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Simulative analysis of a flexible, robust and sustainable energy supply through industrial Smart-DC-Grid with distributed grid management

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Abstract

The industrial energy supply of the production with direct current offers the chances of higher energy efficiency, better integration of generative energy and at the same time robust power supply. In addition to the technological challenges for electrical devices, an intelligent grid management, which regulates the load flow between the participants, is crucial. The distributed grid management supports a scalable, modular network with a hierarchical structure. The paper defines a direct current (DC) grid management by the different roles of every participant. Each role provides special services, needed for a stable grid operation. These services are described and a simulative analysis is carried out. The simulation shows that network stability is ensured and at the same time, the possibility of optimizing the operation management is maintained. The presented results are part of the DC-INDUSTRIE research project, funded by the German government.

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Keywords: : Industrial Smart Grid; energy efficiency; energy flexibility, grid management, direct current supply

1. Introduction

The energy supply system faces major changes and challenges, due to a growing share of renewable energy sources as well as a decentralization of energy production [1]. The role of the consumer is getting more and more important, since e.g. the increasing penetration of wind and solar power is necessitating a more active role for energy management in homes, buildings, and industries [2]. High energy consumers like industrial facilities are responsible to lead the change on the consumer side [3]. The intermittency and unpredictability of renewable power generation is in contrast to traditional power generation. With power coming entirely or almost entirely from the traditional power plants, system operators have been able to keep the grid balanced by adjusting generation in real-time in response to demand variation [4]. With unpredictability now extending to generation, imbalances in the grid may cause grid reliability issues. A major challenge in the transformation to a sustainable energy supply is to enable industrial consumers to adapt to these changes.

On the one hand, energy infrastructure of a production system must be adaptable to fundamental changes of the energy system [3]. On the other hand, energy flexibility is required to secure a stable and economic energy supply of the production system [4]. Interruption of the power supply in the range of 3 minutes are decreasing in the German power grid, while short-term interruptions in the range of a few milliseconds up to one minute are increasing [5]. These short-term interruptions can lead to sudden process interruptions with high follow-up costs in highly automated production systems. The industrial Smart Grid offers a solution that intelligently distributes the loads and integrates energy storage capacity efficiently into the energy grid. In the research project DC-INDUSTRIE, funded by the Federal Ministry of Economics and Energy (BMWi), 21 companies, 4 research institutes and an association are

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researching solutions for an industrial direct current (DC) energy supply network.

DC energy supply grids offer big potentials (figure 1) to enhance energy efficiency, reduce device costs, enable the usage of simpler devices, decrease the material effort in wiring and devices and reduce the needed space for control cabinets due to smaller devices while reducing machine downtime. For example, conversion losses of transforming the voltage from alternating current (AC) to DC and backwards are reduced by approximately 10 %, which arise today with the implementation of energy storage systems, the linkage of the production energy system to photovoltaic (PV) systems or the recovery of braking energy from drives in the machines in an AC energy supply grid. Another example of a higher sustainability of the DC supply is the decreased usage of copper in cables up to 50 %. The DC energy supply needs only 3 wires instead of the 5 wires of the AC system. Due to the higher voltage of the DC supply, the cables have a smaller cross-section. This will, combined with the simpler devices with missing conversion components for transforming AC-DC and vice versa, increase the material efficiency of the supply system. Overall, the potentials lead to a reduction in life-cycle costs while at the same time reducing material and energy effort and thus increasing sustainability.

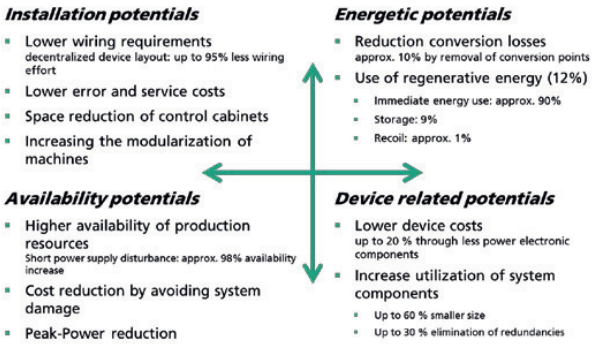

Fig. 1. Potentials of an industrial Smart-DC-Grid [6]

To maximize the energy specific advantages of a DC energy supply grid and to ensure a stable and robust operation of the energy supply at any condition, grid management plays an important role. Inspired by the system services of the transmission networks [7], the grid management secures the voltage level, the restoration of the supply or the restoration of the control operation after a grid breakdown, as well as the system and network management with a guarantee of the balance of energy feed and withdrawal.

2. State of the Art

For grid management in Smart Grids, centralized, decentralized and distributed control architectures can be distinguished, which can also be implemented in hybrid approaches [8, 9].

2.1. Central Grid Control

The central control system is organized according to the top-down principle: a central control unit cyclically receives the energy inputs and outputs of the connected devices (supplier, storage systems and consumers) in very short intervals (range of milliseconds). Based on the received energy data, the central control unit controls, in particular, the amount of energy supplied to the system, but also, if technologically and process-technically possible, the energy consumed in the system. Therefore, also cyclic and high-frequency commands are necessary. On an equivalent basis, storage systems are controlled, taking for example ecological or economic influencing variables into account. The advantage of the central control system lies in the efficiency of the control algorithm [10]. In addition to the energy data of the central control unit, weather forecasts, external electricity price or CO_2 certificate price can be included in the optimization of the energy flow. A disadvantage is the necessary high reaction speed and real-time communication, which limits the number of controlled grid participants [11]. A cascading of the central controllers would be necessary for large networks. In addition, there is the configuration and programming effort in the central control unit for expansion or modification of the power supply units. Ultimately, the system robustness depends on the robustness and failure safety of the central control system including the necessary communication.

2.2. Decentralize Grid Control

In contrast to the central control, the energy balance in the decentralized control is secured by the independent behavior of each supplier, storage system and consumer [12]. For this purpose the network users can be classified into active and passive users: Passive users have no possibility of controlling. They act as disturbances in the energy supply system. Active users measure the state of the energy supply system and adjust their performance depending on the condition of the supply system. In the case of a DC supply, the energetic state of the power supply system can be derived from the measurement of the DC voltage. To balance the system, it is therefore necessary that at least one active energy-providing user is present in the decentralized DC network. The advantage of the decentralized control lies in the flexible and robust network structure. Participants can be added to the system without changing the control algorithms. A network operation is also ensured in case of failure of individual nodes. There are no additional sources of error due to a communication infrastructure. A disadvantage in the decentralized control concept is the lack of optimization in terms of system efficiency under changing environmental conditions. The prioritization and balancing of loads of individual users is possible, but requires the adjustment of the individual control parameters [10, 11].

2.3. Distributed Grid Control

In a distributed grid control the energy balance is secured by the independent behavior of each supplier, storage system and consumer [11]. In contrast to the decentralized grid control the active users can communicate with each other, for example the exchange of system information for forecasting purposes or for optimizing network operations [13]. This exchange does not take place in real-time since only system-optimizing information are transmitted. However, the critical network management tasks required to maintain the system operation are decentralized to the active subscriber. This reduces the communication requirements with regard to cycle time and failure safety. Thus, the distributed control has the advantages of the decentralized control and supports it by the possibility of optimizing the regulation in the sense of an increase in the system efficiency [12]. Therefore, this distributed approach is to be examined in detail for its usability in industrial energy supply systems.

3. Distributed control concept for energy flow control

The proposed distributed control uses the individual response of each users to the voltage level. Therefore, the voltage can be used as a communication link [14, 15] based on the DC bus signaling [13]. The behavior of each user with respect to the control variable can be described by a defined control curve (droop curve). The droop curve defines the relation between voltage level and current level. With an increasing load, the current is increasing as well, while the voltage level is decreasing. The voltage decrease can be traced to the virtual internal resistances of the energy supplier, which are defined by the droop curves. This voltage variation can be detected by all active users, which than react according to their individual control behavior. A new voltage level is set up, balancing energy supply and demand in the system. The right choice of droop curves can be used to prioritize different functionally similar participants. Faults or failures of individual active participants are compensated immediately by the other active users.

A well-defined control requires a defined voltage band in which the DC main voltage fluctuates [16]. Due to the semiconductor blocking voltages of the commonly used components of around 1,200 V, safe operation up to a maximum of 800 V is possible. If the use of uncontrolled feeders in alternating current (AC) grids with up to 480 V is set as the basis for a maximum normal value, then the following is obtained according to IEC TS 61800-8: 2010: 1.35 times the phase line voltage as DC bus rated voltage and thus a value of 648 V. The voltage band for normal operation is set to a range of + 10% and -15% according to the specifications of EN 50160: 2010. This results in a voltage between 459 V and 713 V in which the devices can be safely operated without any power losses. A sufficiently large safety distance to the abovementioned 800 V is thus maintained.

If an active supplier (e.g. active front end) and a storage system are operated in such a DC grid, these two users can be coordinated with each other via the droop curves (Figure 2). Curves (a) and (b) show the respective course of the droop curves of the suppliers in detail. The overall system behavior is represented by the sum of the two curves (c). If the system consumes more power, the storage system will assist the power supply unit. Above a critical value, the storage system will even increase its power supply, so less energy is need from the outer power network. This enables peak reduction in the power supply.

The voltage value increases or decreases dependent to the actual load on the grid, so that each user of the DC supply system is informed at the same time about the power supply in the network. A voltage value above the nominal voltage is equivalent to an energy oversupply, while a lower voltage value is equal to an undersupply.

If these droop curves of consumers are additionally linked to information of the production system, for example material availability or with regard to the utilization of tolerances in the process window, these participants can adapt their energy consumption to actively support the balancing of energy supply and demand without compromising production output or quality [17].

4. Dynamic system analysis of distributed DC network management

The theoretical foundations and preliminary considerations on the distributed control are examined using the example of the energy supply of a production system (Figure 3). For this purpose, a production area is simulated, which is supplied by means of an active power supply, a photovoltaic (PV) system and a redox flow storage system. For the production area the

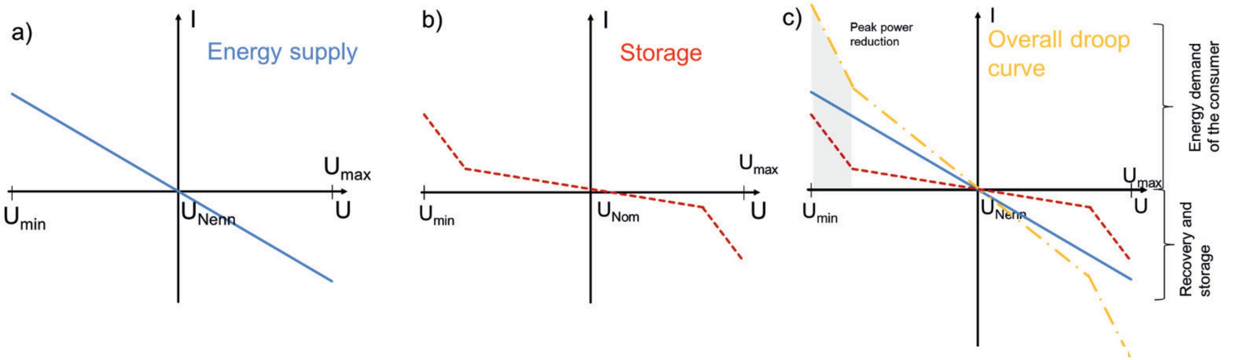

Fig. 2. Droop curves for energy supply (a), storage system (b) and resulting overall droop curve of the system (c)

load characteristic of a plastic part manufacturer is used as base for the model. The active power supply unit (Active Front End - AFE) has a rated output of 100 kW with a maximum possible fed back rate of 30% of the nominal power. The redox flow storage system has a capacity of 800 kWh with a nominal power of 100 kW. The PV plant has an installed capacity of 70 kWp. This results in a nominal output of 38.8 kW during summer for a sunny day in southern Germany.

The DC bus is used to supply or recover energy. The three active power supply units - AFE, redox flow storage system and PV system - regulate the voltage that results on the DC bus. Their behavior is determined by the implemented droop curves. Via the DC bus, the production area as passive consumer primarily receives energy, but also feeds back excessive braking energy generated by motors. In DC supply grids, braking energy can be easily integrated because there neither is the need for synchronization of frequency nor dissipation of excessive energy at a braking resistor. Instead, the braking energy is stored in a dynamic energy storage system linked via DC bus. Thereby, energy efficiency is increased. The distributed grid management approach supports this control scheme inherently due to the implemented voltage droop curves and reduced time lag in regulation.

5. Analysis and evaluation of the simulation results

The simulation of the plastic part manufacturer was run over a period of two weeks. The results show that the voltage band of -15 % and +10 % can be secured (Figure 3). During production time the voltage level drops significantly below the nominal value of 648 V. At weekends, the voltage level exceeds the rated voltage due to the energy supply of the PV system, which is above the weekend consumption of the production. During weekends energy is used to charge the redox flow storage system and excess energy is fed back into the AC grid. At the beginning of the new week, the redox flow storage system is charged and has a voltage-supporting effect when consumers are powered. As a result, the voltage profile on the first working day does not drop as much as on the following days, when the redox flow storage system is already discharged.

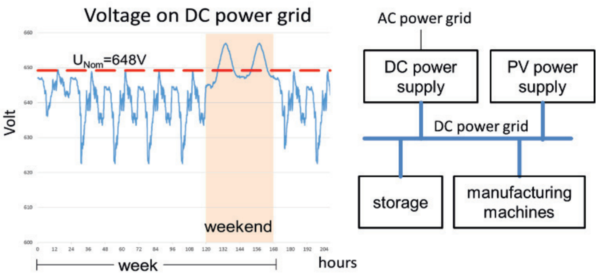

Fig. 3. Structure and grid voltage of the DC power grid

Overall, a dynamic voltage profile can be observed. The voltage drops are caused by load peaks. Load peaks lead to increased wear of the electrical devices and thus possible earlier failures of the devices [18]. In addition, load peaks increase energy costs. Therefore, an optimized operation management reduces these load peaks.

Tuning the droop parameters of the redox flow storage system already lead to a clear improvement. Figure 4 shows the comparison of a simple linear droop curve and an adjusted droop curve for the redox flow storage system. The latter causes the redox flow storage system to be less strongly involved in the supply of energy when the rated voltage (which serves as a voltage threshold) is lower. The storage only provides the total rated power of the voltage backup buffer in the lower range of the maximum tolerable voltage drop of 10 %. As a result, the redox flow storage system is initially discharged less quickly and can be used constantly over a period of time to support the DC power supply as shown in the diagram on the left side. Without the optimized droop curve shown at the right side, the redox flow storage system would be discharged on the second day. The AFE would be supported more intensively on the first day, without capacity remaining to support the system on the following days.

A load-dependent prioritization between the sources AFE and redox flow storage system takes place. Peak load reduction can be increased, by charging the redox flow storage system with excess PV energy and energy of the AC supply grid during times of low energy prices. This behavior can be controlled by

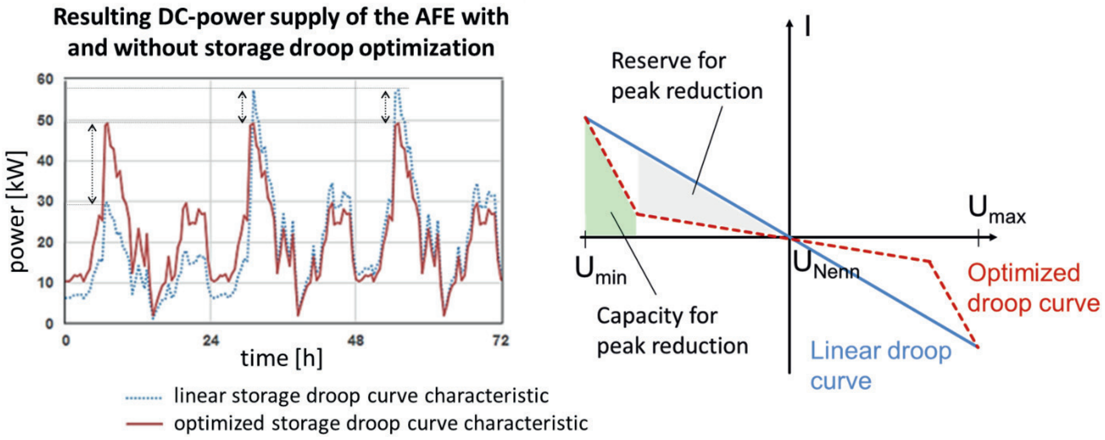

Fig. 4. Power supply of the AFE with two different droop curves of the storage system

tuning the droop curves. A shift of the curve towards lower voltage values activates an earlier charge.

6. Summary

The simulative analysis of a case study for an industrial DC power supply system is carried out. It shows that a stable energy supply system can be ensured using a distributed control concept and thus benefits from the advantages of centralized and decentralized grid control similarly. Several approaches for optimizing system operation can be included and combined only by the use of voltage droop curves and DC bus signaling: The integration of braking energy increases energy efficiency in contrast to AC supply systems; and an energy storage system can be used for peak load shaving in a non-flexible production line. The correct tuning of the droop curve can achieve a significant effect without additional investments. If this method is combined with the characterization and dimensioning of the energy storage, the method of operation in the industrial power supply system can be optimized and the energy supply of the production can be made more flexible to the necessary extent. In addition, the electronic components in the whole system are protected. As a result, the availability of the supply and thus of the entire production system increases leading to lower maintenance costs.

The examined approach of a distributed grid management will be integrated prospectively in a test grid within the DC-INDUSTRIE research project.

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