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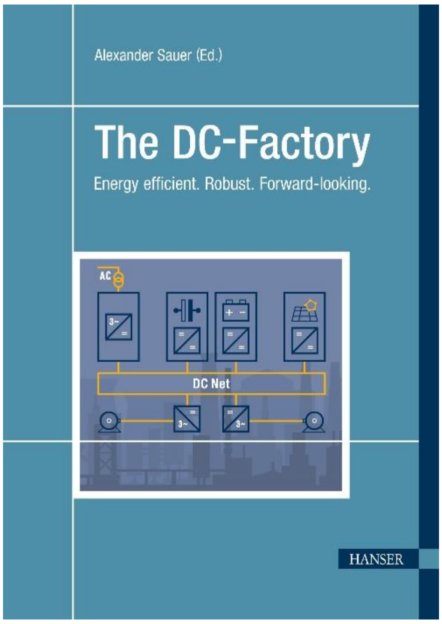

Sample Pages

The DC-Factory

Alexander Sauer

ISBN (Book): 978-3-446-47174-0
ISBN (E-Book): 978-3-446-47179-5

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Contents

Preface VII

1 Direct Current Returns 1

2 Potentials of an Industrial DC Supply 9
2.1 Change from an AC to a DC Grid 9
2.2 Partially Self-Sufficient Energy Supply Using Microgrids 15
2.3 Efficient Energy Supply 18
2.4 Resource-Saving Energy Supply 22
2.5 Robust and Flexible Power Supply 24
2.6 Economic Perspective 29
2.7 Summary 32

3 Requirements for Industrial Energy Supply 35
3.1 Requirements from the User's Point of View 35
3.2 Conclusion from the Requirements 43
3.3 SWOT Analysis of DC Technology 45

4 Opportunities for Drive Technology 49
4.1 Challenges and Operating Principle of an AC Grid 50
4.2 From AC to DC Grids 52
4.3 Technical Evaluation 61

5 System Concept of a DC Power Supply 65
5.1 Topology in the DC Grid 66
5.2 Parallel Operation of Supply Units 71

5.3 DC Voltage Band and Operating Behavior 76
5.4 Supply and Grounding Concept 81
5.5 Smart Breaker for Decoupling and Protection 85
5.6 Precharging and Unloading Concept 87
5.7 EMC Concept 97
5.8 Lifetime of DC Link Capacities 104

6 Grid Management 107

6.1 Grid Management Participants 109
6.2 Options for Load Flow Control 110
6.3 Recommendations for the Design of Power Sources in the Context of a Characteristic-Based Control System 114
6.4 Implementations of Decentralized Group Regulation in Practice 120
6.5 Charge Control of Electrochemical Energy Storage Devices 125

7 DC Grid Protection 131

7.1 Safety Requirements 131
7.2 Plant Safety 136
7.3 Personal Safety 145

8 Planning and Design of a DC Factory 149

8.1 Relevant Design Objects in a DC Factory 149
8.2 Differences in the Design of DC and AC Grids 152
8.3 Defining the Planning Framework 155
8.4 Designing the Operating Equipment 161
8.5 Determining the Settings of the Transformer Systems and Protection Devices 168

9 Implementation Examples 177

9.1 CNC Processing Centerc 177
9.2 Intralogistics Systems 182
9.3 Body Shop 185

10 Summary and Outlook 189

Index 201

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

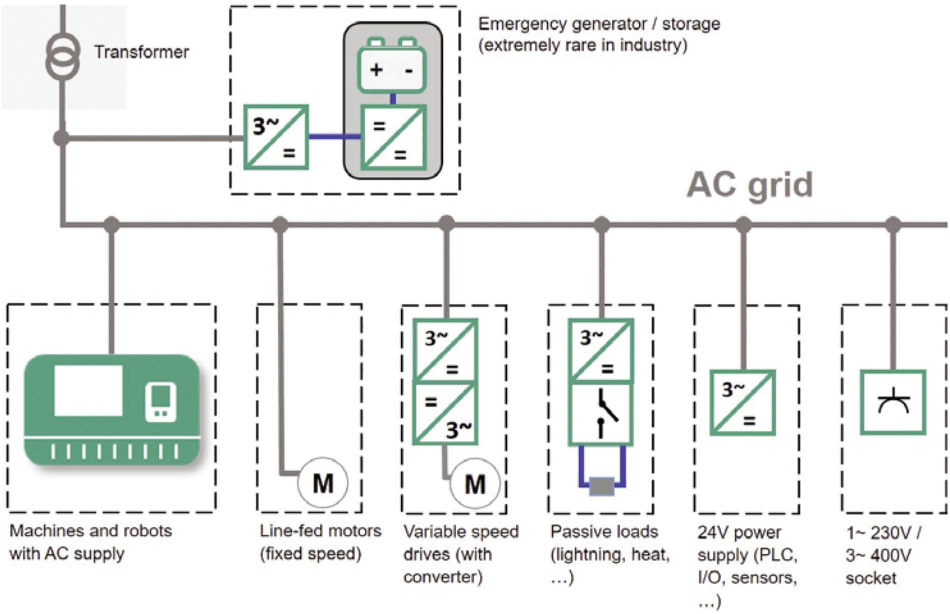

Figure 2.1 Topology in an industrial AC factory grid

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 unidirectional diode rectifiers. Therefore, energy is only fed back into an AC grid if a significant reduction in energy costs covers the investment.

Power Failures in an AC Grid

In the event of a power failure, the entire production process is stopped immediately. This is often the case even with very short interruptions of less than one second. From a technical point of view, there is the possibility to bridge a certain period of power failure with the help of battery storage. However, the costs for acquisition, installation, maintenance and installation space are so high that such systems are usually only used in security-relevant areas such as nuclear power plants, data centers and hospitals.

Reasons for Switching to a DC Grid

An analysis of industrial consumers shows that in all application areas there is an increasing number of interconnected devices that convert the input AC voltage internally into a DC voltage anyway. The battery storage units for bridging AC power failures can only be supplied with DC voltage. The idea of supplying these consumers directly with DC voltage is obvious.

At the same time, there are more and more energy generators that generate a direct current that can be fed directly into a DC voltage grid via DC/DC converters (Figure 2.2). These include the most widespread – since they can be used decentrally practically everywhere – regenerative technologies: wind energy and photovoltaic (PV) systems.

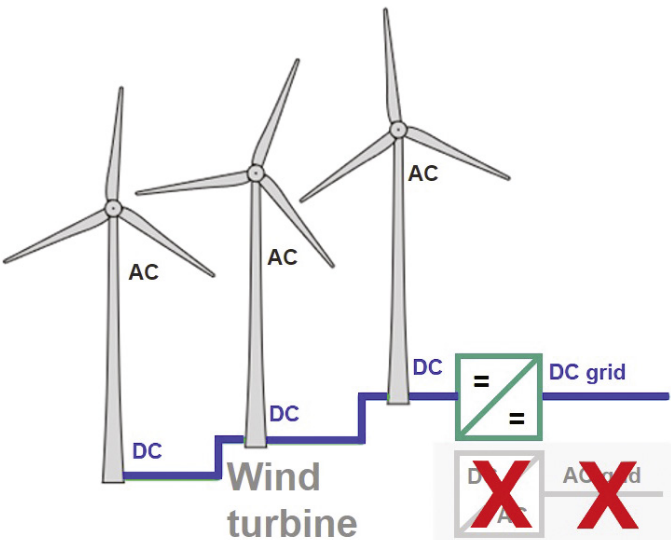

Figure 2.2 Wind turbine, directly at the production site for green energy

In wind turbines, the three-phase voltage system generated by rotation is firstly converted into a DC voltage with the aid of electronic AC/DC converters because the generators initially generate a grid-asynchronous AC voltage. The inverter (DC/AC converter) required today can be replaced by a relatively simple DC/DC converter for connecting to a DC grid. This allows locally generated wind energy to be used directly in a DC factory grid.

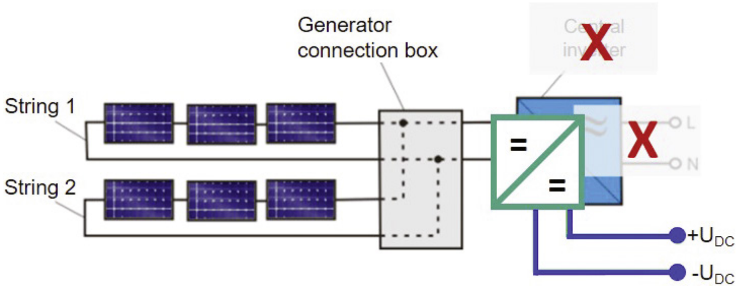

Figure 2.3 Photovoltaic system for green energy directly from the factory roof

In principle, PV systems generate a DC voltage. The level of the DC voltage depends on the interconnection of the solar modules (number of serially connected modules in a string) (Figure 2.3). For use in a classical AC grid, an inverter is also required here, which feeds the current into the grid synchronously and in the correct phase. The connection of a PV system to a DC grid is easier to implement.

Owing to the high importance and the widespread distribution of variable rotation speed drives with a DC intermediate circuit, there have been efforts for a long time to establish an energy exchange at least in the local drive grid. Many manufacturer-specific solutions already make this possible for limited, proprietary interconnected systems. However, they do not offer an open, manufacturer-independent standard for entire plants and factories. These so-called DC link grids already use all the advantages of a DC grid on a small scale. The manufacturers and end users of such drive axles know exactly that in a dynamic multi-axle system a lot of recuperated energy is generated that could be reused. Saving one rectifier and one braking resistor per axis reduces equipment costs and installation space.

Other non-industrial areas use DC distribution grids where compatibility or connection to an AC grid is not necessary. These include, for example, on-board power supplies in electric vehicles and in ships. The charging infrastructure for electric vehicles is partially operated on a DC distribution grid. This is the case, when the DC distribution grid extends beyond individual charging points, thus eliminating the need for multiple conversions from AC to DC. In larger data centers it is already state-of-the-art to supply all units via a DC distribution grid.

The Idea of an Open DC Grid

The comprehensive idea is to supply all the systems mentioned so far – as far as they occur in the industry – continuously via a common, open, i.e., manufacturer-independent DC grid. Such an industrial DC grid should be scalable from individual machines to entire factory floors (buildings). All advantages of DC technology can be used without the need for changes in the external supply lines or at the medium voltage level.

Due to the system-related direct energy exchange between motorized and generative processes, a self-regulating energy balance results in the DC grid. This means that only the energy required for the implementation of production processes, minus any integrated renewable energy sources, can be obtained from the AC grid connection. This energy is mainly converted in machining, processing and conveying processes. Ideally, superfluous energy from motion sequences should no longer be burned at braking resistors.

An open DC grid with typical and possible grid participants is sketched out in Figure 2.4.

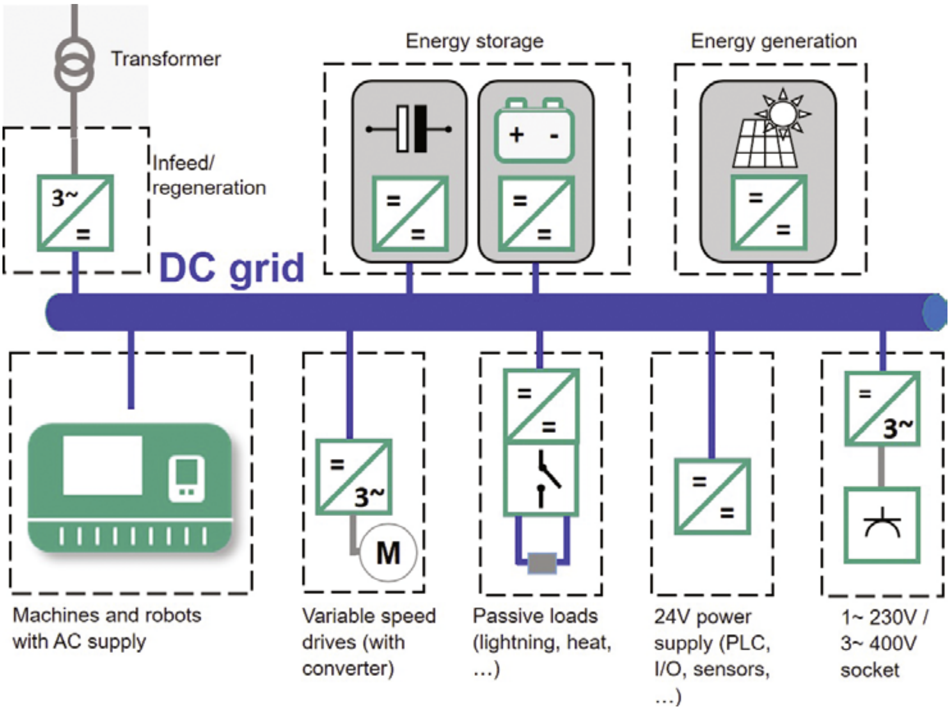

Figure 2.4 Topology in an industrial DC factory grid

In the direct current factory, the same processes and motion sequences must be fulfilled as before. In contrast to the AC factory grid, there are one or more central supply units as AC/DC converters, which provide the energetic connection to the "feeding" AC grid. Depending on the design of the devices, the energy flow would be unidirectional (pure feed, e.g., via diode rectifiers) or bidirectional (feed-in and feedback with the help of rectifiers and inverters).

Other features of the DC factory grid sketched out here are:

- All drives in the machines and robots are directly connected to the DC grid. This enables energy to be exchanged not only within a group of axles, but also between different parts of the plant.
- Grid-synchronous drives are replaced by variable rotation speed drives. This simplifies the topology within the inverters. The input rectifier is omitted, the EMC filter is simplified by the omission of the line reactor, and the required DC link capacity is reduced (see also Chapter 4.2 and Figure 4.5). This reduces costs, energy and space requirements. Furthermore, it is easier to integrate the electronics into the motor, thus favoring the use of decentralized drives. These in turn offer the following advantages over control cabinet devices:
  - no control cabinet
  - no expensive, lossy motor cables
  - reduced reloading losses
  - simple line wiring
  - modular machines
- Passive loads are controlled via DC/DC converters instead of the AC/DC converters previously required.
- The DC power supply units for providing the auxiliary power supply are simpler, more efficient and cheaper than comparable AC power supply units because the internal rectification is omitted and the effort for filtering is reduced, as can be seen with the frequency converters (see Chapter 4.2 and Figure 4.5).
- For the connection of mobile 3-phase and 1-phase AC consumers, which are currently not yet available with DC connection, local connections (sockets as "AC island grids") can be provided via DC/AC converters.
- Static energy storage devices in the form of batteries or capacitors can easily be coupled to the DC grid. Capacitor banks can be coupled directly to the DC grid, for example to intercept local peak loads and to stabilize the DC grid. Battery banks are connected via DC/DC converters for voltage adjustment and power control. Storage capacity and storage technology can be designed to bridge short-term AC grid disturbances up to medium AC grid downtimes.

- Regenerative energy from PV systems or wind power plants can be fed into the DC grid using DC/DC converters. If this energy is not currently being used within the factory, it can be fed into the AC grid and sold via the feed-in/feedback system.

The advantages of the DC grid compared to a comparable system using AC technology are:

- lower energy consumption at same production output levels
- ideally suited for the integration of green energy sources
- round-the-clock availability is possible with the help of modern energy storage systems
- reduced grid connection capacity with correspondingly lower electricity price and resource requirements (copper for transformers and lines), peak load reduction is also possible
- ideal interface for the integration of future technologies (e.g., fast charging points for e-vehicles, forming of batteries for new vehicles, second life for electrical energy storage from the field)

This makes the DC grid particularly suitable for all tasks in factory automation. Typical applications are production lines, machining centers, robots, conveyors, hoists and test benches. A large number of variable rotation speed drives are used in these systems and machines. They generate significant amounts of regenerative power during braking.

From an energy point of view, the DC grid will be less suitable where individual base load drives are in continuous operation. Such applications exist, for example, in the process industry, in water supply or in large conveyor systems. Of course, this does not rule out the possibility that the use of a DC grid may also make sense here due to other advantages.

2.2 Partially Self-Sufficient Energy Supply Using Microgrids

The first attempts to establish electricity in society failed because it was provided by expensive electrochemical storage systems. Only the transmission of electrical power allowed the spatial separation of generation and consumption. Electricity developed into an energy transfer medium that is still only stored temporarily to a small extent [Ditt2013].

As the quota of processes in industry and everyday life supplied by electricity increased, the initial island grid structures transformed into interconnected grid. Today's interconnection of the largest possible number of consumers and producers results in both economic and technical advantages. According to Strauß [Stra2009], an interconnected grid can avoid the high costs that arise from storing sufficient amounts of electrical energy. The reason for this is that the fluctuating demand for electrical power is stochastically balanced out with the increasing number of consumers in the total load. As expected, the installed power plant capacity grows with the increasing size of the interconnected grid. However, the capacity, which is reserved for load fluctuations, decreases in proportion.

Looking at the development of the energy system from the perspective of the energy system turnaround – i.e., from the "Energiewende" –, the paradigm of interconnectedness and size is challenged by three aspects:

1. The capacity of plants making us of regenerative energy depends on meteorological conditions, so that conventional power plants, consumers and operators of energy storage facilities must adapt to the individual generative situation [PeekDiel2015], [Grass2015].
2. Compared to conventional generative plants, plants making us of regenerative energy are mainly connected to the distribution grid [Sola2018]. Therefore, new concepts have to be found to make the grid controllable at the transmission grid level and to integrate the decentralized generative capacities into the operational management of the grid [Dena2014].
3. If one compares regenerative and conventional plants, an essential difference is the lower average plant capacity of regenerative energy sources [BNA2018], [Lass2002]. Thus, the integration of renewable energy sources leads to the need of a more complex control system.

Figure 2.5 illustrates the effects of this development. While in the past the energy flow was mainly directed from the transmission grid to the distribution grid and finally to the end consumer (a), the integration of regenerative producers in today's grid state leads to uncontrolled and bidirectional balancing flows in the distribution grid (b). The concept for a DC grid presented in this book is based on this state-of-the-art. It presents local control zones as a solution for discussion (c). The literature often refers to these local control zones as microgrids.

The idea of a microgrid was first coined by the American scientist Lasseter [Lass2002] and has a wide range of applications in the literature. In the context of the DC grid concept presented, a microgrid is understood as a partially self-sufficiently operated electrical grid system, which integrates local consumers, decentralized generators and storage systems in one control area. The grid is called partially self-sufficient because it does not completely run without a connection to the external AC grid. It can be integrated into the superimposed grid control system as a control variable.

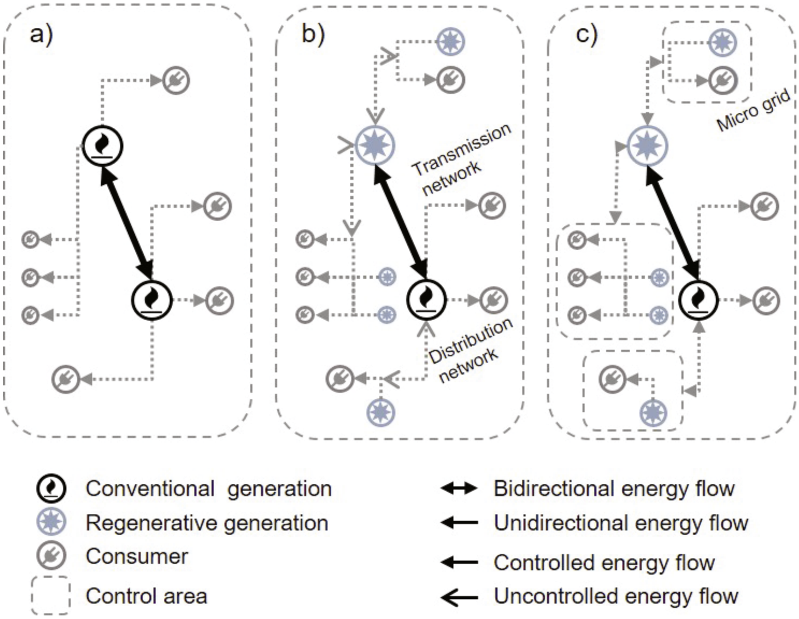

Figure 2.5 Transformation of the transmission and distribution grid to a microgrid architecture

This microgrid architecture has macroscopic advantages for the entire electricity system because energy storage, generation and consumption within the local control zone are balanced in real time. This means that local balancing processes resulting from a change in the feed-in or consumption situation are not transferred to the superordinate grid. At the same time, the energy supply can be adapted from the superordinate grid structure by integration into its grid control system. The microgrid aggregates the connected load of all devices so that a relevant control variable for the next control hierarchy is created.

The local grid control opens up a spectrum of optimization options for operational management. Possible control objectives include, for example, grid failure safety, local consumption of regenerative energies, peak load capping or the energy-flexible operation of consumers.

2.3 Efficient Energy Supply

Central Rectification/Merging of the DC Intermediate Circuits

Omission of rectifiers in the devices

In a DC grid, energy conversion is simplified. While today operating a drive with converter in an AC grid requires a rectifier, rectification is not necessary when used directly in a DC grid. If the device is to be capable of regenerating energy in an AC grid, an additional DC/AC converter must be integrated in the direction of the supply grid. This converter is also not required for direct DC supply.

The efficiency losses of the additional DC/AC converters in the direction of the supply grid are estimated to be 2.5% per conversion [Hamm2007]. Laudani has analyzed the efficiency of converters from different manufacturers and different power classes at different loads [Laud2015]. Converters with higher maximum power have a higher efficiency. Irrespective of this, the efficiency in partial load operation decreases. The analyses indicate a maximum overall efficiency of the inverters of only 92.5%.

A better design of the central rectifier is possible

A DC grid can achieve a further gain in efficiency through a centralized feed-in. The consistancy of the power demand in grids with an increasing number of participants leads to a better utilization of the central AC/DC converter at the supply point.

In contrast, partial load operation of less than 60% leads to additional efficiency losses of 2%.

Use of recuperative energy

In addition to the increase in efficiency, a DC grid, as already mentioned, enables the exchange of the regenerative energy (braking energy) of drives. While this energy is thermally converted in AC devices via braking resistors and is thus lost, a DC converter feeds this energy back into the DC grid with almost no loss. For an industrial robot in automobile production, Meike calculates a recuperation potential of 15% of the energy during operation and a total of 10% of the annual consumption, i.e., approximately 870 kWh [Meik2011].

If the electricity mix in Germany is taken as a basis, which produces 474 g CO_2e/kWh (CO_2 equivalent CO_2e *Global Warming Potential*, indicated as CO_2-mass per kWh, which would produce the same greenhouse potential) [Umwe2019], this energy saving means an annual reduction of 412 kg CO_2e per robot. In Germany about 27,900 new industrial robots will be used in 2018 [Litz2019]. Since these robots are of different sizes and purposes, a conservative estimate of the savings is based on the assumption that only half of the savings can be realized. The energy saving of 12.1 GWh would result in a CO_2 emission reduction of 5747 t CO_2e.

Economically, the energy savings through recuperation at an electricity price of 18.44 c/kWh including electricity tax means a cost reduction of 160 €/yr. per robot. Assuming a useful life of eight years for the robot, its energy costs over its life cycle are reduced by € 1280. With respect to the body-in-white production, for example, around 600 robots are used per model series. This means that energy costs can be reduced by € 768,000 over the life cycle, accelerating the amortization of a conversion to DC technology.

No Capacitive Reloading Losses

DC lines do not have capacitive recharging losses as occur with AC lines. In the distribution grid this advantage is significant. In the case of motor lines, this advantage results indirectly from the fact that DC-fed motor converters are significantly smaller and thus these decentralized drives will be used more often. With these so-called integrated drives, the converter/inverter is directly connected to the motor, so the motor line is almost completely eliminated. This also eliminates the recharging losses in the motor line, which in the case of control cabinet inverters already generate significant losses when idle. These recharging losses, which are independent of the current motor current, are estimated at 30…70 W. Depending on the power of the drive, this corresponds to between 20% and 1% of the total rated power loss.

Connection of Storage and PV

DC/AC converters are replaced by more efficient DC/DC converters

With values up to 99%, DC/DC converters have in principle (1–2 semiconductor switches, continuous current flow) significantly higher efficiencies than AC/DC or DC/AC inverters (6 semiconductor switches, intermittent current, commutating). Only with such energy-efficient converters the integration of storage becomes economically interesting. The same applies to the coupling with wind energy, photovoltaics and charging stations for e-vehicles.

When integrating storage systems, one can assume an increase in efficiency of 5–7.5% (elimination of one conversion stage each for charging and discharging). A PV system increases its efficiency by 2–3% owing to the elimination of the last DC/AC conversion stage.

Storage management becomes more efficient

For storage components that are operated on a DC grid with a wide working voltage range, a very simple and efficient form of storage management is now possible (see also Chapter 6.5). Since the level of the applied DC voltage provides information about the current load state of the DC grid, the charging and discharging phases of the storage can be optimized even without fieldbus and other measuring points in the system.

Use Case Example

In one use case comparative measurements were carried out on a CNC machining center for woodworking. In order to get the best possible basis for a comparison between AC and DC variants, the existing AC axles were converted or modified so that they can be operated in a DC grid (see Chapter 9.1).

The direct comparison between the AC and DC versions of the CNC machining center results in an overall increase in efficiency of at least 5.5% for the same machining profile. This is achieved by recuperating the energy of the milling spindle and the main movement axles.

Figure 2.6 shows that the graph depicting the power of the DC version also assumes negative values. The peaks of down to −8 kW occur when the portal system of the machining center brakes before reaching a new target position, thus making the braking energy from the DC sector (grid of several DC units, see also Chapter 5.1) available to the DC distribution grid.

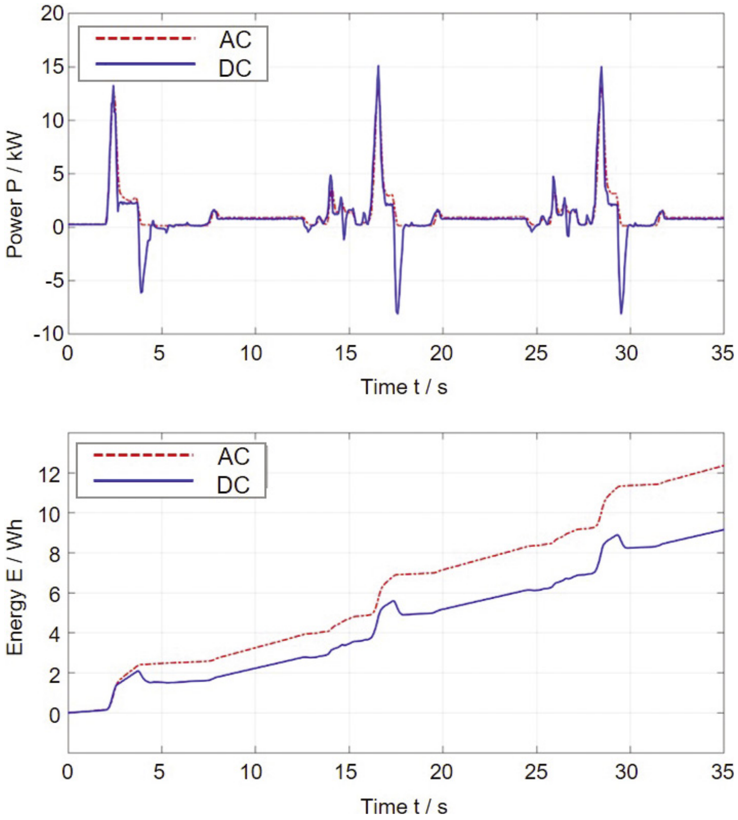

Figure 2.6 Energy consumption of the DC sector "CNC feed drives" before and after conversion to DC

Index

A

AC device 61
AC grid failure 122
AC grids 9
AC mains failure 124
AC mains recovery 123
AC power distribution system 152
AC technology
– state of the art 54
advantages of AC technology 54
agents 112
application example
– body shop 185
– CNC processing center 177
– electric monorail system 184
– intralogistic systems 182
application-specific properties 157
auxiliary power supply
– dimensioning 164
auxiliary voltage supply unit 91

B

basic interconnection 111
battle of the currents 1
breaker 140
breakers 136
brownfield planning 150

C

cables and plugs
– requirements 41
capacitances 148
capacitors 23
central grid management 113
characteristic curve 126
charge control 125, 128
circuit breaker 136
CO_2 footprint 22
communication 111, 112, 113
connection technology
– interchangeability 147
consumer 108, 109, 110
consumer subsystem 114
control characteristics 125
control system of the group 74
conversion losses 5, 50
converters 112, 113
converter systems
– determining settings 168
copper cost
– comparation between AC and DC 57
cost differences 29
cost influencing factors 29
coverter systems
– characteristic based control 170
curve slope 128
curve switching 121
cyber-physical systems 113

D

DC factory grid 14
DC fuses 87
DC grid 11, 110
– advantages 15

– approach for drive technology 53
– connecting new device 95
– discharge 96
– participants 67
– structure 66
– technical evaluation 54
DC intermediate circuit 12
DC link capacitance 62
DC link capacitors 104
DC protection 196
DC sector 67, 110, 136, 163
DC system
– efficiency 52
DC voltage band 76
decentralized energy generation 150
decentralized group control 111
degree of self-sufficiency 158
design 162
design of DC grids 152
design of the equipment 161
device characteristics 156, 157
device classes 70
device costs 29
device description 169
device grid
– evaluation 63
dimensioning 162
direct current consumers
– charcteristics 156
direct current factory 14, 151
discharge 86, 96
distribution grid 153
drive technology 194
– requirements 39
– technical evaluation 61
droop curve 72

E

efficiency 160
efficiency losses 18
efficiency potentials 183
electrical energy supply system 149
electrical storage systems 150
electromobility 3
EMC
– current harmonics 104
– DC RFI filter 103
– interference emissions 98
– interference immunity 104
– leakage currents 104
– limit values 99
– measurement results 101
EMC concept 97
emergency halting 37
emergency stop 37, 38
Energiewende 16
energy consumption optimization 166
energy flexible systems 4
energy storage systems
– design and sizing 165
extended group control 112

F

factory automation 198
feed
– requirements 40
filter corner frequency 115
flexibility potential 159
frequency converters 49, 195
– energy efficiency 52
frequency inverter 51
– changeover to DC technology 58
further energy-saving potentials 194

G

gap operation 119
greenfield planning 149
grid functions 158, 169
grid management 42, 107, 172
– optimized operation management 108
– requirements 41
grid manager 112
grid quality 5
grid system dynamics 150
ground fault detection 87
grounding 131
– AC-side 81

– DC IT grid 83
– operational 83
– protective 83
grounding concept 81
grounding system 68
group control 113
– extended 112

H

hybrid breaker 136, 140
hybrid lines 147

I

impedance 114
impedance center grounding 146
impedance measurement methods 119
increase in efficiency 20
inductor 139
industry 4.0 190

L

large signal effects 115
load flow 109
load flow control 110, 111
load peak reduction 167
lower potential peak power levels 23

M

microgrids 16

N

Not-Aus 38

O

open DC grid 13
operating range 77
operation tasks 162
overload protection 143
overvoltage 86
overvoltage and undervoltage 78

P

parameterizations of the devices 155
participant class 109, 171
participants 110
passivity criterion 115
peak load reduction 180
peak shaving 125
personal safety 145
– critical ranges 146
planning assumptions 160
planning process 154
plant safety 136
plug&play capability 191
potential for saving resources 24
power failures 11, 168
power flow 112
power flow control 112, 114
precharge 86, 152
– defining 164
– design 89
– first feed 91
– storages and sources 93
– switching thresholds 94
– waiting times 91
precharging levels 88
precharging sequences 92
private grid sections 153
producer 109, 110, 114
project planning 153
prosumer 107, 109, 110, 125
protection
– overcurrent 85
protection devices 38

Q

quality factor of a producer 118

R

range transitions 172
recharging losses 19
recovery of power 179
recuperated energy 185

recuperation 18, 52
recuperation energy 121, 166
reduction of power and load peaks 24
redundancy 158
reference grid 105
reference process for design 154
regeneration 10
regenerative energy 15
reliability 24
renewable energies 4
requirements 35
– general 43
– prioritization 44
requirements for switching and protection technology 37
resilience 158
resource efficiency 3
resource-saving 22
robot cell 187

S

selectivity 144, 159
semiconductor breaker 136, 141
sharing limits 172
short-term interruptions 26
short-term supply interruptions 28
small-signal stability 114, 173
smart breaker 67, 71, 85, 110
– dimensioning 163
– for precharging 89
smart DC breaker 109
smart grid 190
smart grid transformation 150
stability 159
stability problems 115
state management 114
storage capacity 162
storage controller 127
storage units 187
stress bands 171
supply devices
– droop curve 72
supply technology 40
supply units
– parallel operation 71
switching technology 196
SWOT analysis 45
– opportunities 47
– risks 47
– strength 46
– weaknesses 46

T

testing DC technology 177

U

undervoltage 86

V

varying energy tariffs 25
voltage change rate 79
voltage ranges 171

W

wind power plants 4