Holistic Concept for Simulation-based Planning and Design of Hybrid AC/DC Energy Grids for Production Systems

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SNE 34(2), 2024, 61-70, DOI: 10.11128/sne.34.tn.10682
Selected ASIM SPL 2023 Postconf. Publication: 2023-09-01;
Received Revised Improved: 2024-04-22; Accepted: 2024-05-10
SNE - Simulation Notes Europe, ARGESIM Publisher Vienna
ISSN Print 2305-9974, Online 2306-0271, www.sne-journal.org

Abstract. This paper proposes a simulation-based planning concept and a simulation architecture for the design of hybrid AC/DC grids, which have the potential to significantly contribute to the energy transition. The paper discusses the lack of knowledge for the design of these grids, and presents a simulation approach to efficiently design hybrid grids and analyze them based on an electrical simulation. The authors also address the need to include process-specific characteristics in the planning and analysis of the electrical network, which is why common simulation tools for production processes are included in the approach. This allows economical, ecological, safety-relevant and technical aspects to be integrated into the planning process. The proposed concept is further discussed and planned for validation on the basis of a demonstrator currently under construction.

Introduction

The use of alternating current for general and widespread electrification was not set from the beginning. The war of currents was fought between the proponents of direct current (DC) and alternating current (AC) represented by Thomas Alva Edison and George Westinghouse respectively. The invention of the transformer in 1881 made it possible to transport electrical energy efficiently over long distances. This central aspect shapes our current electricity grid, which is based on alternating current.

Nowadays, the widespread use of electronic devices has led to questions regarding the usefulness of generalized AC electrification. Most electronic devices require DC supply, which has to be generated from the AC mains through an internal rectifier. Taking a closer look at production facilities, it reveals that many electronic devices, such as converters, inverters, and other consumers, are coupled to the AC mains via rectifiers, taking up space and reducing the efficiency of the devices [1]. In addition, the energy transition with its DC-based generators and storage systems necessitate a reassessment. In this context, system structures based on centralized rectification of AC mains voltage and bidirectional connection of all DC-based consumers and generators via this grid branch have been established in various research projects and are already being used in the first industrial and domestic test networks.

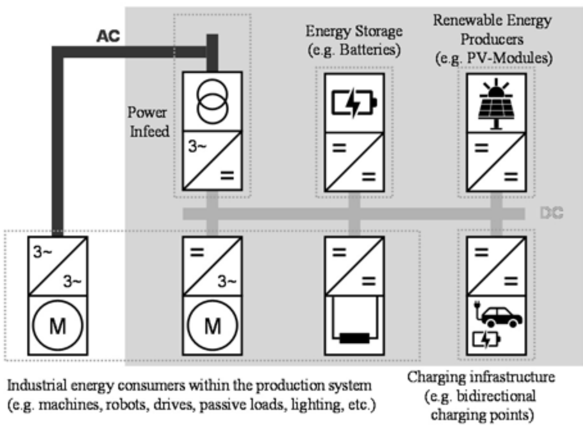

Figure 1: Industrial hybrid AC/DC grid with exemplary generic grid participants.

An exemplary hybrid AC/DC grid with industrial consumers, storage technologies, renewable energy sources and the connection to an electric vehicle charging infrastructure on the DC sector is shown in Figure 1.

The largest previous project works in Germany are DC-Industrie 1 and its follow-up project DC-Industrie 2, which deal with the design of industrial DC grids [2, 3]. The Open Direct Current Alliance (ODCA) of the ZVEI was in turn founded to be the general follow-up research alliance for DC grids [4].

Participating project partners are involved, for example, in the development of power electronic components, switching and protection components as well as the associated standardization in international standards and guidelines. Numerous other research projects like DC-Schutzorgane, DC-Smart or SiC4DC have resulted in a wide range of studies that investigate suitable protection concepts or the use of wide-bandgap semiconductors in power converters, the interaction of grid components and the potential for integration of regenerative energy use and storage or recuperative energy use [5, 6].

For this hybrid AC/DC grid structure, the first quasi-standards and prototypes were developed in the projects, but the general knowledge of economical, ecological and safe planning is still limited to a few experts who are involved in such research projects.

For this reason, there are few people who are able to design such grids correctly so that the systems can be put into operation safely. [4, 7, 8]

This publication presents a concept on the cross-sector integration of research content, new prototypes and proposed standards. Furthermore, it outlines how these areas can be profitably integrated into a simulation environment to facilitate the safe and economic planning and construction of hybrid grid structures promoting distribution of scientific and economic knowledge.

The presented planning concept is based on a modeling approach to efficiently assemble these hybrid grids within a simulation environment and to analyze them based on an electrical simulation for safety-related factors, network stability and load flow behavior.

On the other hand, connecting the electrical grid analysis to simulation tools commonly used in the field of production planning are made possible. This will allow process-specific properties to be incorporated into the planning and analysis of the electrical network.

1 Goals and Purposes of DC Grid Design

Software-based solutions for electrical system planning have great potential in terms of analyzing and optimizing systems for efficiency, economy, safety, and system stability. This chapter provides an overview of the goals and purposes that are relevant for the planning of industrial DC grids.

1.1 Economic Planning

First, knowledge about the grid participants or prosumers must be available so that the electrical energy demand of the grid connection and the technologies for generation plants and storage can be selected and dimensioned appropriately. A simulation of the power demand of the grid shows the utilization of the planned energy converters, the coverage of energy by generators and helps with optimally dimensioning storage devices in terms of charging and discharging power as well as capacity [9]. Coupled with acquisition and operating costs, the simulation data can be used to carry out a profitability analysis, which is often indispensable for the investment decision in the new technology [10].

This results in requirements for planning on an energy-related design and the return and understandable preparation of economic KPIs for the implementation of investment decisions.

1.2 Planning of the protection concept

Personal safety and object protection are essential requirements for electrical installations. In standardization, the aspects basic protection, fault protection and extended protection are concepts that must be considered in a protection concept. This includes protection against electric shock, overcurrent protection of equipment and transmission units as well as the mitigation of fire hazards, e.g. due to insulation faults [11]. Depending on the type of network and the associated earthing concept, different components are necessary to form a reliable protection concept [12]. If, in addition, the aim is to achieve the highest possible system availability with selective protective devices, the design of DC networks with sensitive electronics, storage units and comparably high grid voltages and associated arcing risk is particularly complicated due to the lack of voltage and current zero crossings [7, 13, 14].

For power distributions in the AC voltage range, the planning experience is available and software-based design has been established for a long time (e.g. Simaris Design, Curve Select, Hager CAD etc.). In DC based systems, software solutions and simulations to check the selection and combination of switching and protective devices are lacking.

For modeling, protection device tripping characteristics as well as essential data sheet parameters and electrical properties in the components are required. If these are not provided by the manufacturer, empirical values should be available. Warnings and error messages should be issued if the planning does not comply with the rules.

1.3 Verification of the System Stability

After all grid participants, energy converters, the power system and the switching and protection devices have been suitably selected, there is still the risk of instability of the system. For this, detailed information about the dynamic behavior and parameters such as the current control of the power electronic components as well as the line lengths and resistances, capacitances and inductances are relevant. This detailed information is often unknown to planners and is frequently only provided in anonymized models. The mathematical calculations regarding the overall system resonances and stability criteria are so elaborate and complex and therefore error-prone that simulations validated in practice are the only practical solution.

The requirements for the simulations are, in particular, very detailed models of the power electronics with uniform interfaces, which can be integrated in a combined manner as far as possible with regard to know-how protection for manufacturers. The simulation must cover high dynamics in the time and frequency range.

1.4 Measurement and Automation Technology

Every automated production cell requires at least one supervisory control system, typically a PLC. In addition to process control, it's necessary to manage grid functions such as preloading, switching connection of grid branches, and partially coordinating functional safety according to IEC 61508 [15] and ISO 13849 [16]. In addition, there are measurement functions related to power supply and energy storage systems, as well as monitoring of the grid condition. Especially in complex energy grids with generators and storage systems, it is advantageous to use these control modules to control the connected power electronics and to coordinate the converters with each other. In this way, functionalities such as price-based control of electricity can be integrated.

For software-based grid planning, it is therefore important to consider these control functions and communication interfaces to individual functional components such as switching and protection devices, functional safety, and the energy management.

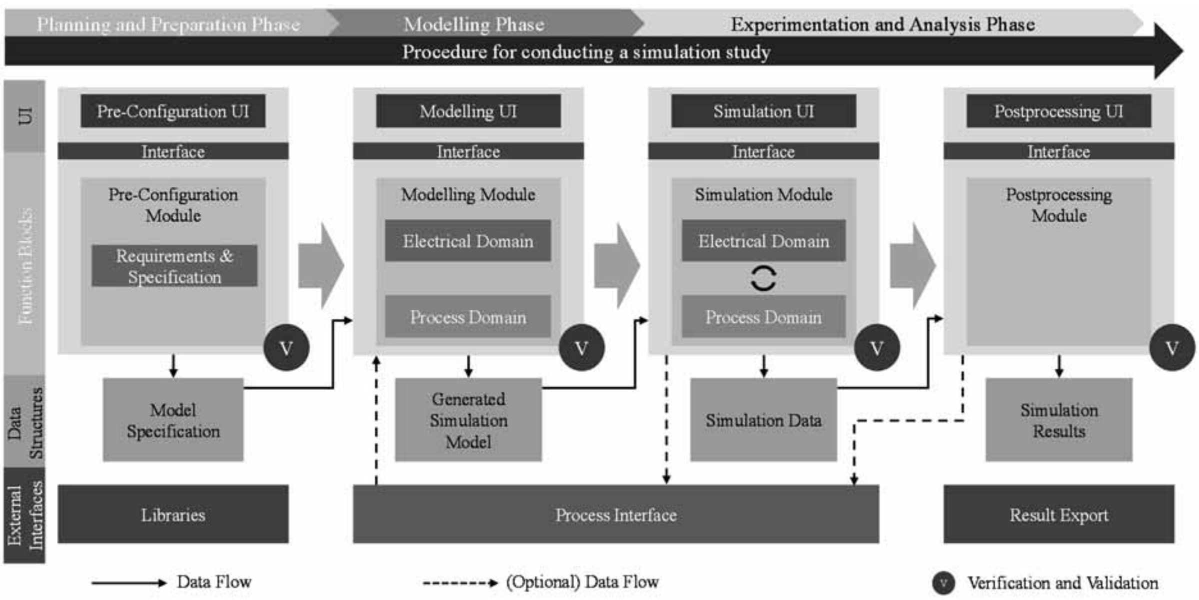

Figure 2: Software Architecture for Simulation-based Planning of hybrid AC/DC Grids.

2 Software Architecture for Simulation-based Planning of Hybrid AC/DC Grids

According to the requirements of the previous chapter, a concept for a simulation-based software for planning hybrid AC/DC grids has been developed. The concept of the planning software is based on an intuitive and user-friendly operation that guides the user step-by-step through the use of the simulation study and is oriented towards the use of common E-CAD tools. The resulting software architecture is shown in Figure 2.

This software should enable the user without the need for simulation skills to optimize these networks with regard to their load flow behavior, to design components sensibly and safely and to carry out analyses with regard to network stability and fault cases.

The software architecture is based on three core concepts: a modular software structure, the chronological execution of a simulation study according to VDI 3633 [17], and the domain coupling from the electrical domain of the electrical grid, as well as the process domain of the production system, which specifies the electrical load and allows production-dependent factors to flow into the analysis.

The modularity of the software architecture is based vertically in the division into a graphical user interface (GUI), function-specific modules, and defined data structures for data exchange. Furthermore, external interfaces form the connection to various model libraries and simulation tools as well as to the data exchange of the simulation results.

The horizontal arrangement of the architecture describes and arranges the functionality of the different modules according to the temporal procedure of a simulation study according to VDI 3633.

The mentioned standard describes the procedure of a simulation study, beginning with a description of the objective and task definition. Based on this, the system analysis, model formalization and implementation follow for the model creation, as well as the aspects of data acquisition and processing in parallel.

Finally, the created simulation model is used to generate added value through the execution of experiments and analysis. Additionally, every aspect of this process is subject to verification and validation activities [17].

Based on this, the proposed simulation tool supports the user in conducting the simulation studies of AC/DC grids in the sections of modeling, simulation, experiments and analysis without the need for an in-depth understanding of simulation and analysis methods. The functional structure of the tool is therefore divided into the modules pre-configuration, modeling, simulation and post-processing which are described in more detail in the following chapters. The tool guides the user through these functions chronologically, picking up the results of the previous function block in each case.

The last core aspect is the coupling of the process domain of the factory with the domain of the energy grid. Energy-related simulation of production systems has become increasingly important in today's world due to the rising significance of energy costs and the CO_2 footprint. It is used for various purposes such as forecasting energy behavior, load-shifting, optimizing energy consumption and energy costs, as well as designing and dimensioning of the energy infrastructure in production systems [18].

In order for realistic and production-related power curves of the individual grid participants within the factory to flow into the analysis of the electrical grid, it is essential to connect and model the energetic behavior of the factory’s resources and processes.

In addition to analyses of the hybrid network, this will also allow energy optimization to be derived in the future with regards to the use of stored recuperation energy, process-oriented energy management as well as the influence of energy storage systems on the process. The coupling strategy is described in more detail in chapter 3.

2.1 Pre-Configuration Module

The use of the simulation tool begins with the pre-configuration phase. Within this module, basic settings are made with regard to the libraries and interfaces used. In the technical sense, basic, unchangeable model properties are set.

Considering common design approaches in Systems Engineering, such as the V-Model or the Quality-Gate Model, requirements and specifications are defined [19]. These properties are stored within the model specification and can be reused in the following modeling module.

2.2 Modeling Module

With the help of the modeling module, the user is able to intuitively design the electrical network in a similar manner to established E-CAD tools.

By using model libraries, no detailed modeling of the electrical components is required by the user, only parameterization. This allows the network to be put together in a plug-and-play manner. The processes at the production level, which as prosumers provide the electrical loads or sources of the network, can also be modeled or coupled to external applications in this module and linked to the network. A detailed description of the modeling of the electrical components as well as the process participants and prosumers within the factory is given in Chapter 3. As a result, the modeling module generates an executable simulation model which is continued in the following simulation module.

2.3 Simulation Module

The Simulation Module is used to run the created simulation models and to define simulation experiments. Basic simulation settings, such as the simulation duration to be carried out and simulation time increments, can be set. Furthermore, basic simulation parameters for the experiments such as the possible dimensioning parameters of an energy storage can be selected and parameterized.

The module provides the raw simulation data as results, which can be analyzed in more detail in the following Post-Processing module. The raw simulation data are primarily the generated current, voltage and power curves of the various network components over time. In the case of the desired stability analysis, the corresponding impedance curves in the frequency range are also transferred.

2.4 Post-Processing Module

The last module analyses the generated raw simulation data in post-processing. The data is analyzed, statistically processed and visualized here to provide the user with a simple, intuitive and provable statement about the simulation results. Depending on the different types of analyses, load flow analysis, fault analysis and stability analysis, appropriate visualization and evaluation forms are selected automatically.

In addition to the fully automated calculation and identification of KPIs and potential patterns in simulation data through established data mining approaches, intuitive visual representations of the processed result data utilize the existing human ability to recognize patterns in visualizations, allowing semi-automatic evaluation and thus supporting the planning process [20].

The most important key figures for decision-making in relation to the design of the components, the security and the profitability of the network should be handed over to the planner through the preparation and the suitable visualization of the simulation results in KPIs.

2.5 Verification and Validation

Verification and validation (V&V) are integral parts of the simulation study process, as per the VDI3633 model. They are not one-time actions but consistently accompany the entire simulation process [17, 21].

Therefore, in each module of the presented architecture V&V is addressed explicitly. It should be noted that V&V also needs to be implicitly considered, for example, when integrating external simulations through the Process Interface (see Chapter 4).

Verification ensures the correct implementation of the conceptual model into the executable simulation models. Validation, on the other hand, guarantees that the model accurately describes the system behavior for the corresponding use case [22]. Various methods for the verification and validation of simulation components are described in [22–24].

The architecture presented verifies and validates the partial results of each module for functionality and compliance with the specified requirements. Automation of these procedures is pursued to relieve the network planner of this task, ensuring a time-efficient and reliable planning process.

3 Modeling and Simulation Concept

3.1 Electrical Simulation of the DC Grid

Pre-Configuration and Modeling Module: Input and Model Generation

The electrical grid of the production plant is modeled and simulated separately from the production process. General system characteristics such as grounding type and grid voltage schemes are set using the interface of the pre-configuration module as previously explained. The grid topology, components, grounding points, as well as electrical parameters are entered into the program using the graphic user interface of the modeling module.

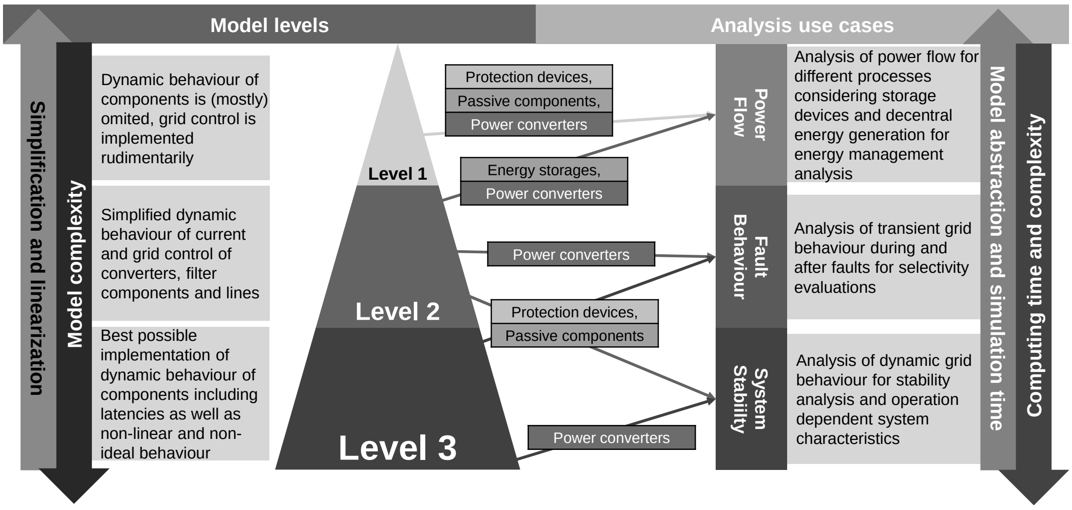

Figure 3: Level Concept for Modelling Grid Components.

Since the computing time of the simulation increases with the size and complexity of the models, different analysis use cases are introduced [25]. For each use case a grid model is generated which uses models with differing level of complexity for the same component. As a result, power flow and energy management simulations with no dynamics but long simulation times do not require as much computation time as using the most complex models for system stability analysis.

Simulation Levels and Use-cases

Three analysis use cases are introduced to keep computing time as low as possible. The use cases employ models of different complexity levels. A summary of the use cases and their respective characteristics is shown in Figure 3. The complexity level models utilized in the grid models of the individual use cases are based on the respective component functionality group: power converters, passive components, and protection devices.

The analysis use cases, and the level models are grouped as follows:

Use case 1 - Power flow and energy management evaluation:

Level 1 component models for protection devices, passive components such as lines and filters, and power converters are used. If large energy storages are directly connected to the grid, or low dynamics are observed in power converters, their level 2 models need to be included into power/energy management simulations.

Use case 2 - Fault behavior and selectivity evaluation:

Level 3 models with non-linear and non-ideal behavior are used for protection devices and passive components. The level of power converter models used depends on whether the control actively regulates faults. If the power converters impact on the fault behavior is negligible simplified level 2 models can be used, if not level 3 models must be chosen.

Use case 3 - System stability and dynamic response evaluation:

Power converters are modeled using non-linear complex level 3 models while passive components and protection devices are modeled using level 2 models as long as there is no impactful operating point dependent change of impedance.

Simulation Module Output: Data Structure Simulation Output

In the simulation module the models are parametrized for the different analysis cases. Furthermore, complex simulations for fault behavior and system stability analysis require data from the respectively less complex simulations. This data is used to set initial conditions for the simulation that define the operating point of the individual grid components. Therefore, the simulations for the use case models must be carried out in a certain order: from least to most complex. These parametrized models are then simulated.

The raw output data includes the voltages and currents of all grid nodes for the different parameter sets and use cases.

This large amount of raw data is the basis of the evaluations carried out in the post-processing module mentioned in the previous chapter.

3.2 Usage of Metadata

The utilization of metadata to provide additional descriptions of grid components is a central aspect of grid planning, especially in the areas of modeling and post-processing, but also in the subsequent project phases of grid planning. Metadata offers supplementary information about the components and facilitates clear assignment between the component in the simulationmodel and the future physical device. The planning process results in a Bill of Material for the energy grid due to the direct connection between the model and the physical component. Additionally, metadata provides further information about the component, such as its type, operating location, manufacturer specifications, and price information, allowing for extended post-processing considerations. Advanced analyses, such as considering the operating location and the associated sizing of control cabinets and their cooling units, are thus possible. In the future, it may be possible to analyze material savings by incorporating metadata about space requirements, weight, and materials used.

The process of selecting and modeling descriptive metadata for an asset depends significantly on its future application to ensure high-quality usage [26]. To consider current use cases in the electrical industry, well-established standards within this industry, such as e.g. the ECLASS Standard, and emerging sub-models of the Asset Administration Shell are employed.

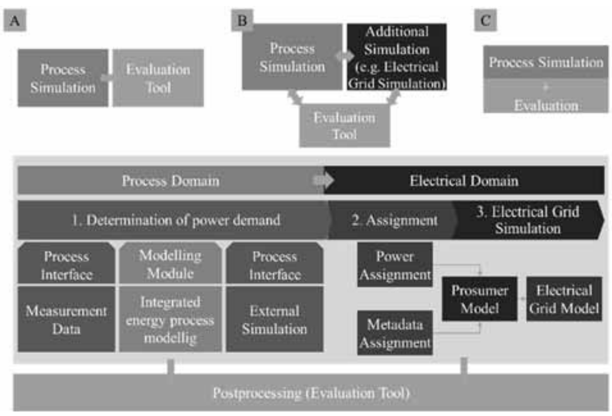

Figure 4: Coupling Paradigms for Simulation of energy flows in Production Systems, adapted from [27] (Top) and Coupling of Process and Electrical Domain (Bottom).

3.3 Coupling and Modeling of the Process Domain

In the realm of energy-related simulation of production systems, coupling is often described in the literature using three paradigms, illustrated in Figure 4 (top):

A) Modeling and simulating the production system in an application for process simulation (e.g., Plant Simulation). The consideration of energy influences of the process takes place in a separate evaluation tool.
B) Coupling different simulation domains e.g. through co-simulation to consider dynamic properties of energy flows. Optionally, an evaluation tool can be included.
C) Monolithic integration of energetic influences into the simulation application of the process domain. [27]

The presented work involves an adaptation of simulation paradigm B. In the process simulation, various methods enable the modeling of energy behavior. These are coupled in a unidirectional linkage to the simulation of the energy grid. The coupling concept presented between the process domain and the energy domain is shown in Figure 4 (bottom).

In the first step, the energy behavior of individual components within the process domain is determined. This includes evaluating the energy consumption of industrial consumers and the energy generation from sources such as renewable energy, like PV systems. In [28] various approaches to categorize modeling methods for the energy behavior of production systems are presented. The energy behavior of production systems can span all hierarchical levels, from individual components and machines to a network of factories.

When modeling the energy network and its respective components, it is crucial to choose an appropriate hierarchical level to accurately capture the energy behavior for the corresponding use case and energy grid analysis. In this case, the modeling of the energy behavior of the process domain can occur in three different ways:

1. Connection of measurement data
2. Linking of external applications or simulations as a Co-simulation
3. Integrated energy process modeling within the tool.

In the second step, the determined power curve is transferred to a prosumer model together with relevant metadata about the corresponding component.

The information about the energy behavior of the components, as well as the metadata, is used in the third step for simulation and the subsequent evaluation in the post-processing module.

Measurement Data

The simplest option is to connect measurement data via the standardized Process Interface in the presented software architecture. Table-based time series of the performance curve can be assigned to various prosumers in the electrical network. This means that the connection and analysis of existing production systems and their behavior can be mapped in the tool without the need of complex simulation of the process. Through this connection, the user is empowered to analyze the electrical DC grid through the load behavior of existing plants in the brownfield.

Usage of External Applications or Process Simulation Tools

Furthermore, it is possible to connect external applications and simulation tools such as material flow simulation software like Plant Simulation or other common tools for virtual commissioning of machines and plants (e.g. NX MCD, ISG virtuos, iPhysics) via the presented Process Interface. In this way, existing simulations in the greenfield can be used to analyze the influence of the electrical network in addition to the analysis of the process behavior. This variant has the greatest effort in regard to the design of the electrical grid, as the process behavior of the factory must first be modeled and, based on this, the electrical behavior model for characterizing the load flow must also be created. Although this approach presents a challenge due to the increased resources and effort required for model creation, which is often seen as a barrier to the industrial adoption of simulations for virtual commissioning [29], it enables more sophisticated analyses for energetic process optimization.

Furthermore, a standardized interface enables the integration of other tools, such as the forecasting tool presented in [30] for predicting the energy produced by PV modules.

Integrated energy process modeling

Lastly, the third variant, which creates a compromise between the two previous methods in terms of detailing and effort, is the integrated modeling of the power curves of the process components. The load behavior of the components can be modeled by the user within the modeling module. Common and proven methods that describe the energetic behavior of the components at different levels of detail and levels within the factory are considered here.

These include procedures and modeling methods similar to the EnergyBlocks method according to [31], state-based procedures as in [32] and physical and analytical modeling procedures as in [33], to further model dynamic components like electric drives.

4 Discussion and Conclusion

This paper describes the advantages of DC grids in production environments and the resulting requirements for the design process of these grids. In order to simplify planning, the paper presents a basic concept for grid design and planning with consideration of connected process participants within a factory by using simulations. The user does not need to have in-depth knowledge of modeling, simulation, grid analysis or statistics. The simulation of the electrical network is based on a use case dependent approach to create a compromise between computing time and detail. Through the connection of external simulation tools, measurement data and the simple modeling of the power curves of the process participants, the electrical network can be planned, analyzed and designed in every life cycle of an existing or planned factory. In future publications, the individual modules, the modeling concepts and the validation by means of a hardware demonstrator currently under construction will be dealt with in more detail.

Acknowledgement

This publication was funded by the Federal Ministry for Economic Affairs and Climate Action through the project “DC|hyPASim” (Project no.: 50 LN/51 LN).

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