Modelling, Planning, Design and Evaluation of DC-Distribution Grids

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Abstract

In October 2014 the Research Campus Future Electrical Networks, funded by the Federal Ministry of Research and Education with around 10 million € over the next 5 years, was started at RWTH Aachen University. Focus of research is the utilization of dc-technology for electrical (distribution) grids. The publicly funded Research Campus consists of four different projects, which are closely cross-linked. Within one of these projects a research demonstration medium-voltage dc-grid is to be built by connecting several test benches in the megawatt range, other projects focus on control and automation as well as devices and grid technologies. This paper will present the project “Modelling, Planning, Design and Evaluation of dc-Distribution grids” which focuses on the development of network planning tools for dc and hybrid distribution grids as well as related interdisciplinary topics such as acceptance, electromagnetic compliance landscape and urban planning.

Due to the interdisciplinary approach the project consortium consists not only of institutes from the Faculty of Electrical Engineering, but also of institutes focusing on political science, landscape architecture, urban planning, medicine, ergo-nomics, and technical communication. Under the project lead of the Institute of Power Systems and Power Economics (IAEW) at RWTH Aachen University they work closely interconnected in order to facilitate an interdisciplinary exchange and interaction. This paper will give a detailed overview on the different work packages of the project as well as on the project targets and the chosen methodologies.

1 Introduction

The existing German electrical supply system is designed for a top-down distribution of energy from central power stations to customers. The energy transition (Ener-giewende) now requires the integration of a high share of volatile renewable generation. As most of this generation capacity arises from small decentralized generation units connected to low and medium voltage networks, especially the electrical distribution grids face new challenges in or-der to integrate distributed generation.

On this background, RWTH Aachen University together with company partners has founded the Center for Flexible Electrical Networks (FEN). The Center sees a high poten-tial in dc-technology as well as in the integration of differ-ent energy networks and ICT technologies to tackle the challenges in the electrical supply system at all voltage lev-els, with a focus on medium and low voltage. Through the

close collaboration with industry partners and the joint re-search in Aachen, the results can quickly be used to accel-erate innovation.

The German Federal Ministry of Education and Research is funding precompetitive research in FEN to develop dc-solutions for medium-voltage distribution grids. With the funding four research projects have been defined to de-velop grid planning concepts, components and control and automation technologies as well as set up a research grid at RWTH Aachen Campus.

Within project 1 „Modelling, Planning, Design and Evalu-ation of dc-distribution grids" research focuses on the de-velopment of new network planning tools for dc and hybrid distribution grids both for greenfield, as well as for brown-field planning. Further areas of research are interdiscipli-nary topics such as acceptance, electromagnetic compli-ance, and landscape and urban planning. Figure 1 displays the topics within the scope of FEN as well as the topics within the focus of project 1 (red edging). This interdisci-plinary approach requires knowledge in the field of electri-cal engineering as well as from other research fields. Therefore the consortium of project 1 consists of institutes from the faculty of electrical engineering but also of insti-tutes from other faculties focusing on political science, landscape architecture, urban planning, medicine, ergo-nomics and technical communication.

Figure 1 topics within the scope of FEN and project 1

This paper gives a detailed overview of the wide scope of the project's research goals. Hence the paper is divided into two main sections, one focusing on technical aspects and one focusing on socio-technical research topics. Both chapters consist of different subsections presenting focus areas as well as the institutes working on these topics. Alt-hough the sections are divided into technical and socio-technical research topics there are many interdependencies, which require a close interaction and collaboration be-tween all researchers. In order to enable and encourage this interaction, the FEN centre offers open work space for all researchers working on the funded projects.

2 Technical Research Topics

2.1 Grid Planning and Operation

The usage of dc-technology in distribution grids might have some technical advantages over conventional ac-sys-tems. Some of these advantages often mentioned are a bet-ter utilization of infrastructure due to the absence of reac-tive power flows, higher power transmission, lower power losses, reduced problems with voltage band violations, the capability of integrating higher shares of decentralized generation and more flexibility due to controllable load flows. But yet there are almost no publications proving these results with simulations of realistic dc-distribution grids. Therefore, one of the main objectives of project 1 is the development of grid planning tools. These tools are to be developed by the Institute of Power Systems and Power Economics (IAEW) at RWTH Aachen University who are also project leader for the whole project.

Thereby, the planning process is separated into two differ-ent steps. The first step consists of a long term greenfield planning. Within this step all existing grid assets are ne-glected and the optimal grid for a given supply task is planned. In order to develop such a planning tool, the tech-nical constraints and degrees of freedom for dc-grids need to be analysed and existing planning tools [1] need to be extended. Furthermore, fundamental planning conven-tions, e.g. the number of voltage levels and the voltage lev-els themselves need to be defined for dc-grid planning. The planning tool needs to be capable of planning conventional ac-grids, dc-grids as well as hybrid grids in order to iden-tify the cost effective grid for a given supply task.

In a second step, the long-term optimal grid is handed over to a brownfield planning tool [2], which needs to be devel-oped in order to identify possible transition paths from the current grid structure to the cost optimal target system. Thereby it may occur, that there are no transition paths to the cost optimal grid structure and the structure can never be reached if the transition itself is too costly.

Besides the development of these two grid planning tools grid operation lies also within the focus of research. On the one hand grid operation procedures, for example, load flow control and curtailment of renewables, are to be analysed and to be integrated into the grid planning tools as these operational aspects also highly affect the necessary grid infrastructure [3-5]. On the other hand the issue of reliability and grid restoration becomes more and more important and existing simulation tools [6-8] need to be extended adequately as there will be more active components, e.g., con-verters in dc-grids, which may influence the reliability of supply.

The construction of dc-distribution grids does also affect overlaying networks e.g. the 110 kV high voltage grids in Germany. Modern VSC converters are capable of controlling active and reactive power independently from each other. Hence they could be utilized to reduce voltage band problems in the high voltage networks and to improve volt-age stability [9]. In order to quantify the effects of a high penetration with medium voltage dc-grids, simulation tools for the high voltage level are necessary. Furthermore, MVDC grids could influence the frequency control in the overlaying high and extra high voltage grids as they reduce the dependency between load and frequency. But also in underlying remaining ac low voltage grids frequency con-trol becomes of great importance.

2.2 Impact of Static Electric and Magnetic Fields

The Research Center for Bioelectromagnetic Interaction (femu) is the university hospital’s department of the RWTH Aachen University, which conducts interdiscipli-nary research on biological and medical effects of electro-magnetic fields [10].

The aim of this part of project 1 is to analyze the effects of static electric and magnetic fields on human health and bi-ological systems as well as measuring the fields emitted by the FEN MVDC test grid and the resulting impact on hu-mans with cardiac implants. The project is divided into three work packages. In the following subsections, the work packages will be described briefly.

2.2.1 Effects of Static Electric and Magnetic Fields on Biological Systems

Due to the energy transition in Germany, an expansion of the electricity transmission network is planned, in part us-ing dc transmission lines. Therefore, the exposure of the general public to static electric and magnetic fields will in-crease. To evaluate the current scientific data and to iden-tify gaps of knowledge, two systematic reviews will be conducted. The first one deals with static electric fields. The second one deals with static magnetic fields below 500 μT, because this value represents the limit value for the general public in Germany [12]. Using defined criteria based on the PRISMA checklist [11] a systematic overview of literature on the effects of static electric and magnetic fields on biological systems and human health is given both in vivo (e.g. human, animal) and in vitro (e.g. cells, tissue slices). The literature overview will be represented in the EMF-Portal (www.emf-portal.org), a scientific literature database on the effects of electro-magnetic fields.

2.2.2 Interference of Cardiac Implants with Static Electric and Magnetic Fields

Cardiac implants such as cardiac pacemakers and implant-able cardioverter defibrillators are susceptible to alternat-ing electric and magnetic fields [13], [14]. However, less is known about the exposure to static electric and magnetic fields and the possible health effects for humans with car-diac implants. In a first step, the scientific literature will be screened to evaluate the current scientific knowledge and to identify possible gaps. Additionally, the coupling of static fields into the human body as well as the effects on cardiac implants will be evaluated via theoretical examina-tions and numerical simulations. Results will be infor-mation regarding potential health risk due to interferences of static electric and magnetic fields with cardiac implants.

2.2.3 Risk Assessment of Field Emissions Occur-ring at the FEN MVDC Experimental Grid

Within project 4 “Design, Construction and Test Operation of the MVDC Experimental Grid Aachen” components and technical equipment (e.g. dc cables, dc converters) will be used to construct a dc grid. In this work package, the oc-curring electric and magnetic field emissions will be meas-ured and compared to already existing limits for the general public as well as for employees. Induced currents in the human body will be determined numerically via finite-ele-ment-simulations. Hence, recommendations for the mini-mization of field emissions, if necessary, can be given at an early stage and taken into consideration for further steps.

3 Socio-Technical Research Topics

3.1 Acceptance of DC-technologies

The public resistance against high voltage grid extension and the planned HVDC corridors shows that public ac-ceptance is crucial for infrastructure projects and technol-ogies although most of the medium and low voltage grids are cabled. The department for Textlinguistics and Tech-nical Communication (TLTK) (as part of the Human-Com-puter Interaction Center (HCIC) at RWTH Aachen Univer-sity contributes to the FEN project by investigating the per-ception and acceptance of dc-technologies as well as digi-tal science communication formats for risk communica-tion. In the following two subsections, the work packages are presented.

3.1.1 Perception and Acceptance of DC-Technol-ogies

Examining the role of technology perception and technol-ogy acceptance allows gaining a better understanding of the public view on transformation issues. The perception of technology differs depending on technology type, con-text-related factors, perceived risks (e.g. trust), benefits (e.g., usefulness), cost-benefit ratios and control [15]. Ger-mans typically show a high level of acceptance towards do-mestic and work technology (production systems, etc.). In contrast, acceptance of complex and highly technical

power stations (e.g. wind farms) and related energy infra-structure technology is lower [15-16], especially if these systems are built in a neighbourly environment (NIMBY-effect) and are beyond the individual’s control (such as complex technical systems) [17]. Therefore, user-gener-ated content from public discourse (e.g. news comments, Facebook-posts, etc.) is analysed with text mining-meth-ods in the present project part. The approach allows for the identification of participating stakeholders in public discourse, the determination of acceptance-promoting and -inhibiting factors or arguments (discourse analysis) as well as the recognition of reference objects of dc-technologies (comparative analysis). Consequently, results of the work package are used as input for the second work package.

3.1.2 Digital Science Communication Formats for Risk Communication

Communication and information play an important role when seeking public acceptance for energy strategies and decisions [18]. Citizens want to be informed about technol-ogy issues, especially regarding projects that are linked to their direct environment (e.g., dc-distribution grids). There-fore, effective communication and information concepts (information policies) should be included to promote public support for energy systems [19]. Hence, researchers should be concerned with the question how citizens need to be in-formed. This includes the information strategy, the infor-mation disclosure level and the amount of information, ef-fective transfer methods and background knowledge. Current approaches focus on the use of Web 2.0 technologies (e.g., wikis such as Wikipedia, microblogs such as Twitter, social networks such as Facebook) as access to government information [20]. Within the scope of project 1, science communication studies are conducted under laboratory con-ditions (simulation). Thereby, it is examined which formats, means, and modalities are preferred by the public regarding risk communication. The results are integrated in an over-arching communication concept.

3.2 Political, Regulatory and Economic As-pects

The objective of the economic analysis is an assessment of the market potential of dc-Grid solutions in Germany (and Europe) The Institute for Future Energy Consumer Needs and Behaviour (FCN) at RWTH Aachen University con-ducts this research. It is focused on applied theoretical and empirical research in energy economics, management, and policy, with a particular thematic focus on the adoption and diffusion of innovative technologies and on energy con-sumer needs and behaviour.

As in the early stage of technical research many relevant properties for an economic or management assessment are still relatively unknown, the perception and acceptance of the general public (voters) regarding the political support for MVDC-grid installations is to be analysed by means of a discrete choice experiment. Choice experiments are an attribute based stated preference method used in various research areas, including energy and environmental eco-nomics [21-22]. The approach is based on the assumption that a technology change towards dc-technology in the me-dium voltage grid will rely on governmental support, as for example the market diffusion process of electricity gener-ation based on renewable sources does. For the planned choice experiment, dc-technology in general and the MVDC components in particular, are regarded as compo-nents of a complex technical system beyond individuals' control and for many laypersons likely beyond any aware-ness. Therefore, the analysis focuses on identifying deter-minants of public approval towards potential future politi-cal support measures for the implementation of MVDC-technology. Such political support might be justified based on positive externalities and social benefits that are not, or only partly, taken into consideration in private supply and demand behaviour. Possible social benefits, might be envi-ronmental benefits, a more efficient way to integrate high shares of (decentralised) renewable energies (e.g. by prosumer-households) in the electrical grid, enabling other innovations regarding the energy transitions as for example smart-grids, to revise the case of path-dependence and technology lock-in in the medium voltage grids. The anal-ysis should provide insights for policy makers, researchers and investors to which extent todays mainly hypothetical benefits, and costs, for implementing MVDC components matter for the population's willingness to support, accept and pay for a possible politically supported technological change towards dc-technology in distribution grids. Fur-ther, it has to be identified which role the lack of visibility and technical nature have on the perception of the technol-ogy and support measures and which role the perception on the related ongoing energy transition and support of renew-able energy has ("is the population willing accept/risk an-other turnaround in the energy sector"). The technology change towards MVDC grids might also be characterized as an ultra-long-lived investment good, because its benefits might go far beyond the planned financial and non-finan-cial consequences of today's decision makers and society, which is interesting from political-economic perspective.

3.3 Power grids as Sociotechnical Systems

A growing body of literature in science and technology studies (STS) draws attention to complex socio-material dy-namics in the production of scientific knowledge, as well as in the development, functioning and use of technological artifacts [23]-[27]. This literature suggests that technology "neither exists nor has meaning without the human activi-ties of which it is part and similarly, many social practices would be impossible or incomprehensible without material objects" [28]. From such an STS perspective it seems par-ticularly instructive to refer to power grid technology as a "sociotechnical system" [28]-[30]: a system that is com-posed of technological infrastructures, products and pro-cesses, as much as it is intertwined with linked networks of people, knowledges and institutional practices [31].

To effectively shape such a system it seems crucial to understand its specifics and complexities. Not only are there many actors at work in the development and deployment of the system [32] but also many kinds of uncertainties that deserve attention [28]. These social, material and temporal dynamics and complexities are addressed by the Institute of Political Science (IPW) at RWTH Aachen University.

3.3.1 Socio-Material Interdependencies

Governments and corporations, e.g., make decisions about which research projects to fund; engineers and scien-tists decide about how technological artifacts are designed and constructed; and users ultimately use (or reject) techno-logical applications and products—including uses (or rejec-tions) not envisioned by the governments, companies, and engineers that crafted them. In turn, the material effective-ness of technologies matters because they are objects “de-signed to accomplish real material purposes” [31]. Thereby, several actors, human relationships, and interactions shape sociotechnical systems, their formation, stabilization, and maintenance. This multiplicity of socio-material interde-pendencies makes it extremely difficult—if not impossi-ble—to predict whether an invention will be adopted, and in what exact way it will be integrated into society [28], [32].

3.3.2 Uncertainties of Engineering

Furthermore, technical aspects of an invention are usu-ally not fully understood before its adoption, neither by sci-entists nor by policymakers nor by users. Knowledge is lim-ited insofar as factors, situations, and side effects might not be considered, sufficiently tested, or even known [28]. In particular, developments and outcomes that concern future times are characterized by various degrees of incertitude re-garding risks, ambiguities, and the unknown [33]. On that account it seems important to approach socio-technical sys-tems with the recognition that their precise functioning and behaviour are unlikely to ever be certain. Still, methods should be advanced to better understand, anticipate and pre-pare for the risks inherent in the systems. [28], [33]

Thinking of power grids respectively dc-grids in terms of sociotechnical systems and applying this concept to qual-itative social science research within FEN provides a fasci-nating opportunity to study a technology in-the-making, e.g. regarding the ways that social dynamics and complexities are co-constitutive with the development, functioning and use of (dc) grids. This understanding promises to be essen-tial to any attempt to meet the challenges of future electrical networks.

3.4 Effects on Occupational Profiles and Consequences for Vocational Training and Education

To implement a new technology like DC-technology in dis-tribution grids, many technical challenges must be re-solved. For a successful implementation, in addition to technical aspects, also social problems must be considered. Both, the acceptance of all affected power grid users and the effect on all people involved in a possible transfor-mation of distribution grids must be analysed.

The adaption to this technological development will also be a central challenge for occupations in electrical engi-neering, especially in the fields of power supply. The new dc-technology will cause a change of the requirements on all levels of skilled work and in consequence of the appro-priate occupational profiles. The assumed changes reflect two important social trends: the rapidly rising complexity of work tasks and the transformation of occupational pro-files [40].

To adequately train skilled workers, technicians and other qualified employees, concepts of initial, continuing and ad-vanced vocational training must meet those changing qual-ifications and skill demands. Thus, existing vocational training concepts and training regulations must continu-ously be advanced and evaluated [40]. To identify the nec-essary objectives of occupational training programs, the re-search field of “Qualifications Research” was established in Germany [34], [37].

“Qualifications Research” in general refers to a set of ex-isting methods and instruments from different well-estab-lished scientific disciplines [36-37]. For both, analyzing qualifications and skill needs and developing didactical consequences for training programs, especially methods and tools of industrial engineering, ergonomics and of ped-agogics can be used. These methods and tools consider, for example, systems of job and work task analysis, interview techniques and expert skilled worker workshops in detail [36], [39].

The Institute of Industrial Engineering and Ergonomics (IAW) at RWTH Aachen University will analyse the con-sequences of the DC power grid technology for future oc-cupational profiles and the influence of the technical fun-damental projects on existing profiles.

The research objective is the development of design rec-ommendations to adapt the occupational profiles for em-ployees in the field of power supply and to improve in-plant trainings and advanced trainings. For this develop-ment, case studies will be operated to identify the changes of skilled work in selected work tasks and the conse-quences for future occupations in electrical engineering.

A further research objective is the preparation of design recommendations for the training system and the exploita-tion of necessary qualifications and skills for the occupa-tion field of power supply. The validation of the results will be supported by expert interviews and workshops with the participating associates from industry, intermediate organ-ization and education providers.

3.5 Landscape and Electrical Network

Since renewable energy solutions become a part of the tra-ditional energy system they have altered our landscape. These changes – from a fossil energy driven landscape to a renewable energy landscape – may be as drastic as the change which took place from the non-electrified land-scape to an electrified [41]. The energy transition, which is a still ongoing process and with it the renewable energy systems will affect landscape and environment in different ways, compared to the introduction of conventional energy production did before.

The most obvious elements of this transformation are new high-voltage transmission lines and renewable generation units, e.g., photovoltaic panels on rooftops as well as on-shore and offshore windmills. Another visible and exten-sive element of the conventional energy production is the extraction of fossil energy sources. In case of renewable energies e.g. biomass this part is not as visible as agricul-tural and forestry biomass production require the fore-knowledge of the observer to become visible. Side effects like the indirect land use change (ILUC) especially the

ploughing up of grassland is another example. A third layer of impact is the emerging relationship between planning, land use, landscape development and the energy system.

The Chair of Landscape Architecture (LA) at RWTH Aa-chen University will focus on the following three research questions within the scope of this project: (A) The effects of direct current distribution grids on the landscape, (B) Landscape development with a high ratio of small-scale re-newable energy systems, and as an inference of these two questions (C) The potential of landscape development through the direct current technology. These three ques-tions will be examined in two different settings: a more ru-ral and distinct area and otherwise a more urban and spoiled area. The study is to show the visible and concep-tual potentials of the direct current technology in shaping different types of landscapes.

3.6 Impact on Urban Design and Regional Planning

Cities and urban as well as rural areas are facing the con-sequences of demographic change, which also offers new possibilities and opportunities. They are forced to develop local concepts for energy efficiency and sustainability based on their existing “hidden” infrastructure. This infra-structure incorporates sub terrain cabling tunnels, which have to be adapted both from a constructional as well as from an operational perspective. This adaption will influ-ence the structure of our cities as well as individual build-ings.

The Institute for Urban Design and Regional Planning (ISL) at RWTH Aachen University deals with complex ur-ban structures from the regional and overall urban context, on the level of the district up to the interface with architec-ture.

Based on the historically grown existing context, the focus is on the design and further renovation of sustainable cities and neighborhoods taking into account their technical, en-vironmental, economic and sociocultural conditions.

Within this project ISL is focusing on the impact of dc-technology on urban structures and systems, public areas and buildings. In close collaboration with other technical and nontechnical institutes within the project consortium the structural and creative impact as well as changes in building culture due to the usage of dc-technology in an exemplary quarter of a city are to be evaluated.

Furthermore the project aims at developing modules for an integrated development of city quarters based on the usage of renewable energies in an urban context under consider-ation of the required grid extension.

Subsequently it has to be evaluated how these modules and results can be transferred to other areas and settlement structures e.g. rural areas.

4 Outlook

The project was officially started in October 2014. Whereas work on some of the introduced research areas has already started, work on others will start within the up-coming years according to the scheduled working plan. First results are to be published in scientific papers and at conferences by the end of next year. Up-to-date infor-mation can be found on the website www.fen.rwth-aa-chen.de.

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