the definition which author uses. However, for Eranet project only a DC-DC conversion part matters, thus a benchmark can be selected later. The low frequency transformers have regulations[13] which specify the efficiencies for each voltage level and power rating. Currently the efficiency regulations form MV oil immersed transformers start at 98% at 35% of the nominal load.

What I find of particular interest it is the influence of modularity on the efficiency. Without considering any particular topology, while this limits the accuracy of the analysis based on the available literature there could be some general conclusions drawn.

The following picture is inspired by a real graph in [93], where a modular structure based on dual-active bridges(DAB) was studied and similar dependence was measured for Silicon devices. As was shown in [93], there is a breaking point after which the efficiency of the modular structure starts to increase. If we increase the no. of modules to relatively high number we can obtain efficiency comparable to that of non-cascaded structure. In the very same paper, it was shown that it does not make sense to increase the no. of modules after some point. The reason for the saturation in efficiency and weight gains was that increasing frequency is not an option after a point where the temperature of the ferrite would rise too much.

Based on the results from [93], I have added a line for SiC. The SiC are well described in for example [77], an application note from Rohm. It seems that SiC can push the efficiency and weight gains a bit higher in the area where the IGBT's would be normally used. I have also added GaN devices. Which could increase the efficiency for the

[12]http://www.speed-fp7.org/
[13]http://www.ecfr.gov/cgi-bin/ECFR?page=browse

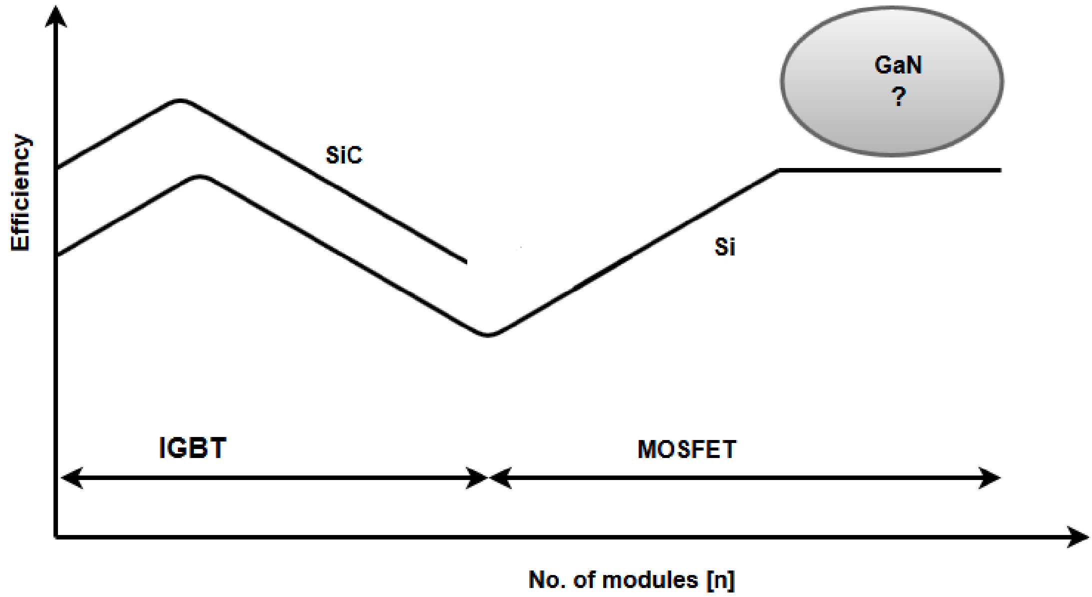


Figure 23: Variation of efficiency based on the number of modules.

cascaded system with many modules. However, this is only guess based on the fact that GaN converters with power rating of 1 kW and switching frequency of almost 1 MHz were already designed [67].

In the summer school prof. Liserre had a lecture on the power electronics fro future grids. As I have noticed he was a strong advocate of modular structures for the future converter, therefore I have went through their articles.

In [76] it is claimed that the modularity can boost the efficiency of the SST. However, only the DC-DC part was considered, and only DAB was considered as a building block. Furthermore, at some point it is claimed that a reliability can be improved because of redundancy. On the contrary during the lecture it was shown that the reliability might even suffer due to uneven thermal stress on the modules. While at this paper the switching losses are considered, other limitations like magnetic material are not thoroughly considered. Making the applicability of the work limited.

In [16] an interesting approach was proposed to increase redundancy of the DC-DC converter.

The idea is, that the power can be routed through either all three modules on the right hand side, or only through two (or one) in case of a failure of the other module. This is an interesting idea, because it clearly increases the redundancy of such a converter. However, as was pointed out that the uneven stress of the modules creates problem with how to integrate these modules inside a package. The thermal expansion coefficients are different for different materials. If we turn on and off the modules too often then the temperatures of different parts of the converter will be different which leads to mechanical stressing ... An interesting project is though starting at this university called The Highly

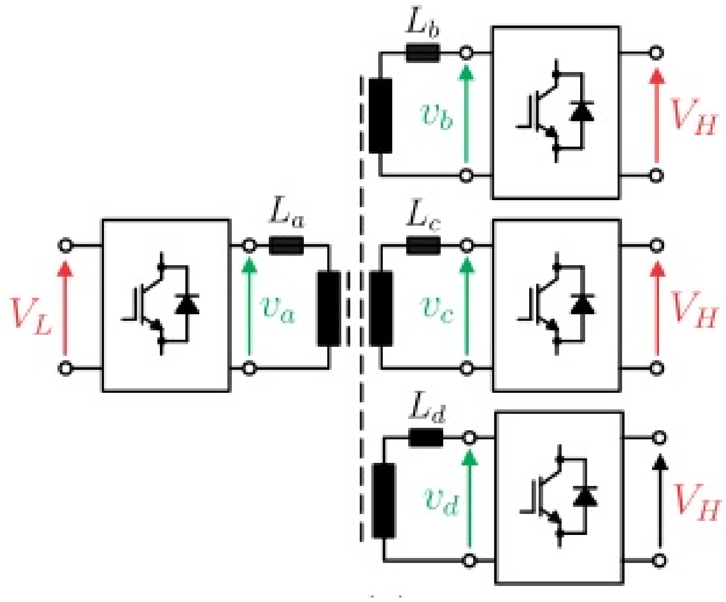


Figure 24: Topology of quad-active bridge converter. Source: [16]

Efficient And Reliable smart Transformer (HEART)[14].

5.11.2. Limited space Reduction & Magnetics design & New semiconductors

In power distribution application the power density is not necessarily the ultimate design factor. However, it can happen that the price of the land is too high (eg. city) and then the power density becomes important. Furthermore, usually power density is an opposing force to improving efficiency [8]. In [8] it is shown for a phase-shift converter with current doubler that very small gains in efficiency can mean significant decrease in power density.

Main part of the converter which volume is being minimized is the inductor/transformer.The design of magnetics and their behaviour under different conditions is being studied quite extensively [83], [67]. As was hinted before as it happens that the semiconductor is not the limiting factor for switching frequency. Rather in the ferrite when flux density is high the hysteresis losses increase, if the switching frequency is high the eddy current losses rise. These two effects lead to increase in temperature, the temperature can rise dangerously close to Curie temperature and that poses a practical limitation for the design. The almost up-to-date research state is nicely captured in the picture from dissertation [81] :

what is missing is the improvements for high power application 1 kW -10 kW with ultra high switching frequency 1 Mhz and more. These improvements were enabled mainly by introduction of GaN devices [67]. In the mentioned paper [67] few interesting

[14] http://www.pe.tf.uni-kiel.de/en/research/fields-of-research/the-highly-efficient-and-reliable-smart-transformer-heart-a-new-heart-for-the-electric-distribution-system

	Ultra-high-frequency Range (1 MHz - 10 MHz)	High-frequency Range (100 kHz - 1 MHz)	Mid-frequency Range (10 kHz - 100 kHz)
Low power range (< 1 kW)	**Goldberg (1989)**: Ni-Zn ferrite gapped pot core,Planar spiral windings, 5-10 MHz, 50 W, Resonant forward converter **Ngo (1992)**: Pot core, Planar spiral windings, 2-5 MHz, 100 W **Evans (1995)**: Toroidal core, copper wires soldered on substrate metallisation as windings, 2 MHz, 150 W **J. T. Strydom (2002)**: Integrated planar core, spiral windings L-C-T transformer, 1 MHz, 1 kW, Asymmetrical half-bridge resonant converter		
Mid power range (1~10 kW)		**Coonrod (1986)**,Ferrite toroidal core, magnet wire windings, 100~300 kHz, Half-bridge converters **Petkov (1996)**, Freeite PM core, magnet wire windings, 100 kHz, 2.6 kW, Microwave heating supply **Canales (2003)**,Ferrite E core, Litz wire windings, 745 kHz, 2.75 kW, Three-level resonant converters **Biela (2004)**, Integrated transformer, ferrite E core, foil windings, 300~600, kHz, 3 kW, Resonant converters	
High power range (> 10 kW)	???	√	**Kheraluwala (1992)**, Ferrite toroidal core, coaxial windings (primary tube and secondary Litz), 50 kHz, 50 kW, Dual active bridge converter **J. C. Fothergill (2001)**, Ferrite C-core, solid magnet wire windings, 25 kHz, 25 kW, 50 kV, Full IGBT bridge converter **L. Heinemann (2002)**, Nanocrystalline wound core, coaxial cable windings (inner aluminum tube and outer braided copper), 10 kHz, 350 kW, 15 kV, Dual active full bridge **Reass (2003)**, Nanocrystalline cut-core, 20 kHz, 380 kW, poly-phase resonant converter

Figure 25: Transformer design status

considerations were made with regards to ferrite. It was shown the ferrite is no longer suitable for frequencies over 900 kHz. And the very prosaic reason is given which is limiting the space reduction. Not enough winding space for the Litz wire. Although it was noted that with a finer Litz the limit can be pushed a bit higher, however it might be just better to use nanocrystaline materials.

An interesting analysis was carried out in [87], were hard switched SiC device was compared with soft-switched Si device. While the efficiencies were comparable, the SiC was cost-wise much better (based on total chip area). However, the soft-switched was smaller and more flexible solution. This is perhaps an interesting implication, the soft-swtiched modules can be less cost-effective then utilization of non-modular device based on SiC, but the modular design has advantages like smaller size and more flexibility.

An interesting source of inspiration is also the market for telecom distribution which has been dc-based for past 180 years. Currently the DC solutions for the market are of very high quality with rectifier efficiencies around 95 % over large range of load fig. 26. The companies operating on this market use modularity to achieve better spatial design

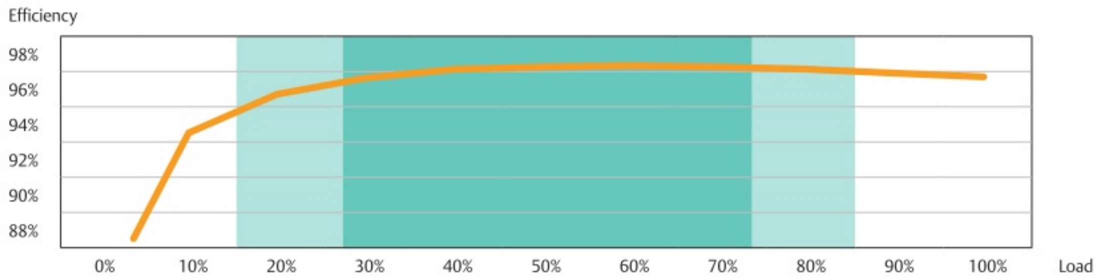


Figure 26: The 15kW high- efficiency eSure rectifier (model R400- 15000e) converts standard AC supply voltages into stable DC voltage, adjustable up to 400V DC. Each unit in the system operates inde- pendently and delivers conditioned, isolated power onto a common distribution bus. The rectifiers function in parallel for seamless redundancy and load sharing within the system. These pure three phase rectifiers provide ideally balanced currents back to the grid with low harmonic content.

of their converters. The idea is that they can better distribute the converters in space and thus save some space even though the power density is a bit smaller. As is noted the efficiency is of utmost importance due to the fact that the data centers consume up to 100 times more energy[15] than the office building of the comparable size.

6. Modular topology for LVDC

From the first part of the document it can be concluded that different parts of the LVDC network need to be connected in a way to generate higher DC bus voltages. As was shown in [93] or [76], it is possible to expect positive effect of modular solution on efficiency and redundancy of the converter. As such there are several modular solution, which seem to be based on either series or parallel connection of converter. The converters can be connected:

- IPOP - input parallel - output parallel
- ISOP - input series - output parallel
- IPOS - input parallel - output series

[15] Source: ABB blog ?

- ISOS - input series - output series

For the LV application it can be hard to validate the series connection, since the voltage levels do not require sharing among the components. On the other hand, the parallel connection can reduce switching and conduction losses, furthermore a power sharing can be created when the power transfered is low, the redundant modules will be turned off.

For the LVDC application IPOP can prove to be worth investigation because of afromentioned positives. Furthermore the IPOP is also a solution on which some stuff can be applied and have a look on EMI. and other things like theory of chaos can be applied to study the emi, reliability, long life and more. To obtain more fundamental knowledge of what is happening.

Multi-cell converter systems, are being studied also in ETH PES, with regards to implementation of renewable sources. In [50], the advantages of parallel interleaving of converters were described as:

- Breaks the Frequency Barrier
- Breaks the Impedance Barrier
- Breaks Cost Barrier - Standardization
- High Part Load Efficiency

The interleaved converters were studied for very long time. However, there are still topics which were not yet described in detail

- thermal cycling and uneven loading of the converters
- EMI, while the parallel interleaving has potential to decrease the EMI there still might be need to quantify it. Furthermore, I came across quite interesting application of chaos theory for mitigation of EMI, however not done for more complex structures.
- furthermore, the redundancy is increased, however the various failures were not studied. In order to achieve longer useful life
- based on the previous knowledge an approach to generation of system safe operation are can be described. This could be an interesting thing for practicing ingeniuers

Apparently the modular design can help and is used to tackle the newest european things for railways.

7. Module review

Remark This section was intended to cover much bigger scope of the converter topologies. However, they were only derivatives of the half-bridge and full-bridge converter. The reason to include only the two was to get more fundamental comparison.

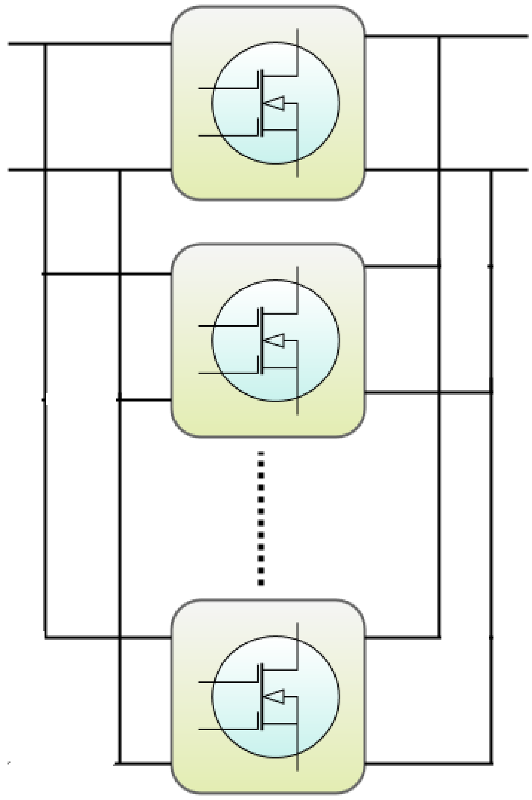


Figure 27: Paralllellll

The modular topologies are usually based on basic switching cell. The switching cell is most of the times either half-bridge cell or full bridge cell. As I have noted before, it is often required from the converters in distribution to have ability to isolate fault.

In multi-source systems it is often required to have galvanic isolation. The galvanic isolation is inside the converter. The requirement can be based on [44]:

- personnel safety
- noise reduction
- proper operation of protection systems

The basic cell is either full-bridge converter or half-bridge.

8. Modular vs. Integral

8.1. What is modularity ?

First and interesting detour can be taken to cross-field study [55]. The authors of this study map modularity ideas in various social sciences. An interesting look can be on

Half-bridge and Full-bridge comparison

Half-bridge		Full-bridge	
Pros	Cons	Pros	Cons
Low switch count	Large current ripple at	Voltage stress over the switch	High ripple content in currents,
.	splitting cap. LV side	is the same as bus voltage	thus large filters
Relatively wide ZVS range	Unbalanced current stress	Almost equal current stress	No inherent DC current blocking
against voltage and load variations	between switches on LV side	on each side	capability for tf winding
Same rating of components as	Low series inductance of TF	Simple structure of transformer	No soft-switching in
for DAB	to limit reactive power	.	light load
Relatively easy control	.	Soft switching can be achieved	Control is sensitive to changes in
.	.	without additional circuits	phase angle, especially for high voltages.
Low ripple current at the	.	Fast dynamic behaviour due to	Large component count,
current fed side(desirable for batteries)	.	lack of additional passives	considerable gate losses
.	.	well known control methods	.
.	.	.	.

Adam' Smith *laissez faire*. Where the core idea is that 10 labours make many more pins than 1. That is because of specialization and division of labour. Which indeed is a modular approach. This is why modularity comes very natural to us, since it reflects the way we think. Simplify the problem into smaller task and solve each one separetly and then combine.

As is claimed in [78] there are over 100 different definitions for modularity in the used literature. Some of them are very similar, some even contradictory. This makes rigorous study of the topic rather hard. However, [78] has proven as a very thorough and useful literature review. Based on the literature study in [78] a definition of modularity was proposed which is connecting both modularity in the production and in design.

In [78] it is very reasonably argued that modularity, **has to be defined for a set of products, namely a product system**. Which can be a car model with its possible variants. Furthermore, the modularity can be defined at one exact point in time, then we talk about *product variety* or over a period of time and then we talk about *product change*.

The modularity is defined based on two terms:

- Component Separability
- Component Combinability

8.1.1. Component Separability

Is a term connected to the production. However, it should be noted that it is more restrictive than per-part manufacturing[16].

Separability is also defined in terms of disassembly. The fast disassembly enables fast maintenance and upgrade. The disassembly can be achieved via *reversible* interface which drasticly reduces the requirements on time and tools. Furthermore, separability

[16]"There were once two watchmakers, named Tempus and Hora, who manufactured very fine watches the watches the men made consisted of about 1000 parts each. Tempus had so constructed his that if he put it downto answer the phone, sayit immediately fell to pieces and had to be reassembled from the elements. The watches that Hora made were no less complex than those of Tempus. But he had designed them so that he could put together stable sub-assemblies of about ten elements each Hence when Hora had to put down a partly assembled watch to answer the phone, he lost only a small part of his work, and he assembled his watches in only a fraction of the man-hours it took Tempus." [78]

does not require the module to be constructed of multiple elements. The important thing is that the one element if changed changes the product variant and if it is separable, then it can be a module.

8.1.2. Component Combinability

Definition provided by author of [78]:

"For every product variant A within the product system component compatibility will be embedded in the product system if another product system variant is obtained either 1) by swapping any of As constituent modules with any other product system module, or 2) by taking away any of As constituent modules (provided that A is made of at least two modules)".

It is important to note that such definition captures component combinability and nothing more. Different product systems may have different manufacturing costs or value for the user, while having the same degree of component combinability.

There are two subsequent definitions that can be made

1. maximum number of product variants

$$MVP(n) = \frac{n}{1} + \frac{n}{2} + \ldots + \frac{n}{n-1} + 1 \tag{1}$$

   where n is identified number of modules out of which m products can be build

2. Combinability Index -ratio of the minimum theoretical number of components needed to build m product variants over the actual number of compo- nents required for a given product system

$$CI = \frac{n'}{n} \tag{2}$$

   where *n'* is smallest possible number of components that, in conditions of full combinability, are needed to build m product variants

8.1.3. Modularity conclusion

There are many other definition of modularity. However, I will not mention them here. The most interesting observation is that the definitions are usually made with regards to the expected result.

8.2. Why modularity ?

In [14] there are two important questions with regards to modularity.

1. Which modularity does my product need?

2. What benefit do I expect from modularity?

To me it appears that these two question boil down to the main question, and that is why do I even want to employ modularity. This is rather important question, and seems that it was not satisfactorily answered when employed for power converters. Hence, one of the possible explanation why it was never really picked up by the industry.

Conventional approach to modularity in power electronics, could be described as function-binding. For example in [45] or [**?**] define a canonical switching cell on which they then build a modular converter. Such an approach usually results in a design procedure similar to that in [71]. The typical trait of this approach is the fact that it binds usually one function to one module[17]. This simplification may lead to a simpler design process, however, almost definitely it will not show in the simplified manufacturing process.

Further problem with modularity in Power electronics is that the manufacturing or the supply chain is not considered. Not to speak about a market. The problem with the supply chain is very very nicely described in [29]. The author describes an acquisition of Chrysler by Daimler. The problem is when we compare the two companies. While Mercedes is build as one very luxurious complex product, the Chrysler are usually relatively cheap, and build of modules. Each approach has its benefits, and each is suitable for different types of market. However trying to combine them might not end well.

And this is a point that is almost never treated in the paper in IEEE concerning modularity in PE. The problem is that the converter is usually defined for a specific application or a specific goal. For example if we optimize for high power density, that the process is of integration. We do the manufacturing in house. As the design and building process is design for example in [1], the process is done in one place with one goal, and everything under one roof.

However, modularity of the converter is not usually required. If we take into account the definition from [78], then the converters do not have many modules which are separable nor with high combinability. However, here is the problem that for power converters there are multiple dimensions in which the products can be separable. Lets say power rating or functionality. Therefore a more rigorous investigation is needed here.

Why Modularity in LVDC distribution could make sense ? Generally there are two reasons to go for modular design from the point of view of industrial design or management [38]:

- produce large variety of products at low-cost
- production module can be designed independetly of their function

The second point actually can be quite problematic for the production and modularity. The production is based on standarized modules with standarized interfaces. With introduction of new-to-production [42] can hinder the modularity of the production and move towards more integral production. This can be because of introduction of new functionalities of the module, or even new interfaces ...

Since I have mentioned two distinct approaches to production and design it could be worth to compare them. The following table is taken from [42]:

[17] Actually, as is claimed in [55] this is a source of benefit. Since it reflects the deduction process.

Benefits of Modular Designs	*Benefits of Integral Designs*
• Task specialization • Platform flexibility • Increased number of product variants • Economies of scale in component commonality • Cost savings in inventory and logistics • Lower life cycle costs through easy maintenance • Shorter product life cycles through incremental improvements such as upgrade, add-ons and adaptations • Flexibility in component reuse • Independent product development • Outsourcing • System reliability due to high production volume and experience curve	• Interactive learning • High levels of performance through proprietary technologies • Systemic innovations • Superior access to information • Protection of innovation from imitation • High entry barriers for component suppliers • Craftsmanship
Examples: Elevators, passenger cars, IBM PCs, Lego toys	***Examples:*** Formula One cars, Apollo Computers, satellites

Figure 28: Advantages of integral and modular approach.

It is rather clear that each time we want highly performing product for one particular application then we go for integral approach. This is to be highlighted because that is the case for most uses of the PE. The PE when used in industry is very expensive, and needs to be optimized for highest performance possible. In case PE is used in consumer electronics, the profit margins are very very low, and each cent is important. Either a company can decide to develop its own power supply like Philips in the past, which can lead to high performance, but economically it is not necessarilly cost effective. Or the company can outsource the technology and buy ready modules(whole converters) in such a case it has to change its internal structure and managerial style as well as claimed in [29]. But as stressed for a converter as such, there are rarely reasons for companies to go for a modular design and manufacturing of the converter.

One of the reasons to choose modular design could be an increase in the development. As is quanititatevly studied in [88] for a automobile industry. The modularistaion had measurable effect on the number of patents being produced. However, for example Tesla company seem to defy this theory. Since it achieved such a high performance via highly integral design process.

As is claimed in [79], the modularity and reconfigurability with it will be the key defining process in future of manufacturing. The point is made and demonstrated on the Bosch factories. Where it is shown that manufactuiring in future will become more decentralized thanks to modular design.

There are quite a few efforts to quntify the modularity of the converter such as [38] or [40]. However these are left without futher comments for now.

8.2.1. Why Modularity makes sense in LVDC ?

When examining the functionalities that a distribution converter should have in the future LVDC grid there is little reason to pick the modular design. The reasons comes from examining the market. The LVDC market can be much more different, where a variaty of products can be advantageous for the PE producer or the future TSO, so it can facillitate various grids. If LVDC is used in special cases it is very important to have a simple and cheap solution at hand very fast. This is where the modular approach can help.

Furthermore, when we examine the requirements we can realize that modular design is the only option. Since modularity can have positive effect on the long life, we can even design for it as in [69]. The losses at partial load can be reduced by only turning on fraction of the modules such as [57]. The redundancy N+1 is easily achieved with modular design [19].

As is described in [17] a very easy maintanacce can be achieved via utilizing hot-swap capability. Although, it comes with a prize of an extra switch for a leg.

The prices can be reduced, since the modular design provides and easy way for standarization... The solution can be even enviromentaly friendly in case we employ enviromentally friendly replacable approach as Xerox did in the pas [85].

The product architecture is a crucial term in the industrial design field. The product architecture can be defined as in Ulrich [85]:

Definition Product architecture is the scheme by which the functional elements of the product are arranged into physical chunks. The architecture of the product is established during the concept development and system-level design phases of development.

The physical chunks are major physical building blocks from original physical elements. The modularity of the product architecture follows from two things:

- how many functions the chunks implement
- how well are the interactions between the physical chunks defined

From here it follows that modular architectures are those in which the physical chunks implement a specific set of functional elements and has well-defined interactions with the other chunks. Ulrich defines three types of modularity:

- slot modularity
- bus modularity
- sectional modularity

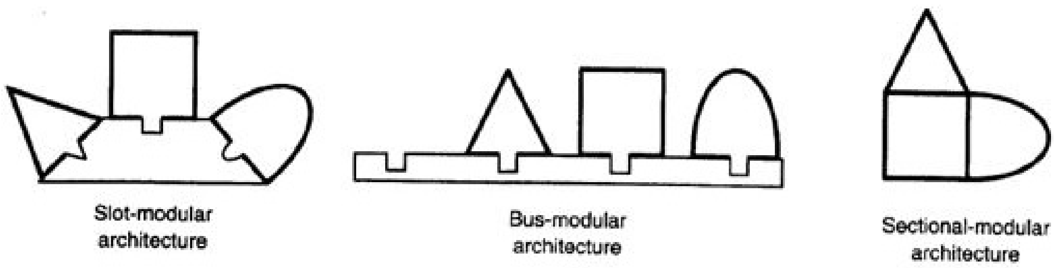


Figure 29: Ulrich types of modularity

Integral architecture is on the opposite side of the spectrum of architectures. For integral architecture it is typical that implementation of the functional elements is spread across tanks, and the interactions between the chunks are ill-defined. As is noted in [85], there is no strict line between the two architectures, rather it is possible to determine a level of modularity of the product.

The product architecture has implications on product change, product variety, component standardization, product performance[18], manufacturability(supply chain),and product development.

9. Modular Converter

9.1. Methodology

Inspired by the thoroughly described decision process during literature review in [78], I have selected criteria for finding a definition of modular topology/design in power electronic literature.

[18]Ulrich also notes that with integral architecture much higher performance of the product can be achieved.

On IEEE library I have selected only *journals & magazines*, furthermore the journals & magazines needed to be published under IEEE or IET. Then I have searched for two key words *modular* and *converter* in *document title* and *key words.*

Searching in document title yielded 316 results and searching in key words yielded 269 results. Then combining the two searches and eliminating the duplicates I had 393 results ranging from 1970 to 2016. Afterwards I have proceed with eliminating redundant papers based on following criteria:

1. Does not use module or modularity in any way connected to power electronics design (eg. modelling of converters based on module routines)
2. Spurious hits
3. Modular Multilevel Converter topics which dealt with fractional problems such as measurement of capacitor voltage, or other incremental knowledge which by no means is important. However, it does not contribute to discussion on modularity in any way.

Based on this initial screening 89 papers were selected. These papers were read for definitions of module, modularity, measure of modularity, distinction between modular and integral(?), for reasons why to choose modularity, advantages and disadvantages of modularity. Based on these results the rest of the report is based.

9.2. Gathered Motivations

The first publication identified with modular design of a converter is from 1970 [53]. In this publication a cascaded design of converter was proposed for satellite system. The main motivation for cascaded structure of several converters was the fact that until the very start of the satellite to the space it was not completely clear what voltage levels and power ratings will be needed. Furthermore, during preparation of the start these modules needed to be changed frequently. Thus a modular design was chosen, where the module was a DC-DC converter. This modularity could be describe in Ulrich' terms as bus modular. However, the replacement were possible only when the system was shut down, not as described in [17].

Then the development of modular converters, was picked due to need for higher power ratings in telecommunication centers as described in [70]. Or sometimes such as in [9] as power supply in laboratories when several DC-DC bus voltages were used as standard. In the 90' before the game changing publication of Marquardt, the modularity in converters was used to build three phase power factor correction converters. Where again modular design helped to increase flexibility in power dimension, and also to define a converter for each phase. The examples of this approach can be found in [35], [39], [36].

After publication of [64] an interest of researchers in modular design and topologies arose again. It does not make sense to mention all reviewed publications. However a certain difference between the publications can be found. There are two streams of research one which is continuation of research of interleaved converters, where different topologies in different connections are studied. In this stream mainly control algorithm are studied for voltage or current balancing. A notable exception is [18], where the power is not shared equally between the modules. Rather an optimal power sharing is sought based on optimal power rating of the converters, which is not necessarily equal along the converters. The second stream of research is continuation of exploration of MMC topology, its various hybrids, and different control mechanism or auxiliary power or black start, fault-ride-through etc.

Based on the literature review a following list of motivations and advantages was created:

- maintainability, ease of maintenance
- reduce propagation of faults
- reduce filtering requirements (eg. one capacitor at the output)
- use of well known LV technology for HV applications
- ease of power scalability
- reliability improvement (this is almost everywhere, but I am not sure that N+1 redundancy is the same as reliability)
- standardization
- reconfigurability
- efficiency and power density
- improve component utilization
- shorter design and production
- physically remove faulty modules
- distribute thermal stress
- plug'n'play
- LEGO design
- considering power module packaging $\implies$ size benefits
- versatility of the product
- transportable, various voltage levels

9.3. Modules definitions

For the stream of research specializing in MMC and related topologies, the most often used submodules can be taken from literature review [**?**]:

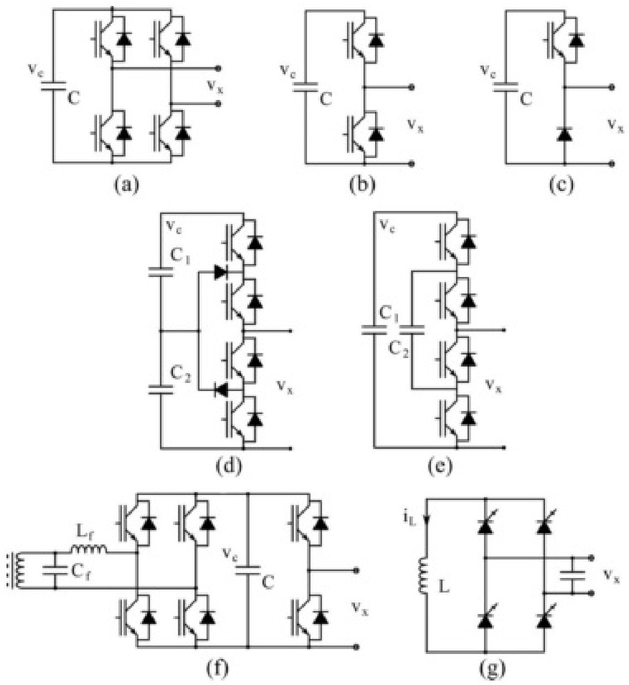


Fig. 4. Power cell topologies. (a) Full-bridge. (b) Half-bridge. (c) Unidirectional cell. (d) Multilevel NPC cell. (e) Multilevel flying capacitor cell. (f) Cell with resonant inverter for inductive power transfer. (g) Current source cell.

Figure 30

In [92] some hybrid modules are reviewed, mainly due to their capability of fault-ride-through. This ability, as shown is enhancing reliability(availability) of the MMC.

Here a picture of cells is missing since it seems redundant.

In the first stream of research, on interleaved converters, the modules are the converters itself. As such they can be either standard full-bridge(or DAB) [13], half-bridge [95], or Cuk [43].

Basically in both streams, the modularity is used as a term describing cascaded topology of the converter. The modularity is rarely understood as something more. A notable exception is [96], where the author mentions that a modular converter should be also modular from the point of view of grid management. And to become a very versatile substation asset, for transmission quality control and contingency management. In order to become such a thing the converter must not be modular only in the power dimension but also in the functionality dimension. Perhaps, somewhat in the application dimension as well.

A. Perhaps a practical issue

One of the problems Edison had was the fact he could not easily rise his voltage levels. Out of the comparison I had calculated the possible distances between the source and the load for LVDC if we use 350 V and allow either 3 % or 5 % of voltage drop.

I have only assumed the dc resistance of the cable, for the cable values I took AC cables:

- AX50
- AX95
- AX150

The limiting values of the cables are maximum current and the dc resistance. Furthermore, one important note. The cables have four pieces. If these pieces are connected in parallel the dc resistance is halved. However, we need a return path, which would double the dc resistance. Thanks to parallel connection, I can just use r_{dc} from the datasheet.

Cable	$r_{dc}[\Omega/\text{km}]$	I_{max} [A]
AX50	0.641	150
AX95	0.320	220
AX150	0.206	290

For the calculation of the allowable cable length I have used simple Ohm's law:

$$U_{\Delta_{wire}} = r_{DC} l_{wire} I_{wire} \tag{3}$$

where $U_{\Delta_{wire}}$ is the allowable voltage drop. In order to have a comparison with the power in the system, the equation 3 is multiplied by minimum allowable voltage. Then, the relationship between power and length of the cable becomes:

$$P = \frac{U_{\Delta_{wire}} (U_{nom} - U_{\Delta_{wire}})}{r_{DC} l_{wire}} \tag{4}$$

In case of higher voltage drop the distance for AX150 is not 350 meters but 550 meters. Just for the fun of it, a radius of 350 meters on the map is on the next figure.

This was a very simple calculation of how far we can supply DC power. The limitation of 350 V_{dc} is quite clear. Therefore it will be necessary to have an efficient converters which are able to change voltage levels, and have high efficiency during partial loads. Furthermore, they need to be able to limit the standby losses which can be very high.

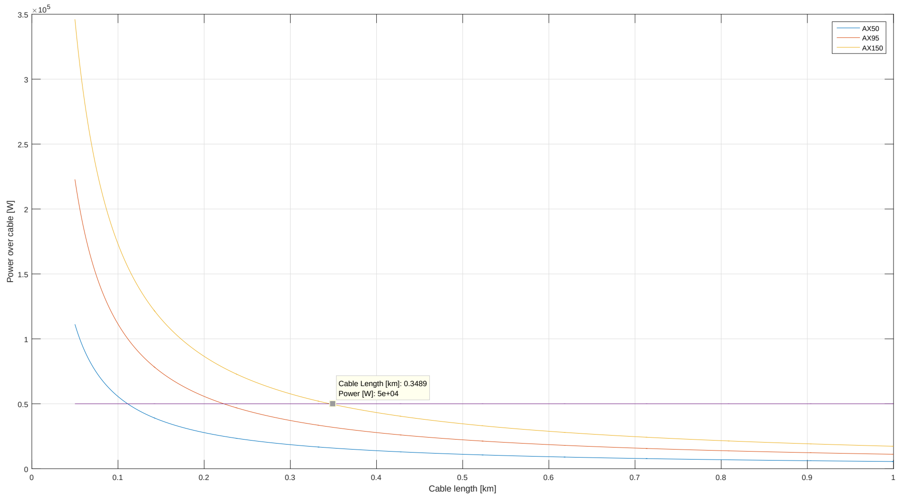


Figure 31: The power in the system as a function of the cable length when 3% voltage drop is allowed.

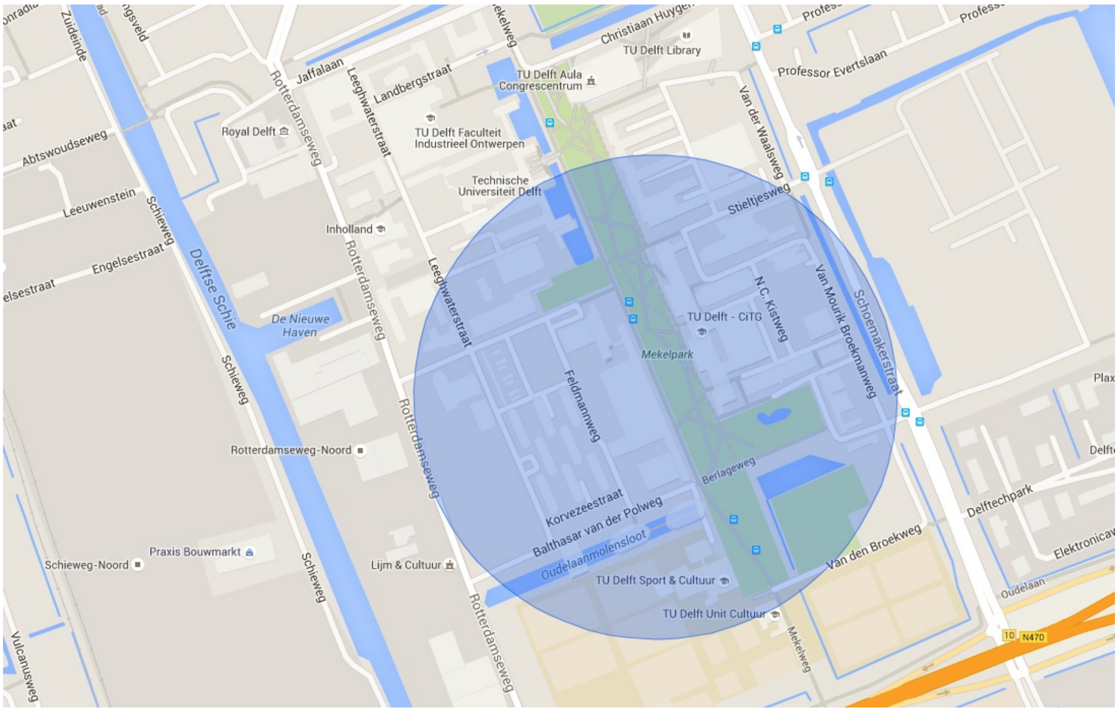


Figure 32: Mekelweg 4.

References

[1] Ferreira Jan Abraham. 867 : An Approach to deal better with Power Electronics Packaging. *Packaging (Boston, Mass.)*, 20(3):867, 2005.

[2] Copyright Julian M Allwood, Hong Kong, and North Pole. Sustainable Materials With Both Open Eyes. *New York*, (C):3–10, 2012.

[3] Company Although. Dc Transformer. pages 117–122.

[4] Mahmoud M. Amin and O. A. Mohammed. Design and implementation of DC-bus system module for parallel integrated sustainable energy conversion systems. *IEEE Power and Energy Society General Meeting*, pages 1–8, 2011.

[5] Nico Baars, Jordi Everts, Cornelis Wijnands, and Elena Lomonova. Performance Evaluation of a Three-Phase Dual Active Bridge DC-DC Converter with Different Transformer Winding Configurations. *IEEE Transactions on Power Electronics*, 31(10):1, 2015.

[6] Nico Baars, Jordi Everts, Korneel Wijnands, and Elena Lomonova. Impact of different transformer-winding configurations on the performance of a three-phase dual active bridge DC-DC converter. *2015 IEEE Energy Conversion Congress and Exposition, ECCE 2015*, pages 637–644, 2015.

[7] Reinhold Bayerer. Power Modules.

[8] Juergen Biela, Uwe Badstuebner, and Johann W. Kolar. Impact of power density maximization on efficiency of DC-DC converter systems. *IEEE Transactions on Power Electronics*, 24(1):288–300, 2009.

[9] J D Bishop. CONVERTERS.

[10] D. Boroyevich, R. Burgos, L. Arnedo, and a. Fei Wang Fei Wang. Synthesis and Integration of Future Electronic Power Distribution Systems Synthesis and Integration of Future Electronic Power Distribution Systems. {. . . } *-Nagoya, 2007. PCC'07*, pages K—-1—-K—-8, 2007.

[11] Dushan Boroyevich. From Power Electronics Devices to Electronic Power Systems . (June), 2015.

[12] Dushan Boroyevich, Igor Cvetkovic, Rolando Burgos, and Dong Dong. Intergrid: A future electronic energy network? *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 1(3):127–138, 2013.

[13] Antonio J B Bottion and Ivo Barbi. Input-Series and Output-Series Connected Modular Output Capacitor Full-Bridge PWM DC-DC Converter. *IEEE Transactions on Industrial Electronics*, 62(10):6213–6221, 2015.

[14] Jonathan Bradshaw. Integration Technologies for a Fully Modular and Hot Swappable MV Multi-Level Concept Converter. 2015.

[15] Sudipta Chakraborty, Bill Kramer, and Benjamin Kroposki. A review of power electronics interfaces for distributed energy systems towards achieving low-cost modular design. *Renewable and Sustainable Energy Reviews*, 13(9):2323–2335, 2009.

[16] Levy F Costa, Giampaolo Buticchi, Marco Liserre, and Christian-albrecht-university Kiel. Quad-Active-Bridge as Cross-Link for Medium Voltage Modular Inverters. pages 645–652, 2015.

[17] Didier Cottet, Francesco Agostini, Thomas Gradinger, Rudi Velthuis, Bernhard Wunsch, David Baumann, Willi Gerig, Andrea Ruetschi, Dacfey Dzung, Harald Vefling, Anne Elisabeth Vallestad, Dalimir Orfanus, Reidar Indergaard, Tormod Wien, and Wim Van Der Merwe. Integration technologies for a medium voltage modular multi-level converter with hot swap capability. *2015 IEEE Energy Conversion Congress and Exposition, ECCE 2015*, pages 4502–4509, 2015.

[18] Bridge Dc-dc. SINGLE-ACTIVE. pages 43–52, 2016.

[19] De Doncker and Storage Systems. Distribution Grids. pages 736–743, 2014.

[20] D Dong, F Luo, X Zhang, D Boroyevich, and P Mattavelli. Grid-Interface Bidirectional Converter for Residential DC Distribution Systems-Part Two: AC and DC Interface Design With Passive Components Minimization. *IEEE Trans. on Power Electron.*, 28(4):1667–1679, 2013.

[21] Tomislav Dragicevic, Juan Vasquez, Josep Guerrero, and Davor Škrlec. Advanced LVDC Electrical Power Architectures and Microgrids. *IEEE Electrification Magazine*, 2(1):54–65, 2014.

[22] Kristof Engelen, Erik Leung Shun, Pieter Vermeyen, Ief Pardon, D Reinhilde, Johan Driesen, and Ronnie Belmans. The Feasibility of Small-Scale Residential DC Distribution Systems. pages 2618–2623, 2006.

[23] Manuel a Vargas Evans. Why Low Voltage Direct Current Grids? page 138, 2013.

[24] EY. Megatrends 2015: Making Sense of a World in Motion. pages 1–54, 2015.

[25] E W I Faculty. ECPE Tutorial Power Electronics Packaging . (September):24–25, 2014.

[26] Haifeng Fan and Hui Li. High-frequency transformer isolated bidirectional DC-DC converter modules with high efficiency over wide load range for 20 kVA solid-state transformer. *IEEE Transactions on Power Electronics*, 26(12):3599–3608, 2011.

[27] Feasibility of DC transmission networks. IEEE Xplore - Feasibility of DC transmission networks. pages 1–8.

[28] Jan Abraham Ferreira and Daan Van Wyk. Electromagnetic energy Propagation in Power Electronic Converters: Toward Future Electromagnetic Integration. *Proceedings of the IEEE*, 89(6):876–888, 2001.

[29] Charles H. Fine. Are You Modular or Integral? Be Sure Your Supply Chain Knows, 2005.

[30] T F Garrity. Innovation and trends for future electric power systems. *2009 Power Systems Conference*, pages 1–8, 2009.

[31] M. Hajian, D. Jovcic, G. Asplund, and H. Zhang. Power flow control in DC transmission grids using mechanical and semiconductor based DC/DC devices. *10th IET International Conference on AC and DC Power Transmission (ACDC 2012)*, page 43, 2012.

[32] Tomi Hakala and Tommi Lähdeaho. 23 rd International Conference on Electricity Distribution Paper 0874 LVDC PILOT IMPLEMENTATION IN PUBLIC DISTRIBUTION NETWORK 23 rd International Conference on Electricity Distribution Lyon , 15-18 June 2015. (June):15–18, 2015.

[33] Tomi Hakala, Tommi Lähdeaho, and Pertti Järventausta. Low-Voltage DC Distribution Utilization Potential in a Large Distribution Network Company. 30(4):1694–1701, 2015.

[34] Alex Hanson, Julia Belk, Seungbum Lim, Charles Sullivan, and David Perreault. Measurements and Performance Factor Comparisons of Magnetic Materials at High Frequency. *IEEE Transactions on Power Electronics*, page 1, 2016.

[35] E Ho, R Hui, and S Lee. tion acto DC-. 34(24):2300–2301, 1998.

[36] Y. K Eric Ho, S. Y R Hui, and Yim Shu Lee. Characterization of single-stage three-phase power-factor-correction circuit using modular single-phase PWM dc-to-dc converters. *IEEE Transactions on Power Electronics*, 15(1):62–71, 2000.

[37] Alex Q. Huang and Rolando Burgos. Review of Solid-State Transformer Technologies and Their Application in Power Distribution Systems. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 1(3):186–198, 2013.

[38] Chun Che Huang and Andrew Kusiak. Modularity in design of products and systems. *IEEE Transactions on Systems, Man, and Cybernetics Part A:Systems and Humans.*, 28(1):66–77, 1998.

[39] S Y R Hui, Yk E Ho, and H Chung. Modular single-stage, three-phase f ull-bridge converter with inherent power factor correction and isolated output.

[40] Y J Ji, R J Jiao, L Chen, C L Wu, H Li, and A Leader-follower Decision Making. A Game Theoretic Model for Analysis of Material Reuse Modularity. pages 2214–2218, 2012.

[41] Dragan Jovcic, Mohsen Taherbaneh, Jean Pierre Taisne, and Samuel Nguefeu. Developing regional, radial DC grids and their interconnection into large DC grids. *IEEE Power and Energy Society General Meeting*, 2014-Octob(October), 2014.

[42] Juliana Hsuan Mikkola. Managing Modularity of Product Architectures - Toward an Integrated Theory. *204 Ieee Transactions on Engineering Management*, VOL. 50(2):204–218, 2003.

[43] Uthen Kamnarn and Viboon Chunkag. Analysis and design of a modular three-phase AC-to-DC converter using CUK rectifier module with nearly unity power factor and fast dynamic response. *IEEE Transactions on Power Electronics*, 24(8):2000–2012, 2009.

[44] Hr Karshenas and Hamid Daneshpajooh. Bidirectional DC-DC Converters for Energy Storage Systems. *Energy Storage in the Emerging ERA of Smart Grids*, pages 162–178, 2011.

[45] Faisal Habib Khan. Modular DC-DC converters. *ProQuest Dissertations and Theses*, Ph.D., 2007.

[46] Hongrae Kim, Babak Parkhideh, Tim D. Bongers, and Heng Gao. Reconfigurable solar converter: A single-stage power conversion PV-battery system. *IEEE Transactions on Power Electronics*, 28(8):3788–3797, 2013.

[47] J W Kolar. Research Challenges and Future Perspectives of Solid-State Transformers Research Challenges and Future Perspectives of Solid-State Transformers. pages 1–90, 2015.

[48] J. W. Kolar, J. Biela, and J. Minib??ck. Exploring the Pareto front of multi-objective single-phase PFC rectifier design optimization - 99.2{%} Efficiency vs. 7kW/dm3 power density. *2009 IEEE 6th International Power Electronics and Motion Control Conference, IPEMC '09*, pages 1–21, 2009.

[49] J. W. Kolar, J. Biela, S. Waffler, T. Friedli, and U. Badstuebner. Performance trends and limitations of power electronic systems. *2010 6th International Conference on Integrated Power Electronics Systems*, pages 1–20, 2010.

[50] Johann W. Kolar. What are the "Big Challenges" in Power Electronics? *8th International Conference of Integrated Power Electronics Systems (CIPS)*, pages 1–112, 2014.

[51] Johann W Kolar and Gabriel Ortiz. Solid-State-Transformers : Key Components of Future Traction and Smart Grid Systems. (Ipec), 2014.

[52] Phyo Aung Kyaw and Charles R Sullivan. Fundamental examination of multiple potential passive component technologies for future power electronics. 2015.

[53] Landsman. M O D U L A R CONVERTERS FOR SPACE P O W E R SYSTEMS. *Air Force*, 1970.

[54] Robert H Lasseter and Paolo Paigi. Microgrid : A Conceptual Solution. pages 4285–4290, 2004.

[55] Jinghua Li and Yan Lu. Cross-fields study of modularity. *ICMIT 2006 Proceedings - 2006 IEEE International Conference on Management of Innovation and Technology*, 2(70402016):595–599, 2006.

[56] Marco Liserre. MARCO LISERRE, THILO SAUTER, and JOHN Y. HUNG. (March):18–37, 2010.

[57] Marco Liserre, Giampaolo Buticchi, Markus Andresen, Giovanni De Carne, and Levy Ferreira Costa. The Smart Transformer. *IEEE Industrial Electronics Magazine*, (June), 2016.

[58] Oscar Lucia, Igor Cvetkovic, Dushan Boroyevich, Paolo Mattavelli, and Fred C. Lee. Design of household appliances for a Dc-based nanogrid system: An induction heating cooktop study case. *Conference Proceedings - IEEE Applied Power Electronics Conference and Exposition - APEC*, pages 1576–1583, 2013.

[59] Xing Luo, Jihong Wang, Mark Dooner, and Jonathan Clarke. Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Applied Energy*, 137:511–536, 2015.

[60] Laurens Mackay, Tsegay Hailu, Laura Ramirez-Elizondo, and Pavol Bauer. Decentralized current limiting in meshed DC distribution grids. *2015 IEEE 1st International Conference on Direct Current Microgrids, ICDCM 2015*, pages 234–238, 2015.

[61] Laurens Mackay, Tsegay Hailu, Laura Ramirez-elizondo, and Pavol Bauer. Towards a DC Distribution System Opportunities and Challenges. *DC Microgrids (ICDCM), 2015 IEEE First International Conference on DC Microgrids*, pages 215–220, 2015.

[62] Laurens Mackay, Tsegay Gebremedhin Hailu, Gautham Chandra Mouli, Laura Ramirez-Elizondo, J. A. Ferreira, and Pavol Bauer. From DC nano- and micro-grids towards the universal DC distribution system - A plea to think further into the future. *IEEE Power and Energy Society General Meeting*, 2015-Septe, 2015.

[63] Chris Marnay, Spyros Chatzivasileiadis, Chad Abbey, Reza Iravani, Geza Joos, Pio Lombardi, Pierluigi Mancarella, and Jan Von Appen. Microgrid evolution roadmap. *Proceedings - 2015 International Symposium on Smart Electric Distribution Systems and Technologies, EDST 2015*, (August 2010):139–144, 2015.

[64] R. Marquardt, A. Lesnicar, and J. Hildinger. Modulares Stromrichterkonzept für Netzkupplungsanwendungen bei hohen Spannungen. *ETG Fachtagung*, 2002.

[65] A Mohamed, Student Member, and O Mohammed. Power Flow Control in DC Distribution Systems.

[66] Subrata Mondal, Member Ieee, and Earl Keisling. Efficient Data Center design using Novel Modular DC UPS , Server Power supply with DC voltage and Modular CDU cooling. 2012.

[67] Mingkai Mu and Fred C Lee. Comparison and Optimization of High Frequency Inductors for Critical Model GaN Converter Operating at 1MHz. pages 0–4, 2014.

[68] Qing Mu, Jun Liang, Yalou Li, and Xiaoxin Zhou. Power flow control devices in DC grids. *2012 IEEE Power and Energy Society General Meeting*, pages 1–7, 2012.

[69] Patrick J. Newcomb, Bert Bras, and David W. Rosen. Implications of modularity on product design for the life cycle. *Proceedings of the 1996 ASME Design Engineering Technical Conference and Computer in Engineering Conference*, 120(September 1998):1–12, 1996.

[70] P Nuechteriein. = I. pages 223–226.

[71] E. Ortjohann, M. Lingemann, W. Sinsukthavorn, A. Mohd, A. Schmelter, N. Hamsic, and Danny Morton. A general modular design methodology for flexible smart grid inverters. *2009 IEEE Power and Energy Society General Meeting, PES '09*, pages 1–8, 2009.

[72] White Paper, Neil Rasmussen, and James Spitaels. A Quantitative Comparison of High Efficiency AC vs . DC Power Distribution for Data Centers. 2012.

[73] M. Pavlovsky. *Electronic DC Transformer with High Power Density*. 2006.

[74] Jelena Popovic. *Improving packaging and increasing the level of integration in power electronics*. 2005.

[75] Allianz Risk Pulse. The megacity state: The world's biggest cities shaping our future. (November), 2015.

[76] Giusi Quartarone, Marco Liserre, Friedrich Fuchs, and Norma Anglani. Impact of the modularity on the efficiency of Smart Transformer solutions.

[77] Rohm. SiC Power Devices and Modules. (August):1–40, 2014.

[78] Fabrizio Salvador. Toward a product system modularity construct: Literature review and reconceptualization. *IEEE Transactions on Engineering Management*, 54(2):219–240, 2007.

[79] Christian Sch??fer. On the modularity of manufacturing systems. *IEEE Industrial Electronics Magazine*, 1(3):20–27, 2007.

[80] Xu She, Alex Q. Huang, Srdjan Lukic, and Mesut E. Baran. On integration of solid-state transformer with zonal DC microgrid. *IEEE Transactions on Smart Grid*, 3(2):975–985, 2012.

[81] Wei Shen. Design of High-density Transformers for High-frequency High-power Converters. 2006.

[82] Michael Starke, Senior Student Member, Leon M Tolbert, and Senior Student Member. AC vs . DC Distribution : A Loss Comparison. 2008.

[83] Yipeng Su, Qiang Li, Mingkai Mu, and Fred C Lee. High Frequency Inductor Design and Comparison for High Efficiency High Density POLs with GaN Device. pages 2146–2152, 2011.

[84] Energy Technology and Don Tan. Power Electronics in Power Electronics in. *IEEE Power Electronics Magazine*, 2(June):38–47, 2015.

[85] Ulrich and Eppinger. Product Design and Development, 2004.

[86] J D van Wyk and F C Lee. On a Future for Power Electronics. *Emerging and Selected Topics in Power Electronics, IEEE Journal of*, 1(2):59–72, 2013.

[87] S. Waffler, M. Preindl, and J. W. Kolar. Multi-objective optimization and comparative evaluation of Si soft-switched and SiC hard-switched automotive DC-DC converters. *IECON Proceedings (Industrial Electronics Conference)*, pages 3814–3821, 2009.

[88] Hailong Wang and Ming Huang. Modularity and Discontinuous Innovation : A Patent Data Analysis in Automobile Industry. (70903009):2235–2241, 2010.

[89] Zhaohui Wang, Zhen Zhang, Junming Zhang, and Kuang Sheng. Power electronic transformer for dc power distribution network. *2014 International Power Electronics and Application Conference and Exposition*, pages 805–810, 2014.

[90] J D Van Wyk. Power Electronics Quo Vadis ? (a Historical and Philosophical Perspective). pages 1–9, 2012.

[91] Feng Xu and Zheng Xu. A modular multilevel power flow controller for meshed HVDC grids. *Science China Technological Sciences*, 57(9):1773–1784, 2014.

[92] Jianzhong Xu, Penghao Zhao, and Chengyong Zhao. Reliability analysis and redundancy configuration of MMC with hybrid submodule topologies. *IEEE Transactions on Power Electronics*, 31(4):2720–2729, 2016.

[93] Tao Yang, Cathal O Loughlin, Ronan Meere, and Terence O Donnell. Solid State Transformers ZwL) ZwL). 2014.

[94] Tao Yang, Ronan Meere, Killian Mckenna, and Terence O Donnell. Evaluate Modular Solid State Transformer and Low-Frequency Distribution Transformer under the Daily Loading Profile Keywords. *2015 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe)*, pages 1–10, 2015.

[95] X Yao, Y Huang, F Guo, and J Wang. Advanced Concepts for Vertical Stability Power Supply in Fusion Devices. *Ieee Transactions on Plasma Science*, 40(3):761–768, 2012.

[96] Nima Yousefpoor, Babak Parkhideh, Ali Azidehak, Subhashish Bhattacharya, and Bruce Fardanesh. Modular transformer converter-based convertible static transmission controller for transmission grid management. *IEEE Transactions on Power Electronics*, 29(12):6293–6306, 2014.

[97] Yingjie Zhou, Nicholas Maxemchuk, Xiangying Qian, and Chen Wang. The fair distribution of power to electric vehicles: An alternative to pricing. *2014 IEEE International Conference on Smart Grid Communications, SmartGridComm 2014*, pages 686–691, 2015.