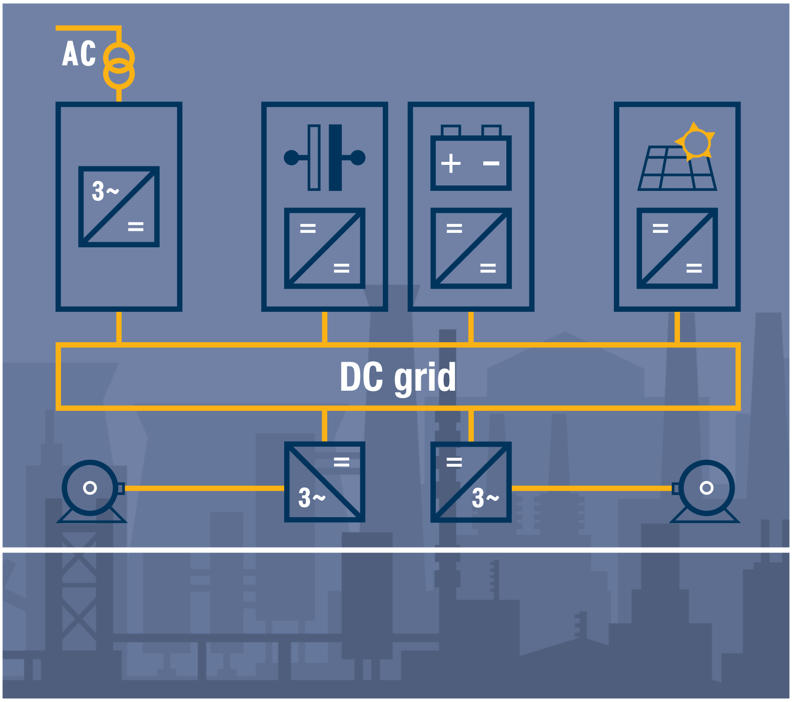
Alexander Sauer (Ed.)

The DC-Factory

Energy efficient. Robust. Forward-looking.



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The Editor:

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Contents

Preface

The book “The DC-Factory. Energy efficient. Robust. Forward-looking.” gives a deep insight into the results of the research project DC-INDUSTRIE. It aims to motivate companies to rethink their own energy supply. A variety of arguments and incentives for this can be found in the following chapters.

Renewable energies usually produce direct current (DC). This is initially converted into alternating current (AC) and fed into the grid. Power electronic devices in the factory then convert this back into direct current, for example to drive electric motors. Storage solutions usually work with direct current, too. Transformations from direct current to alternating current and vice versa, however, damage the quality of supply due to the rapid switching of power semiconductors. In industrial companies this can lead to EMC problems and thus to production damage.

On the other hand, the characteristics of production in DC grids are manifold: high quality, efficient, resource-saving, robust, and inexpensive.

A DC factory, for example, does not need conversion stages in frequency converters or in PV inverters. It saves on components and the remaining devices can be smaller. There is also a lot to be saved with respect to cables. Unlike the industrial 3-phase AC grid, a DC grid is 2-phase. This means that one, sometimes even two conductors in the cabling are no longer necessary. A further efficiency effect is that the braking energy of electric motors can be fed back into the grid more easily.

As a smart grid, today's DC grid can split the power flow between different storage devices and consumers. This makes the supply of direct current particularly robust. With low process dynamics, a battery can reduce the connected load; with higher dynamics, a capacitor can compensate for short-term power boosts. If a lot of power is needed, a flywheel mass storage can be added. The interaction of these technologies was successfully implemented and tested in the DC-INDUSTRIE research project.

The factory's power supply in the DC grid will be even more cost-effective if time-flexible energy tariffs can be used. This is because the system can then change the operating points of the storages and of the controllable consumers by means of a higher-level grid control. In this way, for example, the degree of utilization of the self-generated energy is influenced.

This book on the DC factory addresses all the important questions that arise when the voltage type is changed from AC to DC. Experts explain in detail – and yet easily understandable for the interested layperson – how a DC factory works, what its advantages are and how it can be implemented.

I would like to personally thank all the companies involved and especially the many dedicated experts for their work on the first implementation of an open DC grid in industrial plants and for their support in the preparation of this book. Special thanks go to the Federal Ministry of Economics and Energy (BMWi), which supported the work, as well as to the *Heinz and Heide Dürr Foundation* and the *Karl Schlecht Foundation* for financing this book.

Stuttgart, July 2020

Alexander Sauer

Head of the Institute for Energy Efficiency in Production (EEP) and the Fraunhofer Institute for Production Engineering and Automation (IPA)

Climate change is currently one of the greatest challenges facing humanity. In order to be able to counteract climate change, it is necessary to drastically reduce global CO_2 emissions. This can only be achieved by decarbonizing the current energy production landscape. The expansion and integration of renewable energies into the existing power grid will make a major contribution to this. However, this is accompanied by the great challenge, especially for industrial companies, to be able to react optimally to fluctuating energy supplies and the associated lower quality of energy supply without letting this negatively affect the underlying production process.

In addition to the decarbonization of energy production, increasing efficiency within the numerous energy conversion chains plays a decisive role on the way to a more sustainable and environmentally friendly industrial landscape. Especially considering that in Germany, for example, approximately 45% of electrical energy consumption is accounted for by industry alone.

The DC-INDUSTRIE research consortium, funded by the German Federal Ministry of Economics and Technology (BMWi), has devoted three years of intensive work to the above-mentioned challenges with the development of the world's first open industrial DC grid for factory automation. The primary goal of the project was to ensure a demand-oriented distribution of energy within production plants with a maximum of energy reuse and a minimization of conversion losses. This work has resulted in the present book, which aims to take the reader on our joint “development journey”.

The first part of the book discusses the potential of an industrial DC power supply and the resulting opportunities for drive technology.

In the second part, starting with a requirements analysis, the DC-INDUSTRIE system concept is presented, which – if the specifications agreed upon are met – allows a manufacturer-independent operation of different devices and the simple integration of renewable energy sources and suitable storage systems (batteries, capacitor banks, flywheel energy storages) on a common DC grid. In addition, a cross-manufacturer, decentralized grid management concept for highly dynamic industrial DC microgrids is presented.

In the third and last part of the book, various aspects of safety and protection technology are discussed, particularly with regard to the requirements on and design of DC circuit breakers developed specifically for this purpose. In addition, the reader is guided through a planning and design process that has been specially developed for the novel open DC grid presented here. Finally, the successful implementation and validation of the DC-INDUSTRIE concept in four different demonstration plants is presented.

This foreword would be very incomplete if I would not say a few words about the great commitment of the DC-INDUSTRIE consortium, which made this work possible in the first place.

The prerequisite for the extraordinarily strong innovative power of the project was, in addition to the concentrated technical and interdisciplinary competence of the consortium, a team spirit characterized by trust, respect, transparency, openness, commitment and an open feedback culture.

I would like to emphasize that it would have been contradictory and more than negligent to believe that it would have been possible to jointly design an open system concept without being able to presuppose an openness in thinking and acting on the part of each individual.

On the technical side, it was more important than ever to bundle the competencies of all necessary disciplines in daily work and to always keep the overall system in view in order to avoid conducting isolated or "sterile" research on individual technologies.

Finally, I would like to take this opportunity to thank the German Federal Ministry of Economics and Energy (BMWi) on behalf of all DC-INDUSTRIE team members and partner companies for the support of the project and the trust placed in us.

A very big thank you also goes to all DC-INDUSTRIE steering committee members, represented by their spokesman, Prof. Dr. Alexander Sauer, for their valuable advice and continuous support throughout the project.

My thanks would be very incomplete if I did not include in it the scientific leader (and one of the initiators) of the consortium, Prof. Dr. Holger Borcherding, for his extraordinary foresight and his continuous support, which have greatly shaped the project.

Erlangen, May 2020

André Leonide

Consortium Project Manager DC-INDUSTRIE

1 Direct Current Returns

Alexander Sauer
Karl-Peter Simon
Sebastian Weckmann

At the end of the 19th century, the age of electricity began. At that time, outstanding engineers, inventors and entrepreneurs were striving to develop a power supply system that would ensure both power generation and the transmission and distribution of power. However, what also flared up with the beginning of the electricity age was a battle for supremacy between direct current and alternating current technology (abbrev. DC and AC). It went down in history as the “battle of the currents”.

With the discovery of the dynamoelectric principle in 1866 by Werner von Siemens, larger quantities of electrical energy became available for the first time [Siem1891]. This energy could be transported over long distances without great losses owing to the invention of the transformer in 1881 by Lucien Gaulard and John Dixon Gibbs [Walt2005]. Transformed to a higher voltage, electrical power could from now on be transmitted with lower current and thus lower line losses. In combination with the invention of two-phase alternating current in 1887 by Nikola Tesla and three-phase alternating current in 1888 by Dolivo Dobrowolski, these technologies were so successful that they still form the basis of our electricity system today [Grave1921].

In the early days, smaller island grids were used to supply electrical lighting and smaller DC motors in the 110 Volt range. Edison, the inventor of direct current technology, knew the disadvantage of the smaller transmission distance of his 110 Volt direct current networks compared to highly transformed alternating current and wanted to compensate for it by a large number of local smaller power plants [Cowd2006].

Edison's patent for incandescent lamps from 1880 gave a decisive boost to the development of electricity. He realized that he could only sell his lamps if an electricity network was available to the public. He bought an old building on Pearl Street in New York City and turned it into a power station. In September 1882, 800 lamps were used to light various buildings among which was the headquarters of the New York Times. After this remarkable success, Edison founded the General Electric Company. Fascinated by the burgeoning electrical power business, business magnate George Westinghouse recognized the weaknesses in Edison's DC system in terms of transmission efficiency. He purchased patent rights for the transformer and to Tesla's AC motor. By 1889, Westinghouse had built 870 AC grids thereby limiting Edison's profits. Edison was also concerned about the social acceptance of electricity use. He feared that his business model might be jeopardized by possible accidents at high voltages in the alternating current networks. In particular, the safety of electricity – compared to the fire hazard of gas – was one of his central arguments [Isra2000]. In order to discredit alternating current, Edison proposed it for the execution of the death penalty. To demonstrate its effectiveness, Edison's associate Harold Brown traveled from city to city, publicly killing dogs, cows, horses, and even a three-ton elephant named “Topsy” [Cowd2006].

Ultimately, there were two historical milestones that led to the breakthrough of alternating current technology. At the Chicago World Fair in 1893, the first all-electric world exhibition, 27 million visitors experienced the illumination with 100,000 incandescent lamps. The most spectacular lighting the world had ever seen. In 1890, the International Niagara Commission, led by Lord Kelvin, funded a competition to harness the energy of the Niagara Falls. Originally Kelvin preferred a direct current grid but changed his mind after attending the Chicago Fair. The decision was taken to use alternating current technology. At the time, alternating current technology was the preferred choice because it was about half the price of direct current technology. This was mainly due to the direct transmission of the three-phase alternating current produced by generators in combination with passive transformers for scaling the voltage level [Cowd2006].

Since the Chicago World Fair, the world we live in and the energy system associated with it has changed fundamentally. In 1947, the scientists Bardeen, Brattain and Shockley developed a new electronic component that could control the flow of current by means of an electrical signal – the transistor. Around the same time special semiconductor components were developed: above all the diode, but also the thyristor and the triac, which are suitable for switching currents of several thousand amperes [Klos1987]. The transistor brought new possibilities for the production of integrated circuits. In particular the military and the associated space travel made ever higher demands on electronic components in terms of reliability, performance, volume and weight. Demands that could only be met by integrated circuits. In the course of the development of microprocessors, semiconductor technology found its way into public life everywhere. Today there is hardly a technical device without semiconductor electronics [Fair2012a]. All these electronic circuits require DC voltage. Direct current technology has the potential to replace the alternating current technology sooner or later, because it is more efficient and cheaper.

The number of direct current consumers in our daily life is constantly increasing. LEDs (light emitting diodes), which are a major trend in the lighting industry, are only one example. LED lights have a high energy efficiency and a life span that is ten times longer than that of energy-saving lamps. With an operating time of eight hours per day, LEDs last on average 20 years. Only after that is it necessary to replace them with a new one. LEDs work with direct current. If – as for example in data centers – not every lamp is equipped with an inverter (i.e., an AC/DC converter), instead a local DC network with a central inverter is set up, the overall efficiency (i.e., the minimization of power loss) and resource efficiency can be improved, because today's AC/DC converters have a life expectancy that is significantly lower than that of LEDs. In addition, advanced lighting controls are being developed that are fully integrated into the DC system at no extra cost [Gago2018].

Mobile and Internet-enabled devices like smartphones and tablets are changing the way we communicate with each other today. A basic requirement is that users can connect their devices to a DC power source via a charging cable in order to charge the integrated electrical energy storage device with direct current. State of the art local chargers are used, each of which converts from a power outlet (230 Volt AC) to the required DC voltage (5 Volt DC), thereby generating electricity heat losses. The same applies to integrated power supplies in PCs, monitors and televisions.

Consumers such as heating pumps, air conditioners and fans are parts of building automation. Depending on their output, they also need a DC low voltage or a single-phase frequency converter with a DC intermediate circuit (approx. 325 V).

Data centers, which are necessary for the Internet and our telecommunications networks, nowadays consume more than 1.3% of the world's electricity – and this figure is rising. Instead of installing AC/DC converters in every server, some companies are using large, centralized inverters distributing 380 volt DC in their server farms. Energy savings are achieved primarily by replacing the AC/DC converters integrated in individual servers with more efficient central rectifiers. Switching to these central rectifiers and a more efficient connection of battery backup systems reduces power consumption by 15% compared to conventional AC configurations [Fair2012b].

The spread of electromobility makes direct current technology even more important. Many vehicles are charged with alternating current because it is available at home, at shopping locations or at work. The conversion to direct current is then done in the vehicle itself. However, the installation space for the respective converters is limited due to reasons of cost, space and weight. This means that – depending on the vehicle – it can take between four and over twelve hours to fully charge the battery. DC rapid charging systems bypass the limitations of in-vehicle converters. They can be used to significantly increase the charging speed. DC rapid charging is essential for journeys with high mileage and for large fleets. A fast turnaround allows the driver to charge during the day or during a short break [Schr2012].

Massive changes in the electricity system can also be witnessed on the generation side: the expansion of renewable energies is one of the major development issues worldwide. In Germany it is driven by various policies collectively referred to as the energy turnaround, the “Energiewende”. As early as 2007, the EU decided that the share of renewable energies in the gross final energy consumption (electricity, heat, fuels) of the EU member states should rise to 20% by 2020. In addition, in 2018 the EU presented its long-term strategic vision for a prosperous, modern, competitive and climate-neutral economy by 2050. For Germany, a share of renewable energies of 18% of the primary energy demand is the objective to be met by 2020. By 2030 30%, by 2040 45% and by 2050 60% should be reached [Ren2019]. Overall, renewable energies now account for more than 40% of installed capacity [UBA2020]. The DC voltage that solar power plants produce anyway is converted into AC/DC current via DC/AC converters. The three-phase current produced by wind power plants (rotation frequency proportional to the rotational speed of the blades) is also first buffered in a DC intermediate circuit and then extracted again as three-phase current (rotation frequency proportional to the three-phase grid). This intermediate conversion is necessary in order to be able to feed into the existing AC grid in a synchronized way at 50/60 Hertz.

Energy storage is one of the main factors with regard to achieving energy flexible systems because of the fluctuating energy generation and existing grid bottlenecks. The ability to store locally generated energy and use it later is of great importance. Storage is a solution to the problems of unstable or expensive power grids and it is a crucial incentive for increasing the use and integration of renewable energies. There is a wide range of technologies for storing electricity: accumulators, gas, compressed air and chemicals, and – last, but not least – pumped storage power plants. The growing need for flexibility and autonomy, in which energy consumers also become energy producers, is driving more and more innovations in energy storage, resulting in a wide range of new solutions. The most important storage technologies for commercial and industrial plants are accumulators for storing electrical energy or thermal energy storage systems for storing cold water, ice or heat. These can be operated as stand-alone systems or in collaboration with solar systems. Because of the underlying physical operating principles, the electrical storage systems are almost exclusively operated with direct current [Chio2018].

Power transmission technologies have also evolved. For example, high-voltage direct current transmission technology offers several advantages over alternating current transmission systems because it enables a more efficient transmission of mass power over long distances. If the transmission line is longer than about 480 km, direct current is the better option because alternating current lines have higher line losses [Rai2016].

Direct current is also used in industrial production. In production facilities such as injection molding, machine tool and packaging machines or in industrial robots, motors are driven on demand by servo or frequency converters as electronically variable-rotation speed drives. Within these converters, the AC voltage of the supply network is typically first converted with rectifiers into an intermediate circuit DC voltage in order to then – with the help of a self-commutated inverter – be able to provide an AC voltage for the motor that can be changed in amplitude and frequency.

The simplest and most common form of rectification is by uncontrolled diode rectifiers. These generate high pulse-shaped recharging currents at the voltage maxima.

The increasing use of converters, which – due to the input rectifiers – load the grid with very high non-sinusoidal currents, leads to a decrease of the overall grid quality. Ever more frequently, this leads to a deterioration of the voltage quality to a level that requires considerable filtering measures at the feed-in point of a factory in order not to interfere inadmissibly with the external AC grid. These retroactive grid perturbations are caused because a large number of electrical consumers (such as power supply units or converters) are in operation at a high switching frequency thereby influencing the stability of the power grid. Such retroactive effects can be voltage dips (caused by transient switching operations) or voltage distortions (caused by non-linear consumers). The systems for voltage filtering and reactive power compensation usually require passive components that are not only space-intensive and expensive, but also require the use of valuable resources. See also the explanations in chapter 4 “Opportunities for Drive Technology”.

At the same time, each conversion from alternating to direct current and vice versa causes considerable conversion losses; as already mentioned, this also applies to LED lights, chargers for smart devices as well as for data centers. Thus, the increasing use of variable-speed drives favors the consideration of an alternative network structure in which DC voltage is available everywhere within a factory as a distribution grid.

In 2016, the final energy consumption in Germany for industry, commerce, trade and services was 1128 TWh. This corresponds to around 45% of total German final energy consumption. Since 2008, the final energy productivity (energy efficiency) of the German economy has increased by more than 10%, but at the same time the absolute final energy consumption remained almost constant with a change of −0.1%. Therefore, further considerable efforts are essential to achieve national and international climate protection goals. Without a drastic improvement in energy efficiency, no economic energy turnaround is possible. However, this means – among other things – a significant increase in the use of variable-speed drive systems. EU legislation (19 Commission Regulation (EU) 2019/1781 of October 1, 2019, laying down ecodesign requirements for electric motors and variable speed drives) does not yet promote this system approach, as only individual components continue to be regulated by law. Thus, the focus is not on optimizing the entire application in terms of energy efficiency and economics. A drastic rethinking of the system approach in conjunction with a change in the network structure is necessary if the efficiency goals are to be achieved.

Direct current technology is more present today than ever before. For Europe alone, a market growth of 1000% is predicted for the period from 2017 to 2025 [Fros2020]. Against the backdrop of increasing cost pressure and the social demand for ever greater savings in terms of resources and CO_2 emissions, industry in particular is forced to significantly increase its energy productivity [Gerb2018].

The general conditions have changed: Direct current is generated decentrally directly from solar and wind energy. Today, direct current can also be efficiently transmitted over long distances. In an industrial DC grid, the negative repercussions on the grid quality are eliminated, conversion losses are reduced, and the recovery of regenerative kinetic energy (recuperation) becomes an integral part.

Direct current technology is the essential key to a new energy age. So far, direct current has only been used on an industrial scale to supply production lines in proprietary areas. However, these self-contained subnetworks cannot develop the potential of an entire factory. The following chapters show how an open direct current network can be designed, which technologies would be necessary, how they can be used and where the specific challenges lie.

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2 Potentials of an Industrial DC Supply

Timm Kuhlmann
Patrick Spanier
Martin Ehlich

2.1 Change from an AC to a DC Grid

AC grids are state-of-the-art in all factories worldwide. There are major regional differences in terms of voltage level, frequency and earthing systems. For this reason, AC devices are generally developed and qualified today for variable input voltages and different connection conditions.

Consumer in an AC Grid

In the industrial sector, three-phase electric drives with a DC intermediate circuit (400 V…800 V) are the "driving" force in all machines and systems. They convert over 70% of the electrical energy used in a factory into mechanical motion.

A present-day factory with typical interconnected grid participants is shown in Figure 2.1.

The factory-internal AC distribution is usually fed via a separate central transformer at the grid connection point. There may be several such feed-in points if either the power is insufficient, or it requires redundancy for safety reasons. The AC distribution works in a 3-phase mode. Individual areas, machines, or larger individual consumers can be switched on and off separately via contactors. In the event of a fault, a circuit breaker or fuse separates these energy-using zones from the AC grid. Figure 2.1 does not show these switching and protection elements due to simplification. The focus is on the typical consumers within these zones:

- three-phase motors directly connected to the AC grid, e.g., in pumps, fans, and air conditioners or in use to generate compressed air and hydraulics
- individual processing machines and robots with many individually controllable axes
- position-, rotation speed- or torque-controlled individual drives as found in all production lines as well as in conveying and lifting applications

- welding cases for resistance welding in the automotive industry; these also use converters with a DC intermediate circuit to control the primary side of the medium-frequency welding transformer
- passive consumers, such as heaters for heating furnaces, soldering systems in electronics production or heating applications for plastics or adhesive processing
- all types of automation equipment, such as machine and system controls, communication systems, proximity switches, light barriers, etc. require a DC voltage of 24 V to supply the integrated electronics; this auxiliary power supply is provided by a variety of separate or device-integrated AC power supplies
- sockets for portable devices, electrical tools for local maintenance or assembly work or measuring devices; 230 V sockets are often provided in the switch cabinets as well

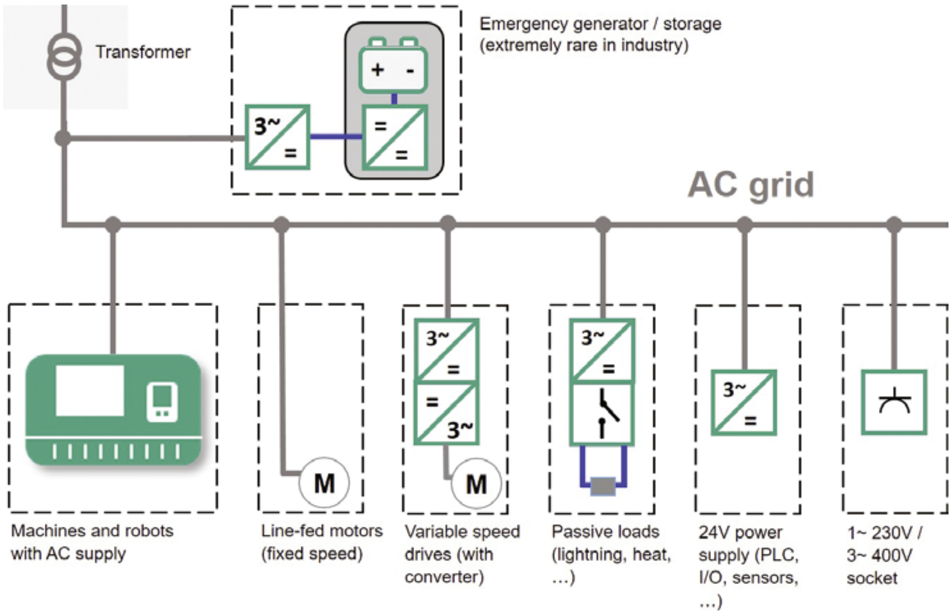

Figure 2.1 Topology in an industrial AC factory grid

Regeneration in an AC Grid

In principle, the current direction in AC distribution is bidirectional, which is actually used in some applications. However, only those consumers can feed back energy, where generative energy is produced in the process. This energy has to be converted accordingly so that it can be output synchronously to the frequency of the AC grid. This is only possible with actively controlled input inverters, which are much more complex and expensive than the most commonly used unidirec-