Design of Benchmark of Medium Voltage Distribution Network for Investigation of DG Integration

K. Rudion, A. Orths, Z. A. Styczynski, K. Strunz

***Abstract*— The widespread use of distributed generation (DG) relies on methods and techniques aimed at facilitating the network integration of DG. In this context a methodology for the evaluation of the quality and relative merits of these methods and techniques is missing. CIGRE Task Force C6.04.02, which is affiliated with CIGRE Study Committee C6, has addressed this problem by proposing a set of resource and network benchmarks. In the present paper, the benchmark for integrating DG in medium voltage distribution networks is described. The proposed benchmark is representative of a real network while it is also designed for ease of use.**

The application of the benchmark is described through several case studies that show the impact of DG on power flow and voltage profiles at the medium voltage level.

***Index Terms* – Benchmarking, distributed generation, distributed energy management system, distribution network, power system modeling, power system simulation.**

I. Introduction

In today's power systems, electrical power is mostly generated in large power plants that are commonly located where sources of fuel are well accessible. The generated power must often be transmitted over long distances before reaching the consumer. The shortage and rising prices of fossil fuel as well as the public resentment towards nuclear power and construction of transmission lines all stimulate interest in novel and alternative solutions of electric power generation. A possible solution involves the widespread commissioning of distributed generation (DG) units that utilize renewable energy sources or deliver heat and power simultaneously.

DG units are usually connected to the local low voltage and medium voltage distribution networks. Only large wind farms with high power ratings are connected to the high or even very high voltage networks. The development of DG in low and medium voltage networks causes a structural change in the traditional centralized power system. In the past, the impact of DG on the power system was not significant because of its low overall share. But today the number of DG units increases rapidly. Therefore, power systems with a high penetration level of DG have to be modeled and simulated in order to investigate new methods of operation and energy management, as for example discussed in [1].

The medium voltage distribution network presented in this paper is well suited for investigations of DG integration. In Section II, the development of benchmarks for DG integration as pursued by CIGRE is introduced. In Section III, the main characteristics of the medium-voltage rural distribution network benchmark are described. In Section IV, the scope of application of the benchmark is discussed. Case studies are given in Section V. Conclusions are drawn in Section VI.

II. Benchmark Development

The problem of evaluating the integration of DG is dealt with by CIGRE Task Force (TF) C6.04.02. In particular, the vocation of this TF is to establish a common basis of evaluation in the form of benchmark systems for DG integration studies [2]. To cover the spectrum of DG studies in a collectively exhaustive and mutually exclusive manner, a DG benchmarking methodology that comprises a set of benchmark configurations was developed. Central to the methodology is the hierarchical structure of four levels depicted in Fig. 1. There is a generalization-specialization hierarchy between any two levels. Starting from the highest level, the electric power system, specializations are carried out down to the levels of detail that are of interest for DG benchmarking.

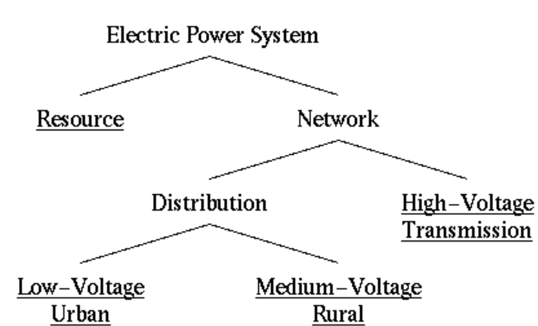

Fig. 1. Hierarchy of benchmark systems for DG integration [2]

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At the same time it is made sure that at any level the entries are mutually exclusive and collectively exhaustive.

The electric power system is described by the underlying network and the resources connected to its nodes. A resource node by itself is an interesting candidate for a benchmark since many of the techniques for the integration of DG units rely on source side control and power electronic conversion. Further specialization is needed for the network, and transmission and distribution networks must be distinguished from one another. The latter can vary significantly in their characteristics depending on whether rural or urban types are considered. Together, low-voltage urban distribution, medium-voltage rural distribution, and high-voltage transmission networks represent a suitable set of candidates for DG benchmarking.

III. Main Characteristics of the Medium-Voltage Rural Distribution Network

As discussed above, three benchmark networks are established in order to deal with studies that are mainly concerned with the network side of DG integration. The medium-voltage (MV) rural distribution network benchmark is derived from a German MV distribution network, which is shown in Fig. 2 [3].

The network has rural character and supplies a small town and the surrounding rural area. The rated voltage level of the network is 20 kV. It is supplied from a 110 kV transformer station. Most connections are made with cables, but there are also sections of overhead lines. The network in Fig. 2 has 30 nodes. To reduce the size to a level that is required for DG integration studies while maintaining the realistic character, the number of nodes was reduced. The resulting network proposed as a benchmark is shown in Fig. 3. The benchmark network is decomposed into two separate subnetworks 1 and 2. The subnetworks are supplied by 110/20 kV transformers, which are referred to as TR1 and TR2, respectively. The medium-voltage DC coupler (MVDC) is optional and the purpose of subnetwork 2 is to study such coupling.

For many types of case studies, it is sufficient to consider subnetwork 1 only. If its coupling switches, indicated with T in Fig. 3, are opened, the network has a radial structure. But depending on the interests of the user, it can be simulated as a closed ring network, too. The total length of the lines in the subnetwork 1 is equal to about 15 km.

Due to the fact that different countries have varying distribution network parameters, the original values given for the German network were transferred into the per unit system. This facilitates the adaptation of the benchmark to regionally varying parameters.

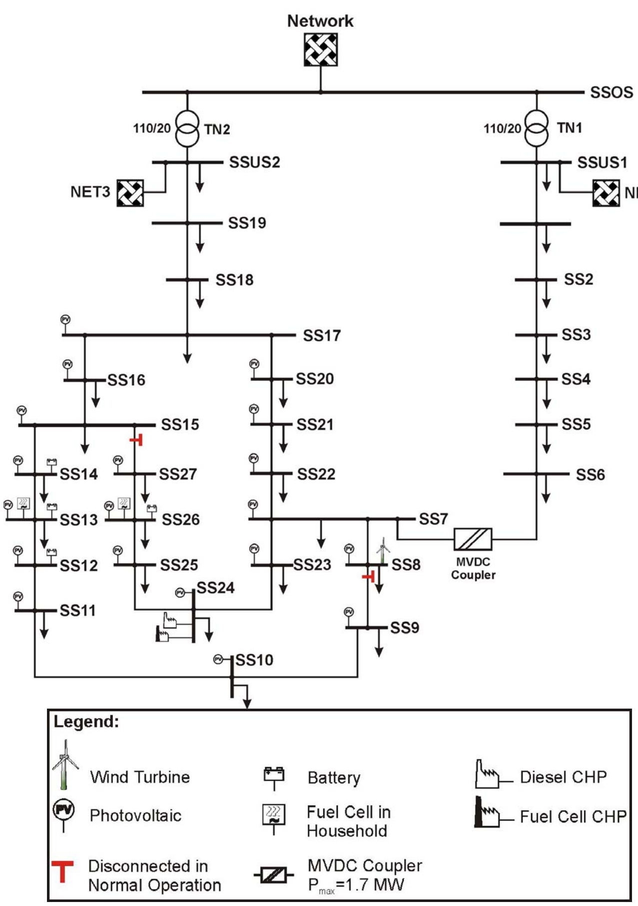

Fig. 2. Test network derived from German MV distribution

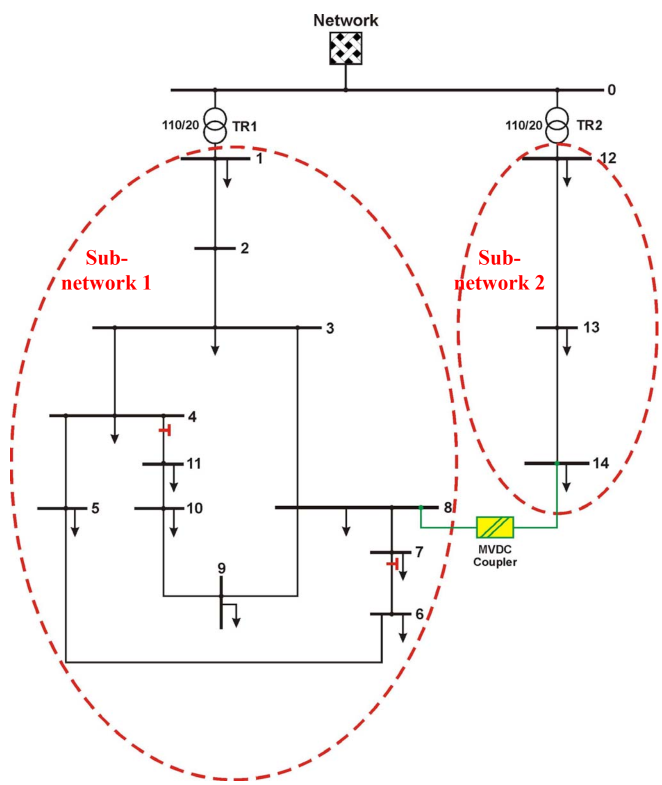

Fig. 3. Medium-voltage rural distribution benchmark network

IV. Scope of the Benchmark

The benchmark network is designed for studying the impact of diverse DG at the medium-voltage level. The list of studies that can be carried out with this benchmark includes the following:

- study of the impact of DG units on the power flow of MV distribution lines;
- study of the impact of DG units on the voltage profile in the MV distribution network;
- study of energy management systems (DEMS) for DG in the MV distribution network;
- study of power quality issues such as harmonics, flicker, frequency variations, and voltage variations;
- study of small signal stability;
- study of voltage stability;
- study of the impact of MVDC coupling on the power flow of MV distribution lines;
- study of the impact of MVDC coupling on the voltage profile in the MV distribution network;
- study of the impact of DG units on transmission capability of the subnetwork 1 feeder;
- study of the protection of the MV distribution network.

V. Simulation Cases

A. General Information

In what follows, several simulation studies are discussed. With the exception of node 2, a load was connected at each node. These loads have either household or industry profile, and are shown in Fig. 4 and Fig. 5, respectively. The load types and maximal power consumptions are summarized in Table 1. The load associated with the two networks NET3 and NET4 in Fig. 2 was aggregated with the total load at the respective nodes of the benchmark in Fig. 3.

NETOMAC [4] was used as simulation tool. The network parameters are given in the Appendix.

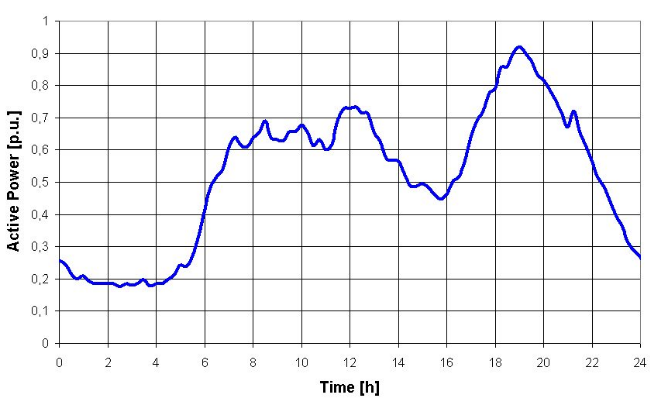

Fig. 4. Typical load profile: household

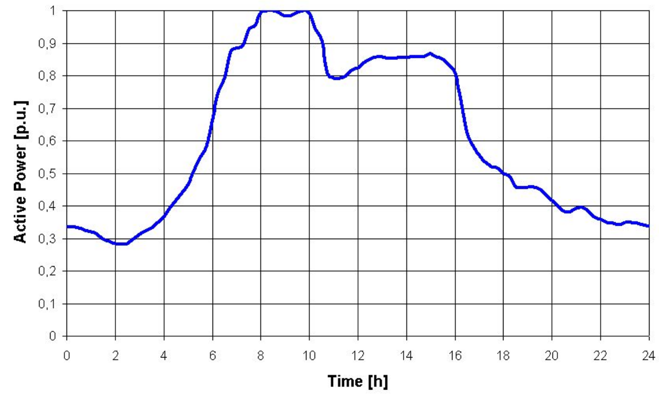

Fig. 5. Typical load profile: industry

TABLE 1
PARAMETERS OF LOADS AT EACH NODE

Node No.	Load Type	P_{max} [p.u.]	Q_{max} [p.u.]
1	Household	0.15000	0.03100
1	Industry	0.05000	0.01000
3	Household	0.00276	0.00069
3	Industry	0.00224	0.00139
4	Household	0.00432	0.00108
5	Household	0.00725	0.00182
6	Household	0.00550	0.00138
7	Industry	0.00077	0.00048
8	Household	0.00588	0.00147
9	Industry	0.00574	0.00356
10	Industry	0.00068	0.00042
10	Household	0.00477	0.00120
11	Household	0.00331	0.00083
12	Household	0.15000	0.03000
12	Industry	0.05000	0.01700
13	Industry	0.00032	0.00020
14	Industry	0.00330	0.00205
14	Household	0.00207	0.00052

B. Simulation without DG

The maximal power transferred over the transformer TR1 is equal to 19.7 MW if no DG units are present in the network. The peak value of the power collected from node number 2 is important for the investigations of the benchmark network. This power is equal to 3.5 MW when no DG unit is implemented in the network.

The starting point for the investigations was the preparation of the voltage profile of subnetwork 1. Loads were connected to the network according to Table 1, and no DG unit was present. The resulting voltage profile is presented in Fig. 6. It shows the minimal voltage values at each node obtained by simulating peak power consumptions at each node. Additionally, in Fig. 7 the voltage profile for the node number 2 is shown over a 24-hour time interval. It can be seen that the acceptable voltage band is exceeded for an extended period.

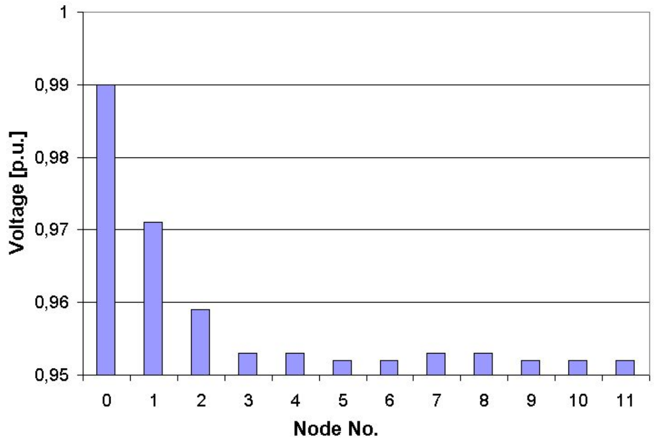

Fig. 6. Voltage profile without DG and without MVDC coupler

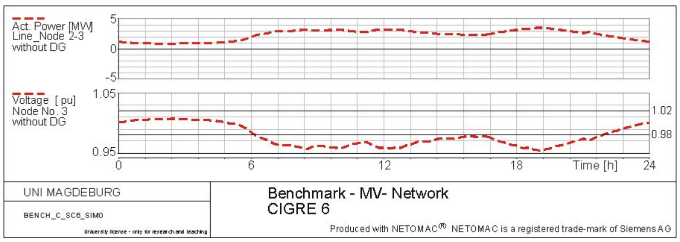

Fig. 7. Time-domain simulation without DG and without MVDC coupler

C. Integration of DG

To evaluate the impact of DG on the voltage profile, DG units were connected as summarized in Table 2. The results are presented in Fig. 8. To better illustrate the impact of DG with respect to the case where no DG is present, the prior simulation results of Fig. 7 were also plotted for both power and voltage. The dashed line shows the result for the scenario without DG units and the solid line shows the result for the scenario with DG. Also shown in Fig. 8 are the accumulated outputs of power of the different DG types wind power, PV, battery fuel cell and CHP.

Thanks to the integration of the DG units, the voltage profile is improved. Nonetheless, the voltage is shown to exceed the acceptable limits in certain intervals. It can be seen that at the beginning of the simulation the power flow direction in the feeder has been changed, and it is during this period of reverse power flow that the voltage is too high. This situation occurs because the power demand in the network is low temporarily while DG output is high at the same time. This situation is very interesting for investigation because the operation of the protection system can be well tested and new protection methods can be evaluated. For a situation of high generation and low load, the study of a decentralized energy management system (DEMS) as a remedy is useful.

D. Integration of MVDC coupler

In the following simulation, an MVDC coupler of 2 MVA rating was integrated to link subnetworks 1 and 2. All DG units were disconnected from the network. The application of the MVDC coupler is useful if a direct AC interconnection is not possible.

The results of this simulation are given in Fig. 9. For power and voltage, the curves for the case without the MVDC coupler are included for the purpose of comparison. The results demonstrate that the voltage situation has improved significantly as a consequence of integrating the MVDC coupler. The last curve of Fig. 9 shows the power transferred through the coupler.

TABLE 2
PARAMETERS OF DG UNITS

Node No.	DG Type	P_{max} [kW]
3	Photovoltaic	20
4	Photovoltaic	20
5	Photovoltaic	30
5	Battery	600
5	Fuel Cell in Household	33
6	Photovoltaic	30
7	Wind Turbine	1500
8	Photovoltaic	30
9	Photovoltaic	30
9	CHP Diesel	310
9	CHP Fuel Cell	212
10	Photovoltaic	40
10	Battery	200
10	Fuel Cell in Household	14
11	Photovoltaic	10

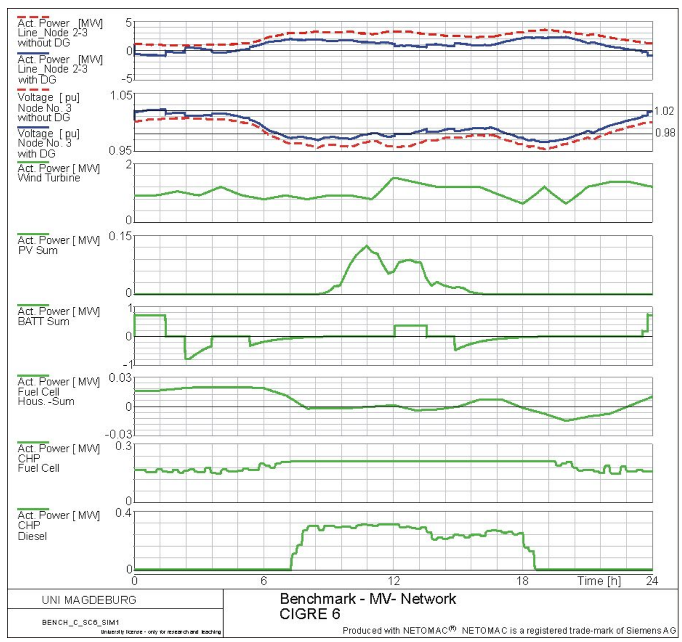

Fig. 8. Time-domain simulation with DG and without MVDC coupler

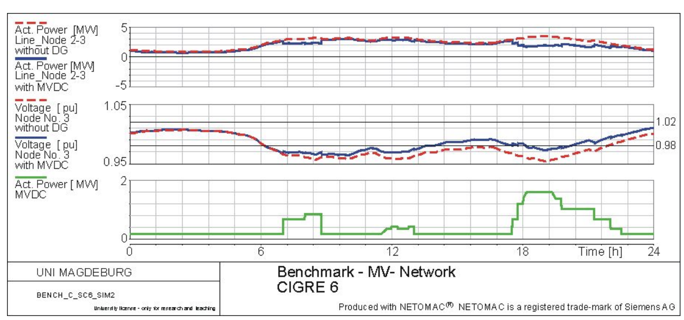

Fig. 9. Time-domain simulation without DG and with MVDC coupler

E. Simultaneous integration of DG and MVDC coupler

In this case DG units are integrated according to Table 2 and the MVDC coupler is present. The results of this simulation are given in Fig. 10. When comparing the results of this case study with the results of previous case studies, it becomes clear that for the assumed load profiles this combination of DG and MVDC coupling presents the best solution regarding the voltage profile.

VI. Conclusions

A medium-voltage rural distribution network was introduced as a benchmark for DG integration studies. The benchmark network retains the characteristics of a real network. At the same time, its complexity does not exceed a level that is required to be representative of real-world situations. The benchmark network can be used for a wide variety of different study cases. Using the network, the impact of DG on power flows and voltage profiles of the medium-voltage rural distribution network were studied. In these example cases, the network provided a suitable test platform. The possibility of including MVDC coupling has delivered additional insight into solutions that integrate DG with other technologies. The proposed network is considered as a CIGRE benchmark by Task Force C6.04.02. Details of the benchmarking will be published by CIGRE in the form of a brochure. This brochure will also contain the description of companion benchmarks. The set of benchmarks will provide a comprehensive benchmarking methodology for the evaluation of DG integration methods and techniques.

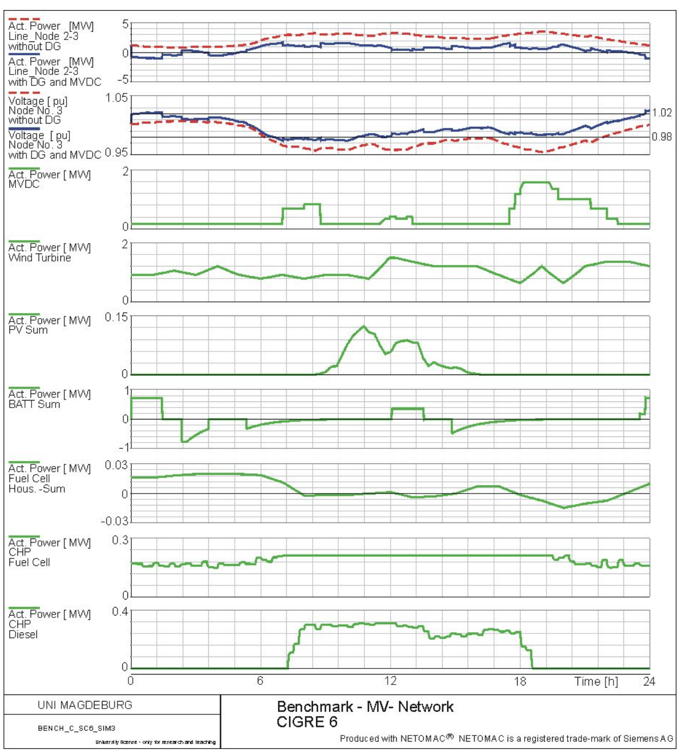

Fig. 10. Time-domain simulation with DG and with MVDC coupler

VII. Appendix

TABLE 3
PARAMETERS OF NETWORK ELEMENTS USED FOR CASE STUDIES

Node From	Node To	R' [Ω/km]	X' [Ω/km]	C' [nF/km]	L [km]
0	1	---	---	---	---
1	2	0,579	0,367	158,88	2,82
2	3	0,164	0,113	6608	4,42
3	4	0,262	0,121	6480	0,61
4	5	0,354	0,129	4560	0,56
5	6	0,336	0,126	5488	1,54
6	7	0,256	0,13	3760	0,24
7	8	0,294	0,123	5600	1,67
8	9	0,339	0,13	4368	0,32
9	10	0,399	0,133	4832	0,77
10	11	0,367	0,133	4560	0,33
11	4	0,423	0,134	4960	0,49
3	8	0,172	0,115	6576	1,3
0	12	---	---	---	---
12	13	0,337	0,358	162,88	4,89
13	14	0,202	0,122	4784	2,99

VIII. References

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IX. Biographies

Dipl.-Ing. Krzysztof Rudion studied electrical engineering at the Wroclaw University of Technology, Poland and the Rostock University of Technology. He graduated in 2003 at the Wroclaw University of Technology with a Dip.-Ing. Degree. He joined the Chair of Electric Power Networks and Renewable Energy Sources at the Otto-von-Guericke-University Magdeburg, Germany as a research engineer. His primary field of interest is wind energy.

Dr.-Ing. Antje Orths graduated in electrical engineering at the Technical University of Berlin, Germany. In 1999 she joined the Otto-von-Guericke-University Magdeburg, where she received her Ph.D with honor in 2003. One year later she joined the Fraunhofer Institute for Factory Operation and Automation IFF Magdeburg, leading the group Critical Infrastructures. In 2005 she joined the System Development and Analysis Department at Energinet.dk, the Danish network operator for electricity and gas. Her interests include electric power networks and systems, modelling of dispersed energy resources, distribution network planning and optimization problems. She is a member of the IEEE, VDE-ETG and CRIS.

Zbigniew Antoni Styczynski (1949) received his MS and PhD at the University of Wroclaw. He finished his professorial dissertation in 1985 at that University for which he received a special award from the Polish Ministry of Higher Education. From 1991 until 1999 he worked at the Technical University of Stuttgart, Germany. In 1999 he became the Head of the Chair of Electric Power Networks and Renewable Energy Sources of the Faculty of Electrical Engineering and Information Technology at the Otto-von-Guericke University, Magdeburg, Germany. Since 2002 he is also the dean of the

Faculty. His special field of interest includes electric power networks and systems, expert systems and optimization problems. He is senior member of IEEE PES, member of CIGRE SC C6, VDE ETG und IBN and fellow of the Conrad Adenauer Foundation.

Prof. Dr.-Ing. Kai Strunz graduated with the Dipl.-Ing. degree from the University of Saarland in Saarbrücken, Germany, in 1996. He received the Dr.-Ing. degree with summa cum laude from the same university in 2001. From 1995 to 1997, Dr. Strunz pursued research at Brunel University in London. From 1997 to 2002, he worked at the Division Recherche et Développement of Electricité de France (EDF) in the Paris area. In April 2002, he joined the University of Washington as an assistant professor. He is the Convener of CIGRE Task Force C6.04.02 on computational tools for the study of distributed energy resources. Kai Strunz received the Dr.-Eduard-Martin Award from the University of Saarland in 2002, the National Science Foundation (NSF) CAREER Award in 2003, and the Outstanding Teaching Award from the Department of Electrical Engineering of the University of Washington in 2004. In 2005, he served as advisor to the University of Washington student team that designed a next-generation hydrogen power park and received the honorable mention award from the National Hydrogen Association.