Autonomous Distribution Grids of the Future
– The specific Role of Fuses

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Introduction
One of the most important tasks of mankind is the preservation of our planet for the generations to come. Therefor civilization based global warming has to be reduced to a minimum. Efficient and effective decarbonisation of economy and society is one of the key elements of this strategy. Use of fossil fuels, above all coal and oil, has to be reduced substantially in short term. The future role of nuclear which is a nearly carbon dioxide free, however, risky technology is heavily disputed. Natural gas has low carbon dioxide emissions and can be used with high efficiencies. Thus, it can take the role of a transition energy carrier. Without taking technologies into account, like nuclear fusion, which still need substantial and long-term technical development and where technical and economic feasibility is not clear so far, the focus has to be put on renewable energy sources. With respect to the electricity system, a clear distinction has to be made between controllable (e.g. hydro, biomass, geothermal or solar with batteries) and non-controllable renewable energies (e.g. wind or solar). The higher the percentage of non-controllable energy sources, the higher is the volatility of load flows and the more complex is the technical solution. Controllable and flexible back-up power plants, demand side management as well as storages become important components in order to create a stable electricity system. The electrical grid as the platform between these components has to be put into the position to manage the increased volatility of load flows. Better and suitable information on the volatile load flow in combination with new dynamic components allows to get access to the inherent technical reserves of the existing grid infrastructure. The result are so-called "Smart Grids". The change in electricity generation leads not only to changes of the load flow but also has an impact on the short circuit power. More converters are connected to the grid, sources with new characteristics occur and the total mechanical inertia of electric generators is reduced. The system of power frequency control but also the role of fuses has to be reconsidered. The coupling of the energy carriers electricity, gas and heat through power-to-heat (electric boilers) and power-to-gas (hydrogen electrolysers) devices allows to create new demand side management and storage options. Finally, the system to be established will also have links to other sectors like mobility, producing industry and housing industry. Assets are replacing fuel, which leads to more capital and less fuel costs. Finally, the legal set up has to be adjusted to the new system.

Overall, we are starting a fundamental transformation process of energy, industry but also society, which has to be designed in a holistic way.

This paper is focusing on the German energy strategy, the so-called “Energiewende”, which aims to have an electricity system that is based on wind and solar energy at the latest by 2050. In this context the management of volatile load flows through smart grids but also the future situation with respect to short circuit currents and the specific role of fuses in the electric grid are analyzed and discussed.

Electricity generation in a system based on renewable energy sources

Controllable renewable energy sources like hydro, biomass or geothermal power plants which are connected through synchronous generators to the electricity system in general have the same technical characteristics as the conventional thermal nuclear or fossil power plants. Only the percentage of energy feed into the lower voltage levels will increase, as the power of these power plants might be smaller. Additionally, converter connected systems might occur. The situation is changing when non-controllable energy sources like wind and solar are used to a larger extent. They are mainly connected to the distribution grid by converters, show a low availability time and the generation is highly volatile with steep gradients. The low availability time of the energy sources wind and solar but also their low energy density requires the installation of a high generation power. The management of this power is one of the main technical challenges of such a system. As far as the percentage of volatile renewable energy sources in an electric system is below 35 % the installed renewable generation power will be below the peak demand. This means, reinforcement and extension of the electrical grid, flexible conventional back-up power plants and limited generation curtailing are sufficient in order to keep the system stable. An increase of the percentage of volatile generation up to 60 % requires extended demand side management as the installed power is exceeding the peak demand. Power-to-heat and the use of thermal masses, like district heating systems but also buildings, as energy buffers is an appropriate and economic solution. Heading for the level of an 80 % share of volatile renewables in the systems, as it is the case in the German Energiewende, means to build energy storages. Batteries, pumped hydro and hydrogen production through power-to-gas devices are appropriate technologies.

It has to be noted that heat-controlled combined heat and power (CHP) systems are increasing the volatility on the generation side as well.

Summarized, electricity systems that are based on volatile energy sources with a low availability time have to cope with a substantial power challenge.

Energy efficiency and energy use on the consumption side

The described electricity system which is based on volatile renewable energy sources has to be completed by efficient and flexible use of energy on the consumption side. Efficient use of electricity means the installation of modern and efficient appliances like low energy fridges or dryers but also the deployment of efficient technologies like electric vehicles or heat pumps. Increase of efficiency often means the transformation of non-electric options into electric ones. However, many of these technologies, e.g. electric vehicles or heat pumps, need high power supply. High energy efficiency on the consumption side without taking heating, cooling and mobility into account is not feasible. Again, coupling of energy carriers is key. Energiewende has to become a real turnaround of energy strategy and doesn't have to be restricted to the electricity sector. Buildings are becoming central elements of the transformation process. They will be partially self-sufficient and will support demand side management, buffering and storing of energy. Thus, they will contribute to the control of the volatile renewable based electricity generation.

Effective and efficient implementation to the new energy system

The transformation of the energy system leads to a reduced use of fuel, however, it needs capital in order to build the new infrastructure. There are some principles which allow to minimize the amount of capital and the range of infrastructure and thus contribute to the economy of the new system.

Diversity on the generation side with respect to type and location of generators but also time of generation supports the stabilization of the electricity system. A mix of different generation patterns levels volatility to a certain extent. The higher the percentage of volatile energy sources in the overall generation portfolio the more valuable becomes homogenous generation. Above all, this allows to reduce the necessary storage capacity.

Modification of existing infrastructure and adding new features is an appropriate means to reduce the capital employed. One good example is the use of district heating systems as a buffer for temporary surplus generation by installing power-to-heat technologies. Also multiple use of devices has the same effect. A battery can be used to contribute to the self-sufficiency of a building. However, there will be always some free storage capacity for a certain time period. With a smart algorithm this free storage capacity can be managed and e.g. used to support the voltage control of the electric grid.

Finally, the principle of subsidiarity combined with the principle of Pareto – 20 % of total expenses create 80 % of the benefit – has to be applied. The most economic implementation of a system based on renewable energy sources is achievable when a modular system is established. There will be generation, storage and buffering on the level of a building, a quarter, a city, a region, a country and Europe. Diverse modules have to be connected and each module has to contribute to a reasonable extent with subsidiary means to the energy balance of the whole system.

Autonomous distribution grids

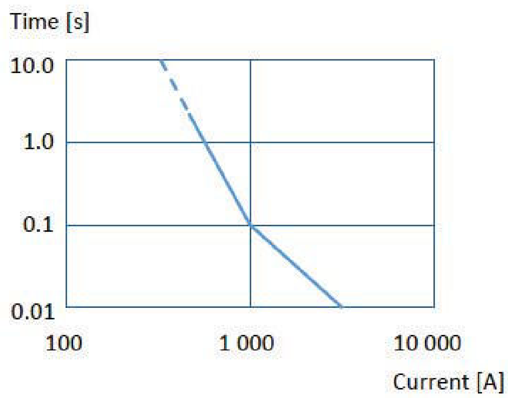
The system described needs a platform in order to exchange energy between the different locations of generation, storage and consumption. The platform has to be flexible and it will not be possible, due to economic reasons, to build a static grid that is able to deal with the high renewable generation power but also with the power of the new electricity applications. Of course, grid reinforcement and grid extension, e.g. for transportation of energy from one module to another, as well as new lines for the connection of renewable energy sources are necessary. However, future design of distribution grids has to take the fact into account that about 50 % of the installed grid capacity is used to transport about 5 % of the energy. Load leveling, i.e. generation and demand side management, including 5 % of the energy allows nearly to double the transported volume of energy. One practical solution in order to exploit this potential is the smart grid concept iNES [1]. In a low voltage system about 5 % of all nodes (generator, consumer, prosumer or connecting point of cables) is equipped with a four phase (L1, L2, L3 and N) voltage and current sensor. The measured dynamic data are transferred through broad band power line carrier technology to a small computer that is located in the MV/LV transformer station. With the help of static grid topology data and a state estimation algorithm – dealing with underdetermined systems – all currents in all branches and all voltages in all nodes are calculated on-line. Despite the fact that the system is substantially underdetermined the accuracy of the result is better than ±1%. The system identifies overloaded grid components as well as nodes with over- or undervoltage. Grid based actors like controllable transformers or voltage controllers in the lines or cables are addressed by the central control unit through power line carrier signals. In about 80 % of all cases grid based measures are able to bring the system back to the rated operation mode. In about 20 % of all cases customers have to be addressed directly. This is done in a minimum invasive manner and adjustment of reactive power is preferred to influence the customer's active power consumption or generation. The whole system works autonomously. On-line data are taken from the public grid. This guarantees data privacy. There is no permanent connection between the control computer and the internet. The system is isolated and thus data protection has a very high level. Smart low voltage grids together with smart transformer stations can be connected as well. The result is a smart medium voltage system where the central control unit is located in the HV/MV substation. The working principles are the same, only the model is reduced to a single phase system.

The implementation principles modification of existing assets by adding new features as well as subsidiarity and modular structure can be recognized. The overall target of this smart grid design is local congestion management, i.e. control of load flow and voltage.

Characteristics of fuses

One of the central elements of electrical systems are electrical fuses in medium and low voltage systems. As a rule, they are used to protect the MV/LV transformer, the low voltage bus bar and the low voltage grid with respect to short circuits fed by the medium voltage grid. Fuses are extremely fast and reliable, they are not direction sensitive and must be replaced having been active once. Fuses have a characteristic function between short circuit current and switching time, shown illustratively in Fig. 1a. This allows a selective arrangement of fuses. Additionally, fuses are limiting the instantaneous value of the short circuit current to a certain level. This value is depending on the short circuit current and the rated current of the fuse. The lower the rated current, the lower is the maximum instantaneous value of the forward current. Fig. 1b shows this illustratively.

Summarized, fuses manage short circuits in a not direction sensitive way, however, they also need sufficient levels of short circuit currents in order to work properly.



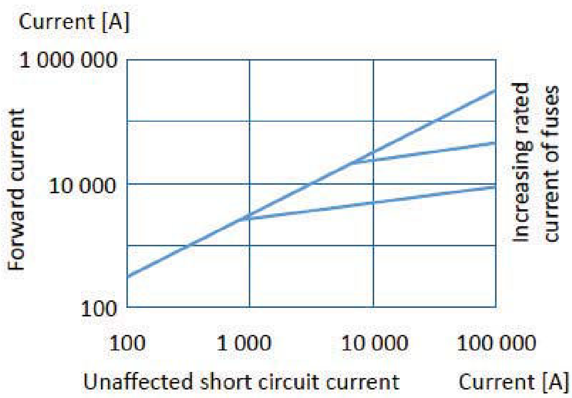


Fig. 1a: Characteristic of a fuse – function between short circuit current (effective value) and switching time
Fig. 1b: Forward current of a fuse – function between short circuit current (effective value) and forward current (instantaneous value)

Generation system	Initial short circuit alternating current
Synchronous generator	8 x rated current
Asynchronous generator	6 x rated current
Doubly fed induction generator	3 x rated current
Converter fed source	1 x rated current

Table 1: Maximum acceptable contribution of different generator systems to the short circuit current as a multiple of the respective rated current [2]

Energy carrier	Voltage level	Generator system
Electricity sources using kinetic energy of inertia of generator, turbine, gear and other rotating elements		
Conventional heat power plants	HV	Synchronous generator
	Extra HV	Synchronous generator
Hydro power plant	LV	Asynchronous generator
	MV	Synchronous generator with converter Synchronous generator
Wind energy and wind farms	LV	Asynchronous generator Synchronous generator with converter Permanent magnet synchronous generator with converter
	MV	Synchronous generator Synchronous generator with converter Asynchronous generator Doubly fed induction generator Permanent magnet synchronous generator with converter
	HV	Synchronous generator with converter Doubly fed induction generator Permanent magnet synchronous generator with converter
	Extra HV	Synchronous generator with converter Doubly fed induction generator Permanent magnet synchronous generator with converter
Biomass	LV	Synchronous generator with converter
	MV	Synchronous generator
Electricity sources without inertia in the generation system		
Photovoltaic	LV	Solar generator with converter
	MV	Solar generator with converter
	HV	Solar generator with converter

Table 2: Generation systems in different plants [2]

Change of generation system

As described above the generation portfolio will change substantially during the transformation process of the energy system. A detailed analysis of the development of the short circuit current in the German electricity system can be found in [2]. Generators with inertia directly connected to the grid will be reduced and through converter connected generators with and without inertia will be increased. According to Table 1 an overall reduction of synchronous and asynchronous generation capacity together with an increase of converter fed sources will result in an overall reduction of short circuit power. Table 2 shows the dissemination of generations systems within the different voltages as well as the related primary energy carriers. The conclusion of the analysis described in [2] is shown in Table 3. In midterm an overall reduction of short circuit power in all voltages in the range of 30 % has to be expected.

Voltage Level	2010	2011	2022	2032
	Reference Year	Actual Data	Scenario B	Scenario B
220 – 380 kV	100,0	100,0	105,6	93,2
110 kV	100,0	100,5	67,5	60,7
10 – 35 kV	100,0	93,2	94,5	75,2
0,4 kV	100,0	101,6	70,9	80,3

Table 3: Change of weighted contribution to the short circuit power in comparison with the reference year for the individual voltage levels [2]

Generally, the analysis in [2] allows the conclusion, that the overall top-down short circuit current will be reduced, due to a chance in the generation portfolio. In this respect it should be noticed that transformers, lines and cables are the main contributors to grid impedance and thus they are dominant with respect to the level of short circuit power. However, the analysis also allows to conclude that a substantial overall bottom-up short circuit current, doesn’t have to be expected. Most of the low and medium voltage connected generators are connected through converters where rated and short circuit current are nearly identical.

Of course, [2] shows a general picture an there will be areas, e.g. in suburbs, where small and midsize combined heat and power generators will increase the short circuit power and measures to control this development have to be taken. There are many examples where short circuit limiters have to be installed. In this respect also undervoltage protection of energy sources has to be mentioned. In case of a short circuit dispersed generators are disconnected form the grid within some seconds.

With respect to future developments, the upcoming building integrated photovoltaic has the potential to further increase the installed generation capacity in low and medium voltage grids to a substantial extent. This might accelerate or even strengthen the development described in Table 3. Independently from the converter photovoltaic modules have the characteristic feature that rated current and short circuit current are equal.

Impact on fuses and conclusions

Fuses will keep their role even the electric system will undergo fundamental changes within the next couple of years. There is no competition between smart grids and fuses. They have a different focus. Congestion as well as short circuits have to be managed. Due to the change in the generation portfolio an overall trend of top down short circuit power reduction seems to occur. In a first evaluation this reduction seems to have no severe impact on the use of fuses. Local situations might differ from this trend. Specific analysis is requested. Bottom-up short circuit power seems to play no dominant role. As a rule dispersed generation is connected through converters which don't contribute to the short circuit power substantially.

Summarized, fuses will keep their traditional role for the predictable future, specific local situation has to be analysed and further transformation of the electricity system needs close observation.

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