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

Simulationsgestützte Planung und Auslegung hybrider AC/DC-Energienetze für Produktionssysteme: Ein ganzheitlicher Ansatz

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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 in the market for the design of these grids, and presents a simulation approach to efficiently assemble hybrid networks and analyse 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 economic, 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.

1 Introduction and Motivation

The use of alternating current to be used 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.

Taking a closer look into production facilities quickly reveals that almost all electronic devices make use of direct current internally and are coupled to the AC mains via their own rectifier (Dragicevic et al., 2016). In addition, the energy transition with its DC-based generators and storage systems necessitate a reassessment. In this context, the system structures based on centralised rectification of AC mains voltage and bidirectional connection of all DC-based consumers and generators via this network branch has been established in various research projects and is already in the first industrial and domestic test networks. This approach leads to energy savings up to 10 %, easier integration of renewable energy and storage devices, and large material savings compared to AC-based decentralized distribution architecture. (Maerz et al., 2017; Savage et al., 2010; Sauer, A. 2020)

The largest previous project works in Germany are DC-Industry 1 and its follow-up project DC-Industry 2. They deal with the design of industrial DC grids (ZVEI, 2017, 2022). The Open Direct Current Alliance of the ZVEI was in turn founded to be the general follow-up research alliance for DC grids (Stern, 2023). 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 the 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 (Fuchs, 2022; PTJ, 2022).

For this new grid structure, the first quasi-standards and new prototype products have emerged from 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. (VDE DKE, 2018; Hirose et al., 2018; Stern, 2023)

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 modelling approach to efficiently assemble hybrid networks within a simulation environment and to analyse them based on an electrical simulation for safety-related factors, network stability and load flow behaviour. On the other hand, connecting the electrical grid analysis to common simulation tools 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.

2 Goals and Purposes of DC Grid Design

Software-based solutions for electrical planning have a lot of potential with regard to aspects of system efficiency, economy, safety and system stability.

2.1 Economic planning

On the one hand, knowledge about the grid participants or prosumers must be available so that the electrical energy demand of the available grid connection and the technologies for generation plants and storage can be selected and dimensioned. A simulation of the power demand of the grid shows the utilisation of the planned energy converters, the coverage of energy by generators and, at best, helps with optimally dimensioning storage devices in terms of charging and discharging power as well as capacity (Schaab et al., 2018). 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 (Weckmann and Sauer, 2019).

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.

2.2 Planning of the protection concept

Personal and object protection are essential requirements for electrical installations. In standardisation, the terms 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 (DIN VDE, 2018). Depending on the type of network and the associated earthing concept, different components are necessary to form a reliable protection concept (Gutwald et al., 2023). 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 (VDE DKE, 2018; DIN VDE, 2014a, 2014b). 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 the DC voltage range, software solutions and simulations to check the selection and combination of switching and protective devices are lacking.

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

2.3 Verification of the system stability

After all network 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 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 anonymised models. The mathematical calculations regarding the overall system resonances and stability criteria are so elaborate, complicated and 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.

3 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 and is oriented towards the use of common E-CAD tools. The resulting software architecture is shown in Figure 1.

This software should enable the user without the need for simulation skills to optimise these networks with regard to their load flow behaviour, 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, and the domain coupling from the energetic level of the electrical network, as well as the process domain, which specifies the electrical load and allows production-dependent factors to flow into the analysis.

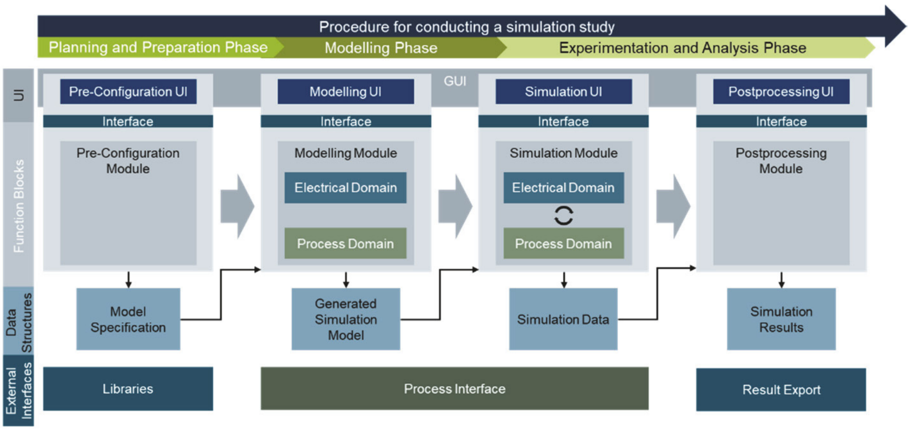

Figure 1: Software Architecture for Simulation-based Planning of hybrid Grids

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 norm mentioned 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 (VDI, 2014).

Based on this, the proposed simulation tool supports the user in conducting the simulation studies of AC/DC grids in the sections of modelling, 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, modelling, 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. In order for realistic and production-related power curves of the individual network participants within the factory to flow into the network analysis, it is essential to connect and model the energetic behaviour of the factory’s processes. In addition to analyses of the hybrid network, this will also allow energy optimisation to be derived in the future with regard to the use of stored recuperation energy and process-oriented energy management. The coupling strategy is described in more detail in chapter 4.

3.1 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. In the context of the electrical DC network, this includes the grounding model and the desired voltage range. These properties are stored within the model specification and can be reused in the following modelling module.

Furthermore, the desired forms of analysis can already be selected in this module, as these already have an influence on the creation of the simulation model. For the electrical network, the analysis of the load flow behaviour, the stability as well as the fault analysis are possible.

3.2 Modelling Module

With the help of the modelling module, the user is able to intuitively design the electrical network based on well-known E-CAD models. By using model libraries, no detailed modelling 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 modelled in this module and linked to the network. A detailed description of the modelling of the electrical components as well as the process participants and prosumers within the factory is given in Chapter 4. As a result, the modelling module generates an executable simulation model which is continued in the following simulation module.

3.3 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 here. Furthermore, basic simulation parameters for the experiments such as the possible dimensioning parameters of an energy storage can be selected and parameterized here.

The module provides the raw simulation data as results, which can be analysed 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 curves in the frequency range are also transferred.

3.4 Post-Processing Module

The last module analyses the generated raw simulation data in post-processing. The data is analysed, 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 analysis, load flow analysis, fault analysis and stability analysis, appropriate visualization and evaluation forms are selected automatically.

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.

4 Modelling and Simulation Concept

4.1 Electrical Simulation of the DC Grid

4.1.1 Pre-Configuration and Modelling Module: Input and Model Generation

The electrical grid of the production plant is modelled 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 and physical values are entered into the program using the graphic user interface of the modelling module. Since the computing time of the simulation increases with the size and complexity of the models, different analysis use cases are introduced. For each use case a grid model is generated which uses models with differing level of complexity for the same component. Therefore, simulations to study the power flow and energy management with no dynamics but long simulation times do not take nearly as long as when using the most complex models for system stability analysis

4.1.2 Simulation Levels and use-cases

The three analysis use cases are introduced to reduce the computing time. The use cases employ models of different complexity levels. The complexity level models utilized in the use case models 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 behaviour and selectivity evaluation: Level 3 models with non-linear and non-ideal behaviour 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 behaviour 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 modelled using non-linear complex level 3 models while passive components and protection devices are modelled using level 2 models as long there are no impactful operating point dependent change of impedance.

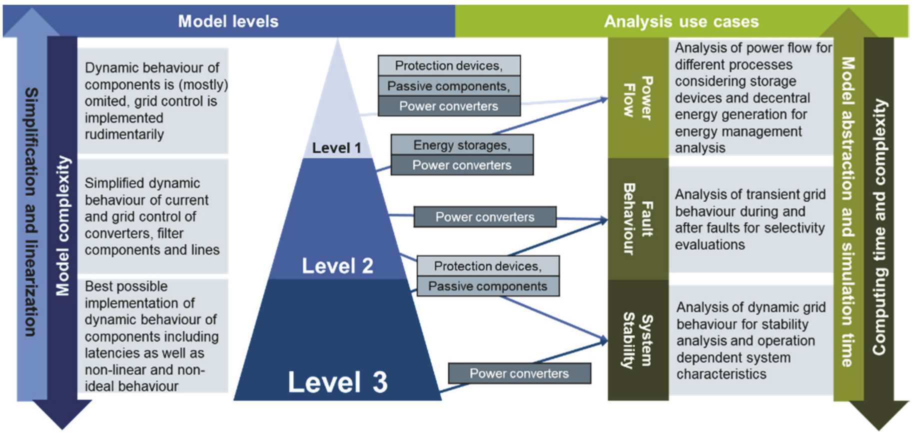

Figure 2: Level Concept for Modelling Grid Components

4.1.3 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 behaviour 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.

4.2 Coupling and Modelling of the Process Domain

The integration of the process domain of the production systems in the factory and thus the influence of production systems on the behaviour of the electrical network is possible through three different forms, each of which has a different level of complexity and detail. In each case the coupling concept between the process domain and the energy domain is identical and shown in Figure 3.

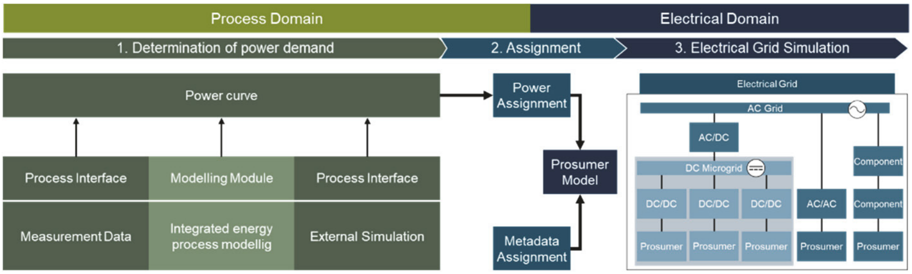

Figure 3: Coupling between the process and energy domains

In the first step, the power demand of the individual components is determined within the process domain. This power determination can be done in three ways: Connection of measurement data, linking of external simulations as co-simulation and an integrated energy process modelling within the tool. In the second step, the determined power curve is transferred to a prosumer model together with relevant meta-information about the corresponding component. This is part of the electrical network and now enables the simulation of the electrical domain. According to this procedure, a unidirectional coupling of the domains from the process simulation and the electrical network results.

4.2.1 Measurement Data

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

4.2.2 Usage of External Process Simulation Tools

Furthermore, it is possible to connect external simulation tools such as Plant Simulation or other common tools in the use of virtual commissioning of machines and plants via the presented Process Interface. However, this requires the determination of the necessary performance. In this way, existing simulations in the greenfield can be used to analyse the influence of the electrical network in addition to the analysis of the process behaviour. This variant has the greatest effort, as the process behaviour of the factory must first be modelled and, based on this, the electrical behaviour model for characterising the load flow must also be created. The advantage here is the profound possibilities of the analyses with regard to energetic process optimisation.

4.2.3 Integrated energy process modelling

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

These include procedures and modelling methods similar to the EnergyBlocks method according to (Weinert et al., 2011), state-based procedures as in (He et al., 2012) and physical and analytical modelling procedures, to further model dynamic components like electric drives.

5 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 modelling, simulation, grid analysis or statistics. The simulation of the electrical network is based on a level-based approach to create a compromise between computing time and detail. Through the connection of external simulation tools, measurement data and the simple modelling of the power curves of the process participants, the electrical network can be planned, analysed and designed in every life cycle of an existing or planned factory. In future publications, the individual modules, the modelling concepts and the validation by means of a hardware demonstrator currently under construction will be dealt with in more detail.

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