IEEE POWER ENGINEERING SOCIETY
ENERGY DEVELOPMENT AND POWERGENERATION COMMITTEE

PANEL SESSION: EUROPE:IMPACT OF DISPERSED GENERATION ON POWER SYSTEM STRUCTURE AND SECURE POWER SYSTEM OPERATION[#].

(Tom Hammons and Zbigniew Styczynski)

IEEE 2007 General Meeting, Tampa, USA, 24-28 June 2007
Tuesday,2:00 pm—6:00 pm, Technical CC Room 12

Sponsored by: International Practices for Energy Development and Power Generation[#]

Chairs: Tom Hammons, University of Glasgow, Scotland, UK
Zbigniew Styczynski, University of Magdeburg, Germany

Topic: Integrating New Sources of Energy in Power Systems

PAPERS

Panel Introduction
EUROPE: IMPACT OF DISPERSED GENERATION ON POWER SYSTEM STRUCTURE AND SECURE POWER SYSTEM OPERATION (PAPER 07GM 0431)

Tom Hammons and Zbigniew Styczynski

INTRODUCTION

The power system is a critical infrastucture for which its secure operation has a decisive influence on the development of industrial nations. Changes in structure of primary energy resources will also modify the structure and operation of the power system in order to fulfill the high requirements of the infrastructure.

One aspect is that dependency of Europe on imported primary energy increases from year to year. As a countermeasure, national programs inside the European Community are directed to increase the share of renewable energy sources and the efficiency of power generation by cogeneration of heat and power (CHP). Targets are set by the European Commission for each country for a sustainable electricity supply. Generally, the share of renewable energy sources has to be increased from 14% to 22% and the share of CHP has to be doubled from 9% to 18% by 2010.

The question arises, how can the power system be operated securely with such a large share of mostly non-dispatched power sources? How can the reserve power which is required for compensation of power fluctuations and ensuring a safe network operation be limited?

In this context, a vision sees the power system of the future consisting of a number of self-balancing distribution network areas. In each of these areas a significant share of power demand will be covered by renewable and CHP generation. However, the power balance of these areas should be plan-able and dispatch-able in such a way that import or export of power from or into the higher-level network has to follow a schedule that can be predicted in advance with a high level of accuracy.

[#] Document prepared and edited by T J Hammons

The distribution networks will become active and have to provide contributions to such system services like active power balancing, reactive power control, islanded operation and black-start capability. These services have to be coordinated with the transmission system operators where responsibility for system stability will be allocated in the future as well.

This Panel Session panel fits very well with the scope of the advisory council of the European Commission "Platform of the Electricity Network of the Future".

Some of the key persons of the advisory council will participate with technical presentations.

The Panelists and Titles of their Presentations are:

1. Nouredine Hadjsaid, Director of IDEA, Grenoble, France. *Modern Power System as a Critical Infrastructure* (paper 07GM1008)
2. Johan Driesen, G. Deconinck, W. D’haeseleer, and Ronnie Belmans, KU Leuven, Leuven, Belgium. *Active User Participation in Energy Markets through Activation of Distributed Energy Resources* (paper 07GM 1111)
3. Pier Nabuurs Chief Executive Officer, KEMA, Arnhem, The Netherlands and Peter Vassen KEMA, *Dispersed Generation and System Structure - Active Asset Management for Improving of the Power System Security*. Invited Discusser.
4. Bernd Michael Buchholz, Director, PTD Services, Power Technologies, Siemens AG, Erlangen, Germany and Zbigniew Antoni Styczynski, President of the Centre of Renewable Energy Sachsonia Anhalt, Germany. *Communication Requirements and Solutions for Secure Power System Operation;* (paper 07GM0208)
5. Antje Orths, Peter Børre Eriksen and Vladislav Akhmatov, Energinet.Dk, Analysis and Methods, Fredericia, Denmark. *Planning under Uncertainty—Securing Reliable Electricity Supply in Liberalized Energy Markets* (paper 07GM0778)
6. Bruno Meyer, Director Power System and Economics Department, EDF R&D, Clamart, France. *Distributed Generation: Towards an Effective Contribution to Power Systems Security* (paper 07GM0679)
7. Evangelos Dialynas and Nikos D. Hatziargyriou, National Technical University Athens, Athens, Greece. *Impact of Microgrids on Service Quality;* (paper 07GM1062)
8. Kurt Rohrig and Bernhard Lange, ISET Kassel, Germany. *Improvement of Power System Reliability by Prediction of Wind Power Generation* (paper 07GM0397)
9. Invited Discussers.

Each Panelist will speak for approximately 20 minutes. Each presentation will be discussed immediately following the respective presentation. There will be a further opportunity for discussion of the presentations following the final presentation.

The Panel Session has been organized by Tom Hammons (Chair of International Practices for Energy Development and Power Generation IEEE, University of Glasgow, UK) and Zbigniew A. Styczynski (Director of Centre for Renewable Energy Sachsonia-Anhalt and Professor at the Otto-von-Guericke-University Magdeburg, Germany).

Tom Hammons and Zbigniew Styczynski will moderate the Panel Session.

The first presentation is made by Noredine Hadjsaid, IDEA, **France.** It is entitled: *Modern Power System as a Critical Infrastructure.*

Nouredine Hadjsaid is a Director of IDEA, Grenoble, France and full Professor at the INPG in Grenoble. He was with VirginaTech in 1999-2000 as a Visiting Professor. He is currently General Director of IDEA—France, and the President of CRIS (International Institute for Critical Infrastructure), Sweden. He conducts research on distributed generation, including renewable energy systems, power system planning and operation and security of critical infrastructures.

****

The second presentation is made by Johan Driesen, G. Deconinck, W. D’haeseleer, and Ronnie Belmans, KU Leuven, Leuven, Belgium. It is entitled: *Active User Participation in Energy Markets through Activation of Distributed Energy Resources.*

Johan Driesen is an Associate Professor at the K.U.Leuven and teaches power electronics and drives. In 2000-2001 he was a visiting researcher in the Imperial College of Science, Technology and Medicine, London, UK. In 2002 he was with the University of California, Berkeley, USA. Currently he conducts research on distributed generation, including renewable energy systems, power electronics and its applications, for instance in drives and power quality.

Ronnie Belmans is a full professor with K.U.Leuven, teaching electrical machines and variable speed drives. He is an appointed visiting professor at Imperial College in London.

He was with the Laboratory for Electrical Machines of the RWTH, Aachen, Germany (Von Humboldt Fellow, Oct.’88-Sept.’89). From October 1989-September 1990, he was visiting associate professor at Mc Master University, Hamilton, Ont., Canada. During the academic year 1995-1996 he occupied the Chair at London University that was sponsored by the Anglo-Belgian Society. Dr.Belmans is a Fellow of the IEE (United Kingdom) (now IET) and a Fellow of IEEE. He is also Chair of the Board of Elia, the Belgian TSO.

****

The third presentation is an invited discussion by Pier Nabuurs, Chief Executive Officer and Peter Vaessen, KEMA, Arnhem, **The Netherlands**. It is entitled: *Dispersed Generation and System Structure - Active Asset Management for Improving of the Power System Security.* Peter Vaessen will present it.

Pier Nabuurs held jobs for many years in management of R&D at Philips and Océ. At Océ he became responsible for managing global purchasing in the supply chain. After that he was CEO of Océ-Belgium and Executive Director of the Strategic Business Unit Document Printing. His responsibility included the product development program. In January 2002 he became CEO of KEMA, an international company specialized in high-grade technical energy consultancy and R&D, inspection, testing and certification.

Peter Vaessen joined KEMA and has held several research positions in the field of large power transformers and measurements in high-voltage networks. From 1991 to 1996, he managed several realization projects, among them construction of Dutch 400 kV substations. As a consultant he has experience in the conceptual design of integrated electrical systems and innovative techniques and tools for transforming existing large-scale hierarchical systems into flexible dynamic structures, allowing economic utilization, competition and integration of RES and DG.

****

The next presentation has been prepared by Bernd Michael Buchholz, Director, PTD Services, Power Technologies, Siemens AG, Erlangen, Germany and Zbigniew Antoni Styczynski, President of the Centre for Renewable Energy Sachsonia Anhalt e.V., Magdeburg, Germany. It is entitled: *Communication Requireents and Solution for Secure Power System Operation.*

Bernd Michael Buchholz is director of the business unit “Power Technologies” in the “Service” division of the Power Transmission and Distribution group in Erlangen, Gewrmany. Between 1995 and 2000 he worked as editor for the parts 4 and 7 of IEC 61850. He is the German member of the SC C6 of CIGRE “Dispersed generation in distribution systems”.

Zbigniew Antoni Styczynski became in 1999 the Head and 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 2006 he is also the president of the Centre of the Renewable Energy Sachsonia Anhalt. His special field of interest includes electric power networks and systems, expert systems and optimization problems. He is a senior member of IEEE, member of CIGRE SC C6, VDE ETG und IBN and fellow of the Conrad Adenauer Foundation.

****

The next presentation is entitled *Planning under Uncertainty—Securing Reliable Electricity Supply in Liberalized Energy Markets*. It has been prepared by Peter B. Eriksen, Antje G. Orths and Vladislav Akhmatov , all from Energinet.dk, Fredericia, Denmark**.**

Peter Børre Eriksen is head of *Analysis and Methods* of Energinet.dk, the Danish Transmission System Operator for Electricity and Gas. After a career in system planning for the Danish utility ELSAM he joined Eltra, the former Western Danish TSO in 1998, where he was leading the Development Department from 2000 until 2005. In 2005 the two regional TSOs on power (Eltra and Elkraft) and the TSO on natural gas (Gastra) merged forming the new national TSO Energinet.dk, which bears overall responsibility for power and natural gas systems in Denmark. Peter Børre Eriksen is author of numerous technical papers on system modeling.

Antje G. Orths joined the Planning Department (*Analysis and Methods*) of Energinet.dk, the Danish TSO for Electricity and Gas in 2005. Before, she was a researcher at the OvG-University Magdeburg, Germany and also head of the group Critical Infrastructures at the Fraunhofer Institute for Factory Operation and Automation IFF in Magdeburg. Her special fields of interests include electric power networks and systems, modeling of dispersed energy resources, distribution network planning and optimization problems. She is member of the IEEE-PES, VDE-ETG and CRIS.

Vladislav Akhmatov since 2003 is with the Planning Department (*Analysis and Methods*) of Energinet.dk, the Danish TSO for Electricity and Gas. Before, he worked for the Danish electric power company NESA A/S, investigating power system stability of the eastern Danish power system with incorporation of large offshore wind farms. He has developed detailed wind turbine models for different power system simulation tools and carried out a lot of respective analyses. His special interests are power system analysis, wind power and simulation tools.

****

The next presentation has been prepared by Bruno Meyer, Director, “Power Systems Technology & Economics", EDF R&D, France. It is entitled*: Distributed Generation: Towards an Effective Contribution to Power Systems Security.* . Bruno Meyer will present it.

Bruno Meyer holds degrees in physics from Unicamp (B.Sc.), Sao Paulo (M.Sc.) and Edinburgh (Ph.D.). He is director of Power Systems Technology and Economics at EDF R&D. He joined EDF in 1985 where he has held several positions in the R&D Division as well as in the Marketing and Commerce Divisions. He is a Senior Member of IEEE, and is Region 8 Representative for IEEE PES. He is also an Eminent Member of CIGRÉ.

.***********************

The seventh presentation is entitled*: Impact of Microgrids on Service Quality* and has been prepared by Evangelos Dialynas and Nikos D. Hatziargyriou, National Technical University of Athens, Athens, **Greece**. It will be presented by Nikos D. Hatziargyriou.

Evangelos Dialynas is Professor of Electrical Power Systems at the School of Electrical and Computer Engineering of NTUA. His research interests include power system analysis, generation simulation and renewable energy sources.

Nikos D. Hatziargyriou is Professor at the Power Division of the School of Electrical and Computer Engineering of NTUA. His research interests include dispersed and renewable generation, artificial intelligence techniques in power systems and power system dynamic analysis and control. He is a Senior Member of IEEE, a member of CIGRE SC C6, and a member of the Technical Chamber of Greece.

****

The final presentation will be given by Kurt Rohrig, ISET Kassel, Germany. It is entitled: . *Improvement of Power System Reliability by Prediction of Wind Power Generation*.

Kurt Rohrig is Head of ISET's Program Area Information and Energy Economy. He has worked with ISET since 1991 and has been the scientist-in-charge for projects handling the online monitoring and prediction of wind power for large supply areas – operated in co-operation with large power transmission utilities. The computer models and approaches developed in his work are in operation with all the German transmission system operators that have high wind power penetration.

Bernhard Lange is head of Information and Prediction Systems of the Program Area Information and Energy Economy at ISET. After graduating he worked in Denmark with Risø National Laboratory and Wind World A/S. His main research interests for the last 10 years are wind power meteorology and wind farm modeling.

PANELISTS

1. Mr Nouredine Hadjsaid, Prof.
   IDEA
   LEG/ENSIEG/INPGrenoble
   Domaine Universitaire
   38402 Saint Martin d'Héres – Grenoble
   FRANCE
   E-mail: nouredine.hadjsaid@leg.ensig.inpg.fr
   Tel: +33 476 827 152
   Fax: +33 476 826 300

2. Mr Ronnie Belmans, Prof.
   Mr Johan Driesen, Prof.
   KU Leuven
   Kasteelpark Arenberg 10
   B-3001 Leuven
   Belgium
   E-mail: ronnie.belmans@esat.kuleuven.be
   Tel: + 32 16 32 10 20
   Fax: + 32 16 32 19 85

3. Mr Pier Nabuurs
   CEO
   KEMA
   PO Box 9035
   6800ET Arnhem
   The Netherlands
   Tel: +31 26 356 3511
   Fax: +31 26 443 4025
   E-mail: Pier.Nabuurs@kema.com
   www.kema.com
   Tel: +31 26 356 3511
   Fax: +31 26 443 4025

Mr Peter Veassen
CEO
KEMA
PO Box 9035
6800ET Arnhem
The Netherlands
Tel: +31 26 356 3511
Fax: +31 26 443 4025
E-mail: Pier.Nabuurs@kema.com
www.kema.com

4. Mr Bernd Michael Buchholz, Dr.
Chief Consultant
PTD Services,
Power Technologies
Siemens AG PTD SE NC,
Paul-Gossen- Str. 100,
91052 Erlangen,
Germany
E-mail: bernd.buchholz@siemens.com
Tel: +49 91317 34443,
Fax: +49 91317 34445

Mr Zbigniew Antoni Styczynski, Prof.
President Center for Renewable Energy Sachsonia-Anhalt, and
Chair Electric Power System and Renewable Energy
Faculty of Electrical Engineering and Information Technology
Otto-von-Guericke-University
Magdeburg
Universitaetsplatz 2
D-39106 Magdeburg
Germany
E-mail: sty@e-technik.uni-magdeburg.de
Tel.: +49 391 6718866
Fax: +49 391 6712408

5. Mrs Antje Orths, Dr.
Mr Vladislav Akhmatov, Dr
Analysis and Methods
Energinet.Dk
Fjordvejen 1-11
DK-7000 Fredericia
E-mail: ano@energinet.dk
Tel: +45 7622 4426/4000
Fax: +45 7624 5180

Mr Peter Børre Eriksen
Head of Analysis and Methods
Energinet.dk
Fjordvejen 1-11
DK-7000 Fredericia

Denmark
E-mail: pbe@energinet.dk
Energinet.dk
Tel.: +45 7622 4000
Fax: +45 7624 5180
www.energinet.dk

6. Mr Bruno Meyer , Dr
Director Power Systems Economics Department
EDF R&D
1, Ave. du General De Gaulle
92141 Clamart
France
E-mail: bruno.meyer@edf.fr
Tel: +33 1 47 65 4006
Fax: +33 1 47 45 4006

7. Mr Nickolas Hatziargyriou, Prof.
E. Dialynas
National Technical University Athens
9 Heroon Polytechniou Str
157 73 Zografou
Athens
Greece
E-mail: Nh@power.ece.ntua.gr
dialynas@power.ece.ntua.gr
www.ntua.gr
Tel: +30 210 772 3661
Fax: +30 210 772 3968

Mr J. Kabouris
Hellenic Transmission Operator
Amfitheas 11
N. Smyrni
Greece
E-mail: kabouris@desmie.gr
Tel: +30 210 772 3661
Fax: +30 210 772 3968

8. Mr Kurt Rohrig, Dr
Head of Division Information and Energy Economy
Institut für Solare Energieversorgungstechnik
Königstor 59
D-34119 Kassel
Germany
E-mail: k.rohrig@iset.uni-kassel.de
Tel: +495617294330
Fax: +495617294260

Mr Bernhard Lange, Dr

Head of Department Information and Prediction Systems
Institut für Solare Energieversorgungstechnik
Königstor 59
D-34119 Kassel
Germany
E-mail: blange@iset.uni-kassel.de
Tel: +49 561 729 4358
Fax: +49 561 729 4260

9. Invited Discussers

PANEL SESSION CHAIRS

Tom Hammons
Chair International Practices for Energy Development and Power Generation
University of Glasgow
11C Winton Drive
Glasgow G12 0PZ
UK
E-mail: T.Hammons@ieee.org
Tel: +44 141 339 7770

Zbigniew Antoni Styczynski
President Center for Renewable Energy Sachsonia-Anhalt and
Chair Electric Power System and Renewable Energy
Faculty of Electrical Engineering and Information Technology
Otto-von-Guericke-University
Magdeburg
Universitaetsplatz 2
D-39106 Magdeburg
Germany
E-mail: sty@e-technik.uni-magdeburg.de
Tel.: +49 391 6718866
Fax.: +49 391 6712408

BIOGRAPHIES

Thomas James Hammons (F'96) received the degree of ACGI from City and Guilds College, London, U.K. and the B.Sc. degree in Engineering (1st Class Honors), and the DIC, and Ph.D. degrees from Imperial College, London University.

He is a member of the teaching faculty of the Faculty of Engineering, University of Glasgow, Scotland, U.K. Prior to this he was employed as an Engineer in the Systems Engineering Department of Associated Electrical Industries, Manchester, UK. He was Professor of Electrical and Computer Engineering at McMaster University,Hamilton, Ontario, Canada in 1978-1979. He was a Visiting Professor at the Silesian Polytechnic University, Poland in 1978, a Visiting Professor at the Czechoslovakian Academy of Sciences, Prague in 1982, 1985 and 1988, and a Visiting Professor at the Polytechnic University of Grenoble, France in 1984. He is the author/co-author of over 350 scientific articles and papers on electrical power engineering. He has lectured extensively in North America, Africa, Asia, and both in Eastern and Western Europe.

Dr Hammons is Chair of International Practices for Energy Development and Power Generation of IEEE, and Past Chair of United Kingdom and Republic of Ireland (UKRI) Section IEEE. He received the IEEE Power Engineering Society 2003 Outstanding Large Chapter Award as Chair of the United Kingdom and Republic of Ireland Section Power Engineering Chapter (1994~2003) in 2004; and the IEEE Power Engineering Society Energy Development and Power Generation Award in Recognition of Distinguished Service to the Committee in 1996. He also received two higher honorary Doctorates in Engineering. He is a Founder Member of the International Universities Power Engineering Conference (UPEC) (Convener 1967). He is currently Permanent Secretary of UPEC. He is a registered European Engineer in the Federation of National Engineering Associations in Europe.

Zbigniew Antoni Styczynski (SM '01) received his MSc and PhD at the Technical University of Wroclaw and served there from 1973 until 1991, last as an Associate Professor and a deputy in the Institute of Power Systems. From 1991 until 1999 he worked at the Technical University of Stuttgart, Germany. In 1999 he became the Professor and 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. From 2002 until 2006 he was the dean of the EE Faculty and since 2006 he is the president of the Centre of the Renewable Energy Sachsonia Anhalt, Germany. His special field of interest includes modeling and simulation of the electric power networks systems, renewable, and optimization problems. He is author of more then 150 scientific papers, senior member of IEEE PES, member of CIGRE SC C6, VDE ETG and IBN, and fellow of the Conrad Adenauer Foundation.

1. MODERN POWER SYSTEM AS A CRITICAL INFRASTRUCTURE (PAPER 07GM1008)

N. Hadjsaid, *Senior Member, IEEE,* T.T.Ha Pham, Y.Bésanger *Member IEEE,*

***Abstract* --** The expected insertion of DG (Distributed Generation) in the distribution networks entailed by environmental, regulation and economical aspects will modify the way the entire system is planned and operated. Due to its dispersed nature, DG will require more flexible operated system. This situation will emerge through various applications and developments of the Distribution Automation.

In addition, DG has already showed some impacts on system security. Thus a special attention should be paid to the DG influence during emergency states such as the propagation of cascading failures or other major events. Indeed, in one hand, a high amount of DG can improve the system response to these disturbances but, on other hand, a massive DG insertion could endanger the system operation.

The presentation will cover the criticality of power system, particularly distribution networks, with regards to DG insertion. New ICT functions needed for improvement of DG insertion and performance will be discussed.

***Index Terms*—** Distributed Generation, System Robustness, Critical infrastructures, Fault handling, Intentional Islanding, ICT components.

I. INTRODUCTION

During the last years, some important blackouts and cascading failures (USA, Italy, Sweden & Denmark, Algeria…) and more recently the power shortage occurred in Europe with an initiative events in Germany have appeared affecting the normal life of countries and causing important economic costs. The causes of these blackouts are different depending on the nature of the failure but, in general, the consequence of heavier system loading and almost revolutionary changes in industry structure.

The decentralization of the energy production in the system could help operators limiting the impact of these blackouts. The flows of energy in the transmission sub-system are reduced by the dispersed generation (DG) insertion and saving parts of the system in autonomous sub-systems in case of very critical state of the whole system is favored. Thus, a high amount of DG could improve the EPS robustness [1]. However, the large scale introduction of dispersed generation can result in more vulnerable situations and decrease the system robustness because of the DG dynamic performance and integrated system controllability.

Therefore, an appropriate amount of DG insertion should be defined through an evaluation of the system operating point not only as a reinforcement factor of generation system but also a supplementary vulnerability element for the whole Electrical Power System (EPS).

II. PLANS FOR DG INSTALLATION

The international agreements to reduce the Greenhouse gazes emissions and new rules such as European directives to increase the renewable energy sources have promoted the creation of national plans to install new DG resources, e.g. The EU (European Union) goal is a 22% production from RES in 2010 [2]. The estimation of new DG based on RES (Renewable Energy Source) is shown in Fig. 1. by ETSO (European Transmission System Operators) data [4] for the percentage of the total capacity which is based on renewable energies. In this figure, it is also shown the tendency to new DG installations. Hydro and wind power is the renewable energy source that contributes the biggest share to the renewable generation in

Europe.

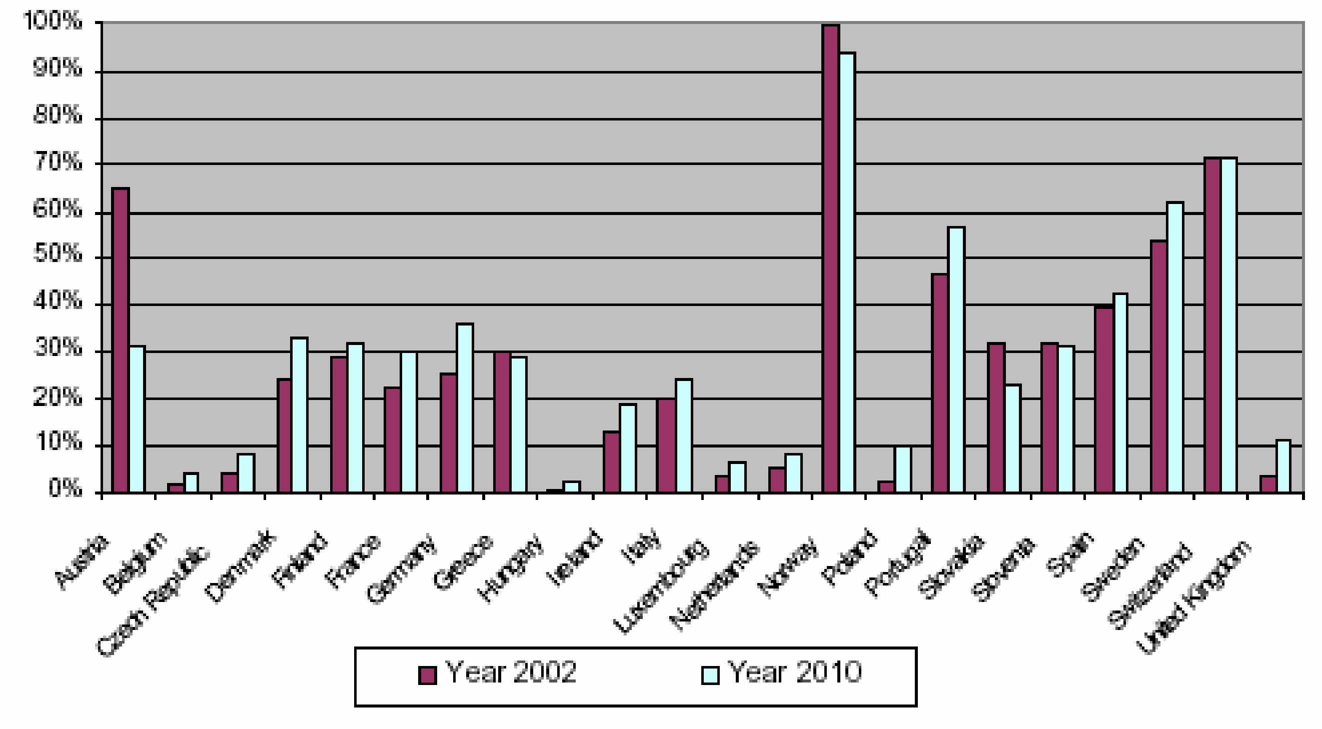


Fig. 1. ETSO data about the DG-RES capacity

The DG penetration rate in a country should be established on different points:

- The RES possibilities of the country: solar, hydro and wind potential. This first parameter befits the natural (cheap carbon, weather conditions, hydro reserves…) and social (acceptance degree of nuclear power, availability to pay a cleaner energy at a higher price…) characteristics of the country.

- The second parameter is the strengthening network costs. This is remarkable in MV and HV, notably by congestions on the sub-transmission and distribution systems. The construction of new lines to avoid local bottlenecks is expensive and it could block and delay the DG connection.

- The third parameter to define an appropriate amount is taken into account technical criteria as :

    - *Static security*: technical limits of the system (max line currents, voltage, powers in lines, transformers and generators).

    - *Dynamic security*: that is a variety of studies such as small-signal stability, transient stability, voltage stability, (n-1) criterion and reserves margins for the operation of a given network.

The general tendency and goal in EU are therefore as followed. Countries such as Denmark, Germany or Spain are promoting the wind energy installation. Germany is planning to increase its wind capacity from around 18 GW wind capacity installed to an expectation near to 30 GW in 2010. The Danish Government is planning to install 4GW off-shore and 1.5 GW on-shore before the year 2030 [3], [4].

A. IMPACTS OF LARGE SCALE OF DG IN EPS

The voltage level for the DG connection (sub-transmission or distribution) depends essentially on the amount of injected power and the local network characteristics. The interconnexion of DG units in the lower voltage level includes advantages in economic and energy point of view; but it would be penalized in operation plan. By the small and medium size nature, almost DG units are connected to distribution system which is the first one influenced by DG penetration's phenomenon. When DG insertion becomes more excessive, its impacts will be more widespread, affect even to transmission system.

The direct impacts that DG could cause on the distribution system are the next ones [6], [7] :

- *Impacts on the energy direction*: Traditionally the EPS was designed for an up-bottom energy flow but the DG implies a bottom-up energy flow. Thus, it is possible that the energy is injected into the sub-transmission and transmission systems. Although, transit capacity might not limited in the near future because distribution grids are normally oversize to face to the increase of consumption; it might be a true problem like local congestion with an appropriate amount of DG introduction.

- *Impacts on the protections*: the short-circuit current could be increased by the DG insertion (mainly by synchronous generators). It is thus necessary to review setting points, selectivity, and bidirectional characteristic of equipments …etc. to avoid bad operations.

- *Impacts on voltage profile*: DG increases the voltage in the connection bus and in the buses around the DG connection. Furthermore, fast changes in the voltage level are caused by the DG's flicker effect.

- *Impacts on stability*: The insertion of synchronous generators could cause power oscillations in case of fault; power exchange between different distribution networks could be created by these oscillations.

- *Impacts on power quality* (harmonics, sags, surges and deeps): some DG sources need power electronic interfaces to be connected; these inject harmonics in the grid and can provoke unacceptable voltage distortions.

- *Economic impact on the energy markets*: The associations and agreements of DG producers permit to propose bids in energy markets (day before, 15 min before or ancillary services markets).

The issues of impact of high penetration rate of DG on transmission system appear recently when some RES's technologies reach to a certain maturity degree (case of wind power). However, it becomes a veritable need especially after some major power incidents around the world where the inadequate DG operation strategy had been contributed to decisive causes of generalized blackout (example of blackout on September 2003 in Italy).

Thus, the most impacts on transmission networks can be summarized as follows:

- *Incertitude in EPS planning phase*: As shown in plans for Dg installation in some EU countries, among available RES, hydro and wind power are well-exploited. Nevertheless, the exploitation of theses sources based principally on weather forecast carrying the unforeseen aspects. An uncertain prevision often leads to over-sizing of installation causing many difficulties in long time scheduling and generation system planning.

- *Incertitude in operation reserve margin estimation*: The intermittence of RES implies a very flexible control in the system in terms of enabling the large active and reactive power reserve margins to avoid alert or emergency states. The dispatching of the system is now responsible both to follow the consumption variations and to accommodate the system to lack or surplus of productions.

- *Sensibility of system due to reactive management*: Many DG systems use induction generators rather than synchronous generators. These units, like induction motors, consume reactive power and contribute to voltage drops during periods of high demand. Inductive DG systems brought on-line to help meet peak demand could destabilize the grid voltage to the point that a transmission line trips and contributes to the initiation of a blackout.

- *Sensibility of system due to unplanned DG off-loading*: Interconnection standards often include a requirement that DG automatically disconnect from the grid when system frequency or voltage deviate from a prescribed range. In general, this authorized deviation limits are very restricted:

    - whenever voltage deviates over ±(10 - 15%) of nominal value
    - or, system frequency raise above or falls below over ±(0.5 - 0.6 Hz) from nominal value.

These requirements are necessary to protect against unintentional islanding for public safety reasons. However, if the grid is experiencing stress, it may also be experiencing voltage and frequency deviations. If these deviations force a large quantity of DG capacity off-line, the sudden increase in load (assuming the DG users revert to grid power) might trigger blackout. The fact that DG is often installed as a peak-shaving strategy makes this scenario even more likely.

B. NEW ADOPTED DG OPERATION STRATEGIES IN CRITICAL SITUATIONS

As we can see, DG units, as long as they were marginal sources, had no great influences, neither on operation, nor on service quality of networks. With expected rate of DG insertion in the coming years, critical situation management in EPS will be a new challenge for system operators.

One of new strategies for more benefit of using DG in critical situations is proposed based on concept called "*intentional islanding*" multilevel. The Fig. 2 shows a case of intentional islanding in distribution network. The mains idea is that, in case of failure, some DG could facilitate the apparition of a lot of autonomous areas or cells providing the local service continuity and energizing the grid as large as possible by switching operation. Numerous parts of system will be saved by autonomous sub-systems at distribution level as well as transmission level which will be mutually synchronized.

The intentional islanding could be ordered in two ways: during disturbances if possible to limit its propagation; or after partial or total blackout using the black-start capability of DG units to accelerate the restoration of system

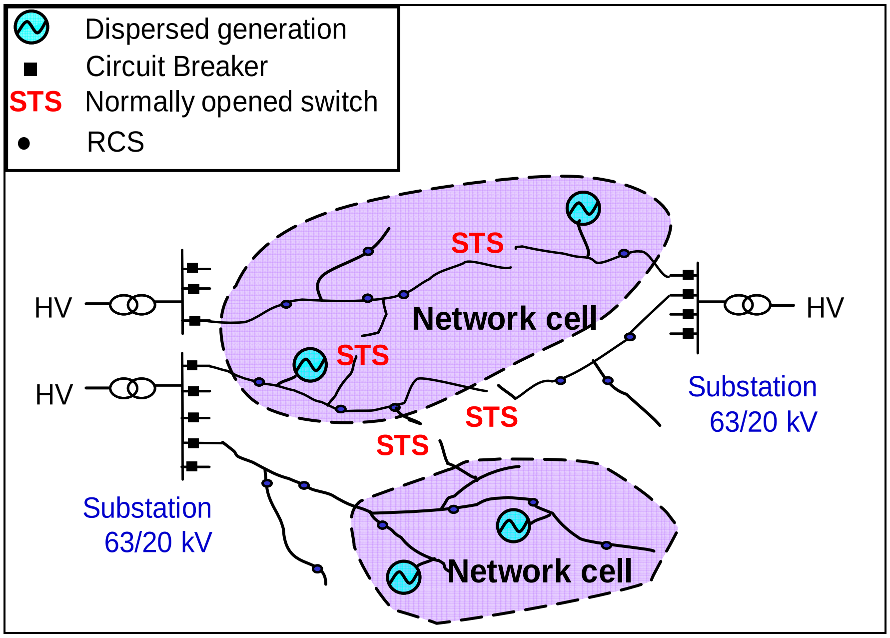


Fig. 2. Intentional islanding operation mode in distribution network

Naturally, this "*intentional islanding*" concept refers not only to an EPS topology but also to a distributed part of intelligence or in other words, a local decisional capacity associated to a network cell. This intelligence consists several local coordination purposes including DG unit controls, local demand controls, optimal switching sequence determination based on computing processors connected by communications means.

Since this emergency operation mode has not existed yet on distribution level, the procedure for network cell forming and system synchronizing are the main results of an optimization study in [8].

III. NECESSARY NETWORK INFRASTRUCTURE UPGRADING

The application of using DG to help the system in critical situation induces more complexities in system exploitation plan, and requires certainly more investments in existing electrical network infrastructures (measurements, remote controlled switches, Fault Path Indicator devices … etc.) and operating tools (SCADA, WAMS …). But it also allows more flexibility and automation for the distribution systems of the future, and more benefits for the service quality by using the full potential of dispersed generation (interest for the network operator, the consumer and the DG producers).

The new requirements of electric power operation by means of an increase of system observability and controllability imply the development in parallel of communication and information network infrastructures. The use of the communication will be spread not only to the control, protection and acquisition tasks but also to the maintenance or the metering. The communications must be then operated with high reliability and security as a means to guarantee a high quality power supplies. The transmission of data and information must be carried out with a security protocols and procedure in order to prevent the intrusion of external agents which could put the system in danger.

Distribution Automation (DA) analysed and experimented for a while should have a larger insertion in the MV EPS. Many different definitions and views of the DA are given world wide, as shown in [5]. The new concept called ADA (*Advanced Distribution Automation*) combines appropriate IT technologies in order to achieve fast and accurate data transmission and processing, for real time operation applications [6].

These functions are essential to the process of Distribution Automation. Furthermore, they can contribute to enhance DG participation to system performance and security. Indeed, DG can have in some cases a critical influence in the sequence of events before a blackout. As a result, local and distributed intelligence is penetrating the network while optimizing system response and investments. Those functions are combined with new network architectures and services.

IV. CONCLUSION

The influence of the new DG leads system operators to carry out new challenges to take into account. Besides economic and energy interests, the large scale DG insertion has also the impacts on planning, scheduling and operating.

Distribution networks are therefore upgrading their role and actions within the whole EPS structure and operation. Indeed, Political incentives, environmental concerns, electric market liberalisation, continuous progress in ICT (*Information and Communication Technology*) and the last wide blackouts outlining the need of supply reliability are some example pulling the development and the implementation of new distribution functionalities for monitoring and remote control as well as advanced protection systems.

The main challenges are related to upgrading network infrastructures (including electric, communication and information) and new operating rules.

The work to be presented during the panel will concern those issues and make the link with the overall criticality of the system.

V. REFERENCES

[1] M. Fontela et al., "On the use of Distributed Generation to increase EPS Robustness", IEEE GM, June 12-16 2005 San Francisco,, USA.

[2] EU Directive 2001/77/EC on the promotion of the electricity produced from renewable energy source in the internal electricity market. [Online]. Available: http://europa.eu.int/comm/energy/res/legislation/electricity_en.htm

[3] ETSO report, "Report on Renewable Energy Sources (RES) ", Brussels, December 2003. [Online]. Available: http://www.etso-net.org/activities/Renewables/e_default.asp

[4] Rapport final de la Commission Ampere, October 2000. [Online]. Available:http://mineco.fgov.be/energy/ampere_commission/ampere_commission_fr.htm

[5] EPRI (Electric Power Research Institute), IntelliGrid Project. Available:http://www.intelligrid-architecture.com/IntelliGrid_Architecture/Use_Cases/DO_Distribution_Use_Cases.htm.

[6] J.F.Canard. “Impact de la génération d’Energie Dispersée dans les réseaux de distribution”. INPG PhD Dissertation, December 2000.

[7] R.Caire. “Gestion et Strategies de conduite de la Production Decentralisee”.INPG PhD Dissertation, April 2004.

[8] T.T.Ha Pham. “Impacts of dispersed generation on the critical infrastructure management in transmission power system”. INPG PhD Dissertation, October 2006.

[9] B. Enacheanu, A. Martin, Ch. Andrieu, B. Raison, N. Hadjsaid,, D. Penkov “Future Distribution Network Architechtures: Approach with a CRISP Experimentation”, FPS conference, Nov. 15-18, 2005, Amsterdam, NL

VI. BIOGRAPHIES

Nouredine Hadjsaid received his Ph.D degree from INPGrenoble in 1992. From 1988 to 1993, he served as a research and teaching assistant at the Associate Professor at the National Superior Electrical Engineering School of Grenoble (ENSIEG) and the Power Engineering Laboratory of Grenoble (LEG). He is presently professor at INPG-ENSIEG-LEG and Manager at GIE-IDEA. His research interests are power system operation and security in power system.

Thi Thu Ha Pham received her Master and PhD degree from INPGrenoble in 2003 and 2006. Her research areas include the reliability of electrical power network, the impacts and control of dispersed generation insertion in power system. She is now working as Postdoctoral researcher at Power Engineering Laboratory of Grenoble (LEG).

Yvon Bésanger received his Ph.D degree in Electrical Engineering from the INPGrenoble, 1996. He is currently Associate Professor at the National Superior Electrical Engineering School of Grenoble (ENSIEG) and the Power Engineering Laboratory of Grenoble (LEG). His research interests are distribution networks operation and reliability, FACTS devices and power system dynamic security.

Received January 24 2007

2. ACTIVE USER PARTICIPATION IN ENERGY MARKETS THROUGH ACTIVATION OF DISTRIBUTED ENERGY RESOURCES (PAPER 07GM 1111)

Johan Driesen, G. Deconinck, W. D’haeseleer, and Ronnie Belmans, KU Leuven, Leuven, Belgium[#]

***Abstract* —** Customers in liberalized energy markets do not have tools in hand to contribute to the balancing of undispatchable distributed generation and the uncontrolled loads. This paper discusses how an activation of the loads could make users more involved in energy markets and indirectly support the sustainable deployment of distributed generation often based on locally available renewable energy sources. As such, a contribution is made to the security of supply through a larger resource diversification and the smaller customers may be engaged in delivering certain types of ancillary services such as reserve provision.

***Index Terms*--** Distributed generation, distributed energy resources, energy markets, liberalization, active loads, demand-side participation.

I. INTRODUCTION

The liberalization of the energy markets is starting to take off in Europe: EU legislation states that there should be competition in generation and retail markets upon January 1, 2007. At the same time, sustainable electricity generation is heavily supported bringing along many GWs of installed generation units mainly based on wind power. In a similar way many gas-driven CHP units are being installed.

Locally built, distributed generation (DG) [1-4] may at first sight be a useful technology to function in an open market as it gives users the opportunity to fill in part of the local demand often using locally available sustainable resources (‘power to the people’) and shop around for the remaining bits, perhaps even selling excess generation. This idealistic picture is not what is seen in practice: DG is experienced as a nuisance by the grid operators requiring a relatively large effort in grid adaptation and ancillary services, for instance in balancing [5].

An underlying problem is that the users hosting local generation do not have the full technical capability to participate in the energy market and grid support yet. At this moment, it is practically impossible to perform a local form of balancing between local generation, an occasional form of energy storage and the dynamically changing loads. All three are forms of DER: ‘distributed energy resources’, in which the latter, the loads, currently are almost completely passive and therefore, cannot benefit from energy market opportunities translated into price signals.

This paper discusses the difficulties and opportunities for activated loads to function in a system with significant amounts local generation.

[#] This work was supported by Belgian “Fonds voor Wetenschappelijk Onderzoek Vlaanderen” and the Energy Institute of the K.U.Leuven.

J.Driesen, G.Deconinck and R.Belmans are Professors of the Katholieke Universiteit Leuven, Department of Electrical Engineering, research group ELECTA, Kasteelpark Arenberg 10, BE-3001 Leuven, Belgium (E-mail: johan.driesen@esat.kuleuven.be, geert.deconinck@esat.kuleuven.be, ronnie.belmans@esat.kuleuven.be; http://www.esat.kuleuven.be/electa). W.D’haeseleer is Professor in the Mechanical Engineering Department, research group TME, Celestijnenlaan 300A, BE-3001 Leuven, Belgium (E-mail: william.dhaeseleer@mech.kuleuven.be, http://www.mech.kuleuven.be/tme).

II. THE ENERGY MARKET AND DER

A. THE USER'S STAKE IN THE ENERGY MARKET

A good working market requires active suppliers and an active demand side. The latter lacks in energy markets. Communication between supply and demand is organized unidirectionally, which makes it impossible for the customer to really take part in the market. The customer presently receives no real-time price information or indications on the origin of the electricity, other than difficult to understand, very general tariff systems. These do not really offer any insight in the relation demand-price and therefore, do not provide any incentives to change his/her demand according to market fundamentals.

In fact, the benefits of energy liberalization will only come true if the demand side gets activated as well. At the same time security of supply has to be ensured at all times and environmental concerns are rising. The demand side, complemented with local generation, can also affect both aspects. Small energy users have potential to increase energy efficiency and to contribute in clean electric energy generation. An active demand side opens opportunities in providing capacity to the market and local generation, if correctly operated, can increase reliability.

However, the way in which energy at small user level (individuals and small business and services) is treated today does not meet current challenges and policy incentives. Energy efficiency is not fully rewarded. Today's energy system offers customers hardly any flexibility. The system is, in practice, not easily accessible for local generation technologies. At a local level, consumers have no possibilities to arbitrate between different energy sources available. Electricity, natural gas and local, often renewable generation are treated separately. Activating households and other small energy users will enhance sustainability, increase efficiency and result in economic value.

B. DG IN THE MARKET

Distributed generation is a technology that received widespread attention in the past years. Some technologies have proven to be successful, but can only survive without lots of direct and indirect support in a liberalized market. This is discussed through the three perhaps most popular DG types: wind power, photovoltaic conversion and combined heat and power (CHP) [4-6]. Note that storage is not discussed separately, but rather seen as a complementary technology that may smooth out irregularities in generation and consumption.

Wind power in the market

In the past ten years many GWs of wind power have been built in Europe (mainly Denmark, Germany, Spain and the Netherlands), the US and other parts of the world follow. Usually, wind power is given a financial benefit through e.g. installation subsidies or tax advantages, 'green energy' certificates functioning in a retail portfolio obligation, grid access priorities or lowered balancing costs. This in fact cannot help that wind power has a fundamental handicap of being hard to predict on longer times scales as encountered in markets, for instance a market with a 24 hour gate closure periodicity. Wind power would most likely become much more interesting in markets with shorter gate closure times such one hour, converging to real-time markets. Alternatively, wind power would benefit significantly from the availability of easily accessible reserve power or storage, regardless of the form in which it is implemented.

Photovoltaics

Pholtovoltaic (PV) generation suffers from similar problems as wind power, be it rather on distribution than on transmission grid scales. It is to be integrated with existing (radial) distribution grids, next to loads having cycles that are entirely uncorrelated with the solar cycle. This causes local balancing inequalities eventually resulting in large voltage changes and protection (selectivity) problems when bidirectional flows occur.

CHP

CHP fundamentally is a heat demand driven generation of electricity, as a by-product. There is the option to include thermal buffering, but this is in general not designed with a smooth electricity generation cycle in mind, yet. CHP in fact links two markets: the primary resource markets which normally is natural gas and the electricity market, but these are usually not approached in parallel.

C. THE RELIABILITY PARADOX

Questions are raised about the difficulties linked to further deployment of certain types of DG as discussed in many papers. Grid reinforcements are required and some operational practices need to be fundamentally reconsidered. On the economic side, the market is distorted or overly complicated by the presence of certain types of DG [5].

Moreover, one can state that a “Reliability Paradox” has emerged: the addition of generation based on energy hard to ignore opportunities, has made the electricity system, in urgent need of extra generation after an investment slowdown induced by the start of the liberalization process, even more insecure.

D. DEMAND CONTROL AS A SOLUTION?

Seldomly suggestions other than slowing down the deployment of DG are suggested. Until now, mainly DG and its problems were discussed. However, a solution may be found in looking at all types of DER, more in particular, the resources represented by the loads (note that the IEA definition of DER includes DG, storage and active loads [1]).

A technology allowing to shed or modulate some load locally on a small-scale following generalized price signals, indicated as ‘active’ loads, contributes to the solution of the balancing problem. As an example, one can imagine a fridge being able to shift its off-take of electricity to cool in time following price signals as control variable. Considering that on average every household owns at least one fridge and the number of households, which is about equal to the number of house connections (equal to about 50-75% of the population of a country), this quickly becomes an important ‘spinning reserve’ for the local as well as for the global electricity system. This ‘spinning’ reserve can be addressed when there is a local overload on the distribution feeder as much as to contribute to a smoother load shedding in case of contingencies.

As such demand control impacts the security, adequacy and stability of supply in multiple senses:

- it allows to better utilize local energy opportunities replacing imported resources and therefore enhances the resource diversification (security of supply);
- it offers additional ancillary services for the system operators in the form of, mainly, (negative) reserve power that can be used in the primary/secondary system control (adequacy and stability).

Therefore, demand control may in the future become an important enabler for the further deployment of distributed generation systems. However, two steps have to be taken in the development of the local energy control. First of all the concept of the required energy controllers needs to be detailed, including their hardware, control and communication. It also turns out that a multi-energy or multi-resource approach is necessary, explained in the next section for the perspective of the users.

III. INCREASED ENERGY MARKET PARTICIPATION

A. TOWARDS EFFICIENT AND FLEXIBLE SMALL ENERGY USERS

From a theoretical perspective, an optimal use of market forces and the price mechanism can strongly improve the efficiency of the whole energy system [7]. These efficiencies are not limited to increased consumer and supplier surpluses but can also include technological dynamics [8].

Adopting a user-centric approach (Fig.1) makes it possible to combine all elements determining the energy use of households and small energy users. Focusing on the user enables to evaluate how users are affected by different technologies. Even more important, this view gives the opportunity to see how technologies can interact and how they can create value for the user. For instance, from a user point of view the integration of electricity, gas, local generation, demand side control (time shift for instance), mobility and local storage opens opportunities to arbitrage between these energy sources and to interact with energy markets. This does not only result in local benefits; society as a whole can gain from it.

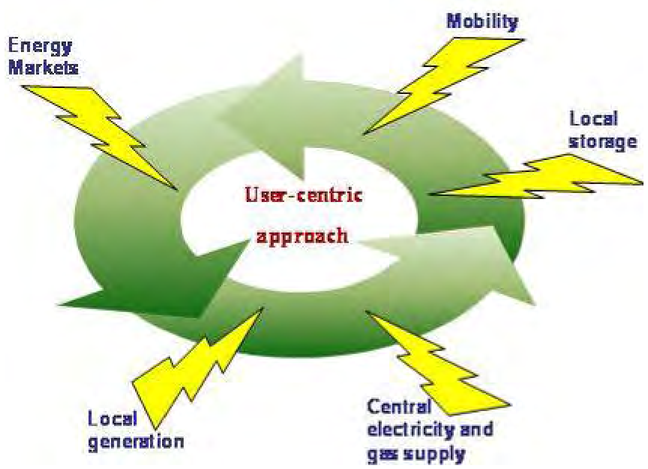


Fig.1 Interaction in a user-centric approach.

More efficient and flexible small users who also implement local generation technologies can help improving overall energy efficiency and increase security and adequacy of the energy system. By installing local generation based on renewable energy sources, sustainability can be improved. A last but important element is user well-being. A user-centric approach allows incorporating user comfort in the analysis. Maintaining and when possible even increasing the current level is an important constraint when such a technology has to be accepted by the public.

B. TECHNOLOGY

A real breakthrough of retail markets can only be initiated by active metering tools. By improving both internal and external communication with market players and devices, a better measuring of relevant data is possible. An intelligent system has to be developed to organize control and interaction, as transparently as possible. The use of real-time prices and information will be crucial. However, the economical feasibility remains to be investigated.

C. LINK TO MOBILITY

On the electricity demand side, plug-in hybrid cars can also be considered an option for efficient energy use. Plug-in hybrid electric vehicles (PHEV) are the next phase in the evolution of hybrid and electric vehicles. Hybrid electric vehicles combine a conventional internal combustion engine (powered by gasoline, diesel or biofuel) and electric motors. There are several engine architectures possible and the size of the internal combustion engines and the electric motor differs. The fuel efficiency of this vehicle is better than that of conventional drive systems, and the batteries can be charged using electric energy from the distribution grid or through on-board electricity generation [9].

Since PHEVs can be controlled in their charging process quite easily, they form an excellent candidate for a controllable load. In theory, their on-board power reserve (and even generation capacity) could be addressed to inject power in the grid.

D. MULTI-ENERGY APPROACH

In order to capture the larger-scale consequences of DG implementation or load activation, the natural gas and electricity networks and the off-take profiles have to be considered in parallel as overlaid networks. This is important as a change for the good in one system may have adverse effect in another, for instance: massive use of gas-based CHP may lift some stress of the electricity transmission system, but will most certainly lead to congestion of the gas distribution. An investigation of the parameters driving the profiles provides information about how they can be influenced accounting for the impact of local, renewable energy sources (Fig. 2). Eventually the three resources have to be distinguished: electricity, natural gas and renewables in a broad sense.

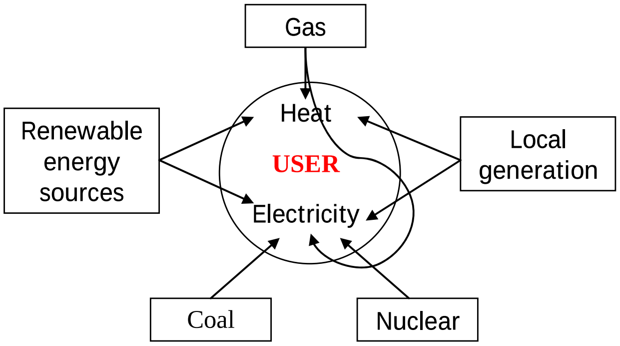


Fig.2. Multi-energy resource interactions.

IV. CONCLUSIONS

The activation of electrical loads with small users, the so-called demand-side participation, helps the further deployment of sustainable types of distributed generation such as wind power, PV and CHP through a contribution to balancing locally as well as globally. As such it represents a contribution to the security, adequacy and stability of supply through the enlarged diversification of primary energy resources and the creation of necessary ancillary services, more in particular reserve provision. Unlike a blunt introduction of DG, a combined introduction of both types of DER, DG and complementary demand control may help to solve the ‘reliability paradox’.

Obviously, further research is required into the technological implementation of demand control. A new class of active metering devices is required. Their communication and distributed control algorithms form a challenge. These devices have to consider all energy resources relevant for the small users, in practice electricity and natural gas. Additionally the exact estimation of the economically feasible demand control potential in realistic circumstances will be a difficult task for the future.

V. REFERENCES

[1] IEA, *Distributed Generation in Liberalised Electricity Markets*, Paris, 128 pages, 2002.
[2] Ackermann T., Andersson G., Soder L., “Distributed generation: a definition,” Electric Power Systems Research, 57, 2001, 195–204.
[3] Jenkins N., Allan R., Crossley P., Kirschen D., Strbac G., Embedded Generation, The Institute of Electrical Engineers, London, 2000
[4] Pepermans G., Driesen J., Haeseldonckx D., Belmans R., D'Haeseleer W., "Distributed generation: definition, benefits and issues," Energy Policy, Vol.33, Issue 6, April, 2005; pp. 787-798.
[5] Driesen J., Belmans R.," Distributed generation: Challenges and possible solutions," 2006 IEEE Power Engineering Society General Meeting, Montreal, Canada, June 18-22, 2006; 8 pages
[6] Voorspools K., D’haeseleer W. “The impact of the implementation of cogeneration in a given energetic context,” IEEE Transactions on Energy Conversion, 18, 2003, pp.135–141.
[7] Horowitz I., Woo C.K. (2006) Designing Pareto-superior demand-response rate options, Energy, Vol. 31, pp 1040-1051
[8] Joskow P. L., Tirole J. (2004) Retail Electricity Competition, MIT Department of Economics Working Paper No. 04-18.
[9] Winkel R, van Mieghem R., Santini D., Duvall M., Conte V., Alaküla M., Badin R., Bleis R., Brouwer A., Debal P., “Global Prospects of Plug-in Hybrids”, The 22nd International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exposition, Japan, October 2006.

VI. BIOGRAPHIES

Johan Driesen (S’93–M’97) was born in 1973 in Belgium. He received the M.Sc. degree in 1996 as Electrotechnical Engineer from the K.U. Leuven, Belgium. He received the Ph.D. degree in Electrical Engineering at K.U.Leuven in 2000 on the finite element solution of coupled thermal-electromagnetic problems and related applications in electrical machines and drives, microsystems and power quality issues. Currently he is an associate professor at the K.U.Leuven and teaches power electronics and drives. In 2000-2001 he was a visiting researcher in the Imperial College of Science, Technology and Medicine, London, UK. In 2002 he was working at the University of California, Berkeley, USA. Currently he conducts research on distributed generation, including renewable energy systems, power electronics and its applications, for instance in drives and power quality.

Ronnie Belmans (S’77-M’84-SM’89-Fellow ‘04) received the M.S. degree in electrical engineering in 1979, the Ph.D. in 1984, and the Special Doctorate in 1989 from the K.U.Leuven, Belgium and the Habilitierung from the RWTH, Aachen, Germany, in 1993.

Currently, he is full professor with K.U.Leuven, teaching electrical machines and variable speed drives. He is appointed visiting professor at Imperial College in London. He is also President of UIE.

He was with the Laboratory for Electrical Machines of the RWTH, Aachen, Germany (Von Humboldt Fellow, Oct.’88-Sept.’89). Oct.’89-Sept.’90, he was visiting associate professor at Mc Master University, Hamilton, Ont., Canada. During the academic year 1995-1996 he occupied the Chair at the London University, offered by the Anglo-Belgian Society. Dr.Belmans is a fellow of the IEE (United Kingdom). He is the chairman of the board of Elia, the Belgian transmission grid operator.

3. DISPERSED GENERATION AND SYSTEM STRUCTURE - ACTIVE ASSET MANAGEMENT FOR IMPROVING OF THE POWER SYSTEM SECURITY. (INVITED DISCUSSER)

Pier Nabuurs Chief Executive Officer, KEMA, Arnhem, The Netherlands and Peter Vassen KEMA

The text of this Invited Discussion will be included later.

Received January 16 2007

4. COMMUNICATION REQUIREMENTS AND SOLUTIONS FOR SECURE POWER SYSTEM OPERATION (PAPER 07GM0208)

Bernd Michael Buchholz[1], Zbigniew A. Styczynski[2]

***Abstract*—**The further increase of the contribution of dispersed and renewable energy resources (D&RES) in the peak power balance up to 60 % in accordance with the goals of the European Communities for the year 2010 requires innovative approaches to keep the security of the power supply at the current high level. Communication will be the key for further suitable operation of the power system.

New communication facilities will be necessary to provide reliable data for decentralized energy management, integrated planning tasks and to ensure the provision of system services by D&RES. Communication networks with different physical communication channels have been investigated in the scope of some pilot projects. Furthermore, the application of communication standards has been investigated and as a result the use of data models and the services of the communication standard IEC 61850 (for substation communication) has been recommended. Also, the standard IEC 61968 has been discussed.

Finally, it has become clear that the implementation of more communication in the distribution level is necessary for secure power system planning and operation.

Index Terms -Power system of the future, energy management, network planning and operation, communication, performance criteria.

I. INTRODUCTION

The future power system in Europe will contain a mixture of centralized and de-centralized power generation. The European Smart-Grid vision [1] identified the role of information technologies in the future power system. Currently, in Europe the Dispersed and Renewable Energy Sources (D&RES) are mostly operated without remote control mechanisms, feeding in a maximum possible generation corresponding to political and regulatory framework conditions. The increase of the contribution of D&RES in the peak power up to 60 % in accordance with the goals of the European Communities for the year 2010 requires innovative approaches to maintain the security of the power supply.

Sustainability in this context requires that the D&RES contribute significantly to the provision of system services like frequency control, power balance, voltage control or supply restoration after faults. For these purposes remote information exchange with the D&RES units will be necessary. Consequently, communication solutions play the key role to ensure the sustainability in accordance with the increasing share of D&RES in the power systems.

Some European projects [1] are considering how the data models and the services of the communication standard IEC 61850 can be mapped to different physical locations and link layers of possible communication such as Distribution Line Carrier (DLC), fiber optics, copper based telecommunication cables (dial up and dedicated lines), and radio channels. The optimization of a communication network with different physical communication media is suggested for a typical medium/ low voltage network with industrial, commercial, rural and household customers each with typical load profiles. A mathematical model of communication networks using different physical channels was

---

Dr. B. M. Buchholz is senior consulter by the PTD SC PTI, Siemens AG, Germany, Erlangen (bernd.buchholz@siemens.com)

Prof. Dr. Zbigniew Styczynski is with the Faculty of Electrical Engineering and Information Technology the Otto-von-Guericke University Magdeburg (sty@e-technik.uni-magdeburg.de)

developed to optimize the structure in accordance with the communication tasks of the distribution system [2,3].

II. SECURE OPERATION OF THE POWER SYSTEM OF THE FUTURE

The operation of the current power system consists of large, centralised power plants, a hierarchical network and a huge amount of dispersed consumers that have to be controlled by central control centres. The future will be characterized by a large amount of small D&RES, many of them with intermittent power output. All these D&RES have to be operated in parallel with conventional power plants. Furthermore, at the consumer side there will be possibilities to influence the consumption by means of flexible tariffs and other mechanisms [2]. Demand side management will play a growing role for power balancing in the future. A coordinated energy generation, load management and an integrated power system planning process will be necessary.

One possible solution for this problem is to transfer a part of the control intelligence close to the D&RES units and controllable loads by using “agents”. Such an agent receives instructions from the higher-level control structure and has a certain range within which it can control its unit or group of units. An example shall illustrate the concept: A household agent receives information about tariffs, electricity demand etc. from the superior control mechanism and information about heat demand, status of storage units etc. in the household. Additionally, the agent gets predictions for these parameters, based on weather forecasts, load profiles etc.

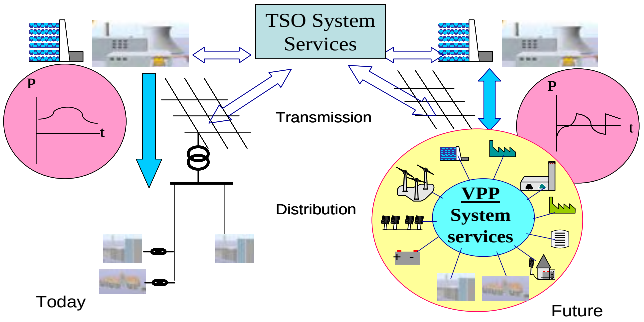


Fig. 1: Power system operations today and in the future

With help of this information the agent is able to optimise the deployment of the household devices e.g. whether to start or stop a fuel cell, the refrigerators, compressors etc.

The clustering of many such small controllable loads, generation and storage units into pools with a manageable power import/export from/to the outer grid provides the function of a virtual power plant which is able to contribute to the system services. This principle is shown in figure 1. Such a system can only be based on a powerful and reliable communication structure.

The communication tasks of the future distribution networks include:

- the contribution to the active power balancing with dispatch of power generation, storage and controllable loads building a virtual power plant (VPP). The VPP of the future shall be able to deal with islanded operation by means of generation and demand side management.
- the transfer of metered values as a support for the wide spread energy management and for billing,
- the provision of further system services like congestion management, reactive power and voltage control, fault location, supply restoration after faults, islanded operation, black start capability etc.

Today the system services are mainly provided by transmission system operators (TSO). In the future the TSOs will also be responsible for the lead, but more and more aspects will be provided by the distribution level. Fig. 2 presents the system services and the changes of their provision.

Responsibility for the system services will be shifted (Fig. 2) from the TSO to the distribution system operator during the next 15 years. It is planned that in 2020 all system services, e.g. primary control power or reactive power control, will also be provided on the distribution level. This situation will make it possible to operate the power system in the island mode.

Frequency stability: **- FP - Primary control power (<30s)**
- FS –Secondary control power (< 5 Min.)
- FM - Minute reserve power (7-15 Min.)
Power Balancing: **- PD – Scheduling and Dispatch**
Voltage Stability: **- VT – Tap changer control**
- VQ - Reactive power control
Restoration of supply: **- RB - Black start capability**
- RI - Island operation
Further system management: **- SQ – Power quality assurance**
- SO – operational and asset management

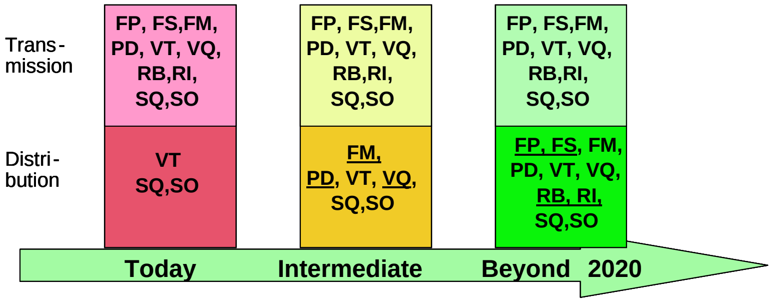


Fig. 2: System Services: Provision Today and in the Future

III. COMMUNICATION STANDARDS

The experience of the first VPPs [3] underlined the need for applying communication protocols based on common standards for all channels used. Otherwise, the engineering expenses will grow and the operation of the communication network will become inconvenient. Contrary to the existing practice, where power generation is concentrated on a rather compact area and therefore information and data is transferred on local networks, the units of VPPs will be wide spread.. For economical reasons the existing infrastructure of communication channels has to be used. Consequently, different communication channels like radio, fiber optics, power line carrier and telecommunication cables will be applied within one network.

The question arises: how can a consistent communication standard be applied for different physical layers? An analysis was provided among the existing IEC communication standards to select a standard which responds in the best way to the following selection criteria

- liberty for mapping the application layer to different physical and link layers,
- plug and play without extensive engineering,
- expandability of the data models and introduction of new models in accordance with the enhanced tasks.

Only the standard IEC 61850 [2, 4] (for communication in substations, published as standard in 2004) responds to the above mentioned requirements. The "Plug and Play"- ability is reached by the detailed object modeling based on logical nodes (objects like circuit breaker or transformer etc.) and data (information like “status ON” or “Buchholz alarm” etc.) with the supplement of different attributes (like time stamps, validity information etc.).

The mapping to different application layers was foreseen in the reference model of the standard IEC 61850 in accordance with figure 3.

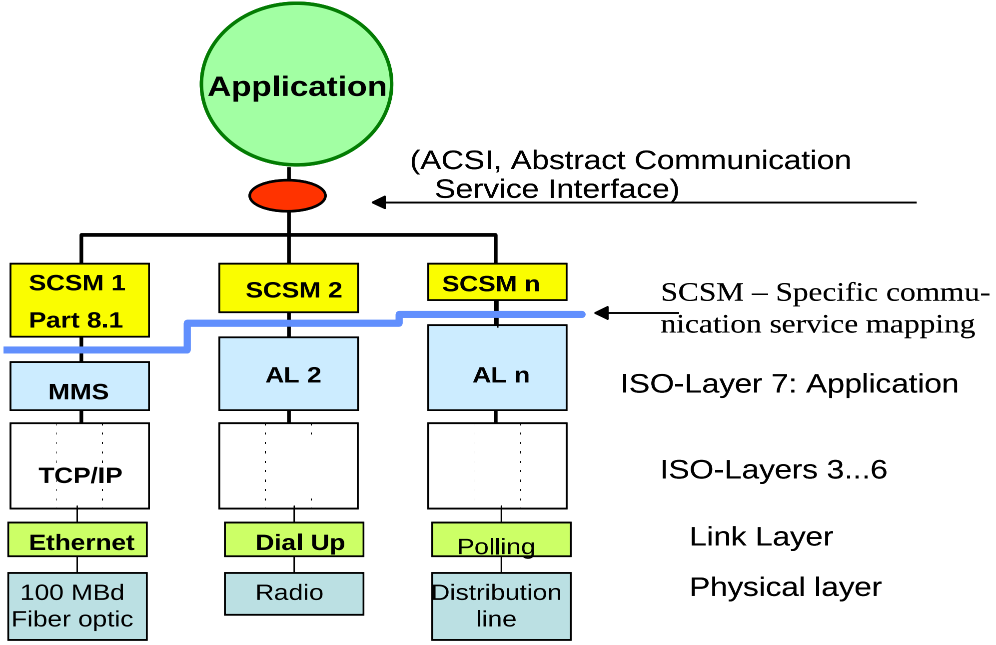


Fig. 3: Reference Model of IEC 61850 and Mapping Opportunities for Various Physical Media

The abstract communication service model describes the data models and the services in an abstract form. It is the interface between the application and the application layer.

The protocol approach requires the definition of all layers of the ISO/OSI model. IEC 61850 defines in Part 8.1 the “Manufacturing Message System” MMS as the base for the first standard conform application layer (AL1) and Ethernet/100 MBd fibre optics as the link and physical layers. The specific communication system mapping SCSM ensures the adaptation of the services and models of the ACSI to the selected systems and methods for the application layer. In this way the IEC 61850 makes it possible to adapt future communication methods to the core elements of the standard - the ACSI (parts 7). Consequently, through the SCSM different application, link and physical layers can be applied. Last but not least, the object models can be extended on demand. IEC 61850 defines the building rules for such extensions.

As a goal for the new standards it was declared that all existing services and models of IEC 61850 would be taken over as defined and only the needed extensions would be added. It is fully unacceptable that in a communication network the data models for the same equipment would be different depending on the data source e.g. - substation transformer (IEC 61850), wind plant transformer (IEC 61400-25) or fuel cell transformer (IEC 62350). Otherwise the acceptance for the application of the new standards will not be reached by both the power automation industry and utilities.

The design of a communication network consisting of different physical media and link layers is an innovative task. Some projects [2] have set up the task to develop a mathematic model for such a communication network to find out the optimum design rules. In principle, the design depends on the scope of information exchange which is always assigned to the actual network and its units (load, storage, generation, substation) participating in the supervisory control and data acquisition.

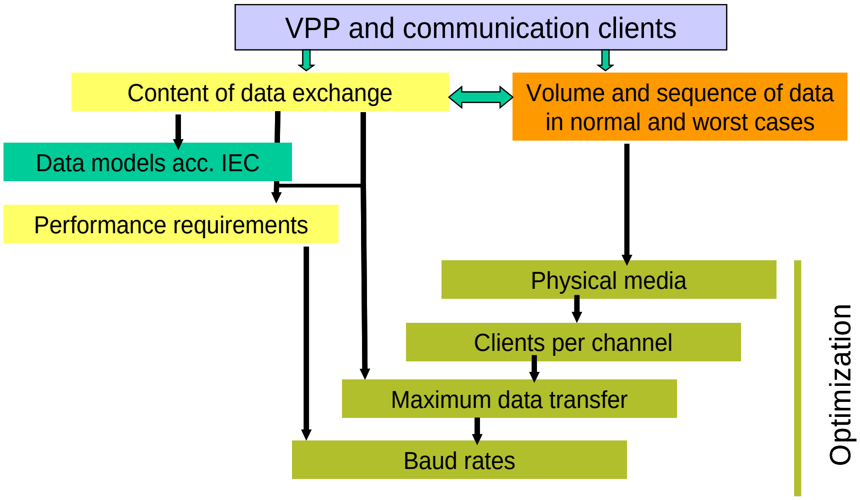


Fig. 5: Scope of communication network design

From the communication point of view these units will act as clients and the control unit as the server. The principle approach of the communication network design is shown in figure 5. Based on the actual virtual power plant and its clients the content of information exchange has to be defined for each client.

The amount of data for communication is quite different for each client. It depends on its weight in the power balance and its possibility to be controlled. Therefore, content and classes of information have to be defined according to the specific client. On the one hand, a small photovoltaic unit reports metering data and status information to the VPP server. Remote control is not foreseen.

On the other hand, a significant co-generation plant for heat and power (CHP) must be able to receive a target generation profile for a day (96 target values) and to transmit information about the storage management of the heating system in addition to metering data and status information.

In this context it becomes clear, that the communication network has to be designed specifically in accordance with its client structure. The performance of the data transfer has to be defined in accordance with a maximum latency time assigned to each class of information, e.g.:

• Control with return information	2 s
• Alarm	1 s
• Event message	5 s
• Metered or measured value	2 s
• Power schedule (96 target values)	20 s

Summarized, the inputs for the communication network design are complete:

- Sequence of telegram transfer for worst and normal cases,
- Data volume of the telegrams in accordance with [2],
- Maximum latency time for each kind of data exchange.

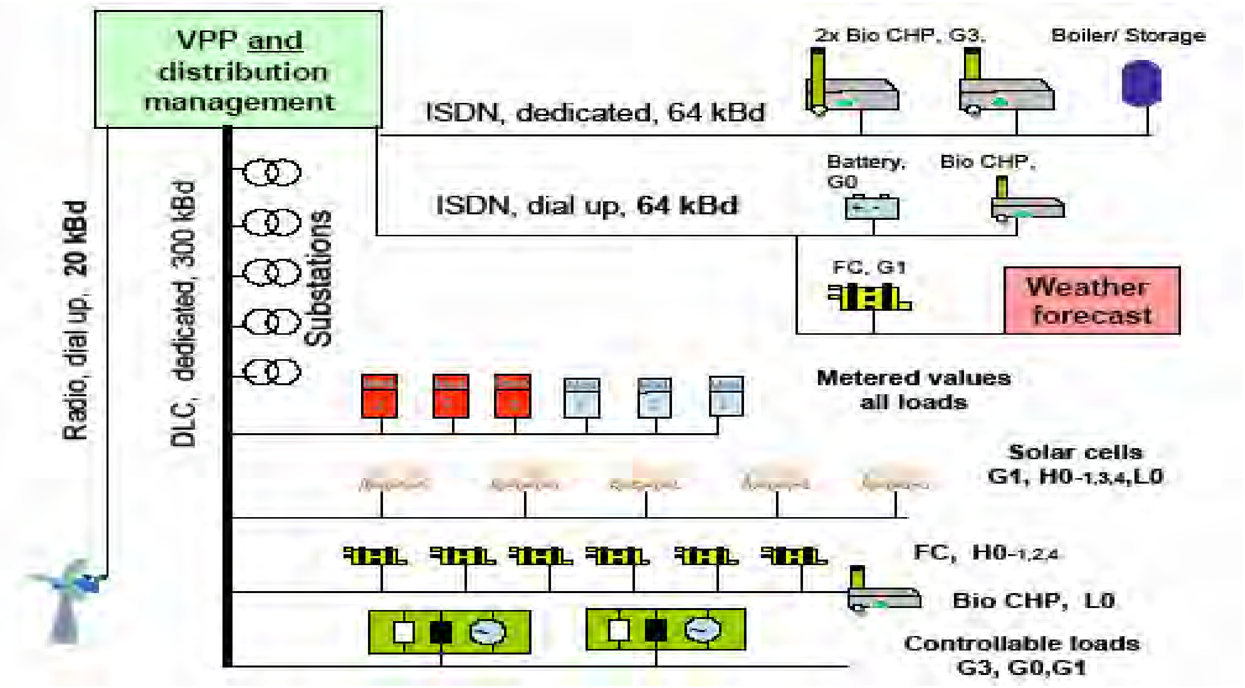


Fig. 5: Communication Network

In accordance with figure 5 the optimization of the network design now includes:

- the selection of physical communication channels,
- the assignment of clients to the foreseen channels and
- the selection of the transmission rate of the channels in accordance with the maximum data load.

A possible design of the communication network which fits with the performance requirements and combines different physical channels is shown in Fig. 5.

The large CHP- plants play a significant role in the power balance of the distribution network and impact the energy tariff of the industrial plant. They are connected by a dedicated ISDN line. The other generation and storage units in the shopping and business area as well as the access to weather forecast data (for load and generation prediction) need only a dial up line. The wind power plant is connected via a radio channel with the target to combine this kind of communication with the others. The main load of communication is assigned to the “Distribution Line Carrier” DLC, where through innovations the baud rate can reach more than 300 kBd [7]. The dispersed generation units in the household and rural networks communicate over these channels, the metered values of all loads are reported every 15 minutes, the control commands for demand side management are sent out and the control of equipment in the substations is incorporated to provide a new class of distribution system management. The multiple application of the mathematical model will create general rules for an optimum communication network design using different communication channels.

IV. INTEGRATION OF THE DATA FOR PLANNING AND OPERATION: THE KEY FOR POWER SYSTEM SECURITY

The communication processes allow transmitting data from the data sources to the process nodes. The consistency of this data is decisive for the secure planning and operation of the power system. This requires a joint data base for both processes in the future, which is quite a big challenge. The optimal scheduling, energy management or blackout prevention calculation (dynamic simulation) used not only the

SCADA information but also the actual planning date stored in the power system data base (Fig. 6). The power system security depends strongly on the accuracy of this data and on the controlled data flow.
During the last few years some works have been done to standardize the general data flow in the power system. The IEC 61968 which defines the Interface Reference Model (IRM) is the first step in the right direction. The challenges of the joint models are:

- model accuracy for different planning and operation tasks in the transmission and distribution system,
- structure of universal data storage depending on the planning and operation tasks (projects),
- integration of different energy media in one data base.

Here the GID- Generic Interface Definition and CIM- Common Information Model are the key for the future.

Proposals for such a complex solution are given in fig. 7.

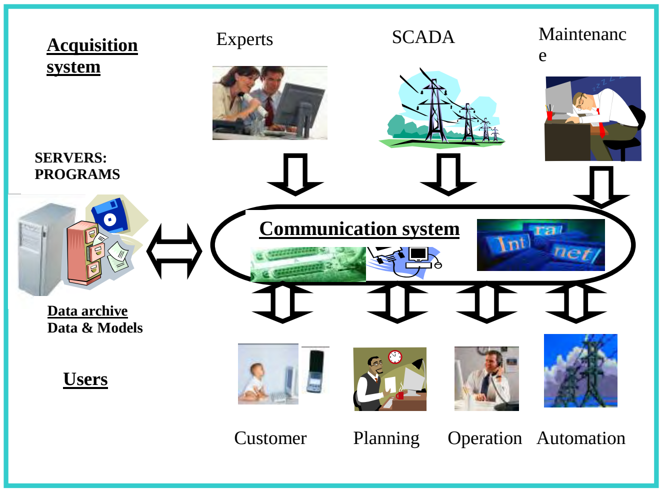


Fig. 6: Complex Flow of the Data in the Power System

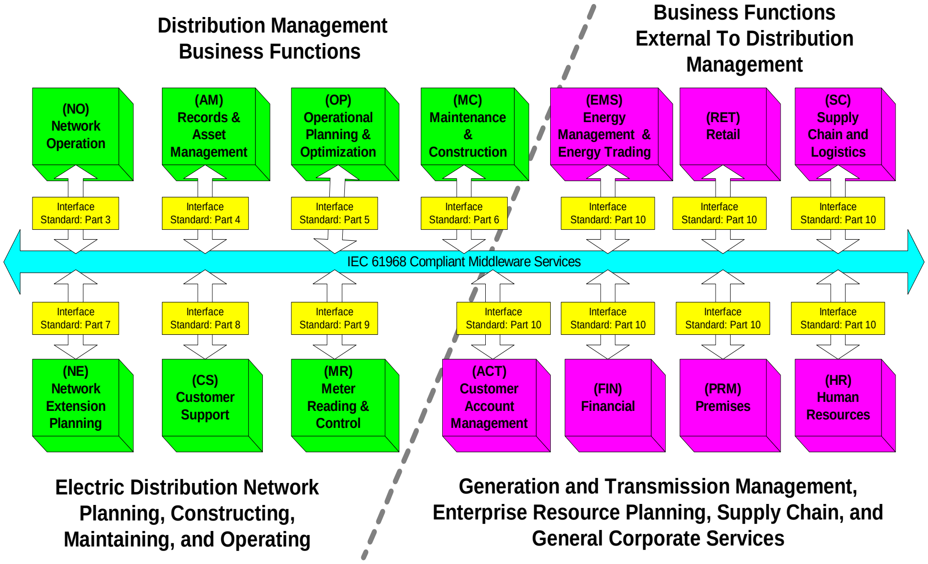


Fig. 7: The IEC 61968-1 Interface Reference Model (IRM)

V. CONCLUSIONS

Electricity supply systems are about to change from a structure with big central power plants, a hierarchical power flow structure and a huge number of dispersed consumers to a structure with

- a lot of D&RES, partially feeding back into the transmission grid with intermittent power and
- consumers that can be influenced by demand side management.

The power system planning process of the future will be more complex and will require more flexibility. The joint data base for planning and operation based on the GID and CIM models will be necessary to make the above mentioned processes both secure and reliable.

Innovative communication systems using the existing infrastructure with different physical channels are required to support the contribution of the D&RES to the system services in the framework of virtual power plants. The mapping of the models and services of IEC 61850 to various physical media is recommended. The consistency of the models shall be ensured in the development of the subsequent communication standards IEC 62350 and IEC 61400-25 for D&RES. On behalf of a distribution network pattern the approach to the communication network design was demonstrated. A mathematical model of the communication network using different physical communication media was developed and its application will create optimum solutions to solve the communication tasks in various distribution network structures by using the existing infrastructure.

VI. REFERENCES

[1] EUR 22040 – *European Technology Platform SmartGrid*. Luxemburg 2006, ISBN 92-79-01414-5

[2] Buchholz B.M., Styczynski Z.: *Integration of Renewable and Dispersed Resources: Lessons Learnt from German Projects*. General Meeting 2006 PES/IEEE June 2006 Montreal. Invited paper. 1-42-0493-2/06/©2006 IEEE. 6S. [electronic resources]

[3] Buchholz B.M. , Saßnick Y.: *The German experience of the grid integration of renewable energy sources.* St. Petersburg Powertech 2005, St. Petersburg June 27-30, 2005

[4] Morovic, T.; Pilhar, R.; Möhring-Hüser, W. *Dynamische Stromtarife und Lastmanagement - Erfahrungen und Perspektiven,* Conference Proceedings Kasseler Symposium Energie-Systemtechnik, Erneuerbare Energien und Rationelle Energieverwendung, Tagungsband 1998, p. 159-191

[5] Buchholz B. M., Schwaegerl C.: *Virtual power plants: Basic requirements and experience in practice*. Cigré 5th Southern Africa Regional Conference Somerset West, South Africa 24 – 27 October 2005

[6] IEC 61850 Part 1-10. *Communication networks and systems in substations*

[7] IEC 612400-25-2. *Wind Turbines. Communication for monitoring and control of wind turbines. Part 25-2. Information models. IEC 88/214/CD*

[8] IEC 62350. *Communication systems for distributed energy resources. IEC 57/750/CD*

[9] Scholtes J., Schwaegerl C.: *Energy Park KonWerl. Energy management of a decentralized supply system. Concept and First results.* First international conference on the integration of Renewable energy sources and Distributed energy resources. Brussels, 1.-3. December 2004

[10] Buchholz B.M., Styczynski Z.: *New Tasks Create New Solutions for Communication in Distribution Systems.* General Meeting 2006 PES/IEEE June 2006 Montreal. Invited paper. 1-42-0493-2/06/©2006 IEEE. 6S. [electronic resources]

[11] Buchholz B.M. a.o.: *Advanced planning and operation of dispersed generation ensuring power quality, security and efficiency in distribution systems.* CIGRE 2004, Paris, 29.August - 3.September 2004

[12] Bumiller G., Sauter T., Pratl, G., Treydl, A.: *Secure and reliable wide area power line communication for soft real- time applications within REMPLI.* 2005 International Symposium on Power Line Communications and its Applications, Vancouver, April 6-8 2005

[13] Styczynski Z., Sachs U., Mauser S: *Complex databases for planning and operation of power system.* 11th Kasseler Symposium Energy System Technology: Information and Communication technologies for tomorrow energy supply. Kassel, 9.-10. November 2006

VII. BIOGRAPHIES

Bernd Michael Buchholz received his MS and PhD at the Power Engineering Institute in Moscow in 1973 and 1976 respectively. After that he was assigned project manager and later director of R&D at the Institute of Energy Supply in Dresden. In 1990 he joined Siemens AG and took over the head of the R&D department of the division “Protection and Substation Control Systems” in Berlin and Nuremberg. Since February 2000 he has been director of the business unit “Power Technologies” in the “Service” division of the Power Transmission and Distribution group in Erlangen. Between 1995 and 2000 he worked as editor for parts 4 and 7 of IEC 61850. He is the German member of the SC C6 of CIGRE “Dispersed generation in distribution systems”.

Zbigniew Antoni Styczynski (SM 92) received his MS and PhD at the Technical University of Wroclaw. He was with the Power System Institute of the TU Wroclaw until 1991, last as an Assoc. Professor and deputy for research. From 1991 until 1999 he worked at the Technical University of Stuttgart, Germany. In 1999 he became Professor and the Chair of Electrical Power Networks and Renewable Energy Sources of the Faculty of Electrical Engineering and Information Technology at the Otto-von-Guericke University, Magdeburg, Germany. From 2002 until 2006 he was dean of the faculty at the University of Magdeburg and since 2006 he has been president of the Centre of Renewable Energy for Saxony Anhalt. His special field of interest includes optimal planning and operation of electric power systems with a focus on distribution. He is a senior member of IEEE PES, member of CIGRE SC C6, VDE ETG and IBN, and fellow of the Conrad Adenauer Foundation.

Received January 18 2007

5. PLANNING UNDER UNCERTAINTY: SECURING RELIABLE ELECTRICITY SUPPLY IN LIBERALIZED ENERGY MARKETS - (PAPER 07GM0778)

Antje G. Orths, Peter B. Eriksen and Vladislav Akhmatov

Abstract**—**The Danish power system is characterized by a high share of dispersed generation (DG) and wind power plants. Today about 24 % of the electricity consumption is produced by wind turbines and about 19 % by combined heat and power units (CHP). The paper shows, how the Danish transmission system operator (TSO), Energinet.dk, handles the tasks of providing secure system operation today and in future, using technical and market mechanisms as well.

Index Terms**—**dispersed generation, wind power, CHP units, regulating power, energy market, forecasting systems.

I. INTRODUCTION

The Danish power system consists of two electrical systems belonging to the two synchronous areas; UCTE in the west and Nordel in the east (Fig.1). Both Danish systems are not connected to each other yet, although an HVDC link between them is planned to be in operation in the year 2010. The national TSO runs the 400 kV and the 150 kV grids (as well as the natural gas grid) and is responsible for security of supply and well functioning energy markets.

Most of the dispersed generation units are located in the medium and low voltage grid (Fig.2) a situation which, on the one hand, complicates their control, but, on the other hand, encourages creating incentives for the operators of the units to control their output according to an overall system optimum.

The wind and CHP penetration, defined as the quotient of installed wind power-, resp. CHP-capacity, divided by maximum (or minimum) load [1] is different in western and eastern Denmark. Currently the wind power penetration equals between 65 % to 189 % in western, and 29 % to 85 % in eastern Denmark. The respective values for CHP-penetration are 46 % to 136 % for western, and 25 % to 73 % for eastern Denmark. Looking at the energy, about 52% (29 %) of the consumed energy is produced by dispersed generation units in western (eastern) Denmark. The absolute values are shown in Table 1.

P. B. Eriksen, A. G. Orths and V. Akhmatov are with the Planning Department of Energinet.dk, the Danish system operator for gas and electricity, DK-7000 Fredericia, Denmark (e-mail: PBE@energinet.dk; Antje.Orths@ieee.org, VLA@energinet.dk).

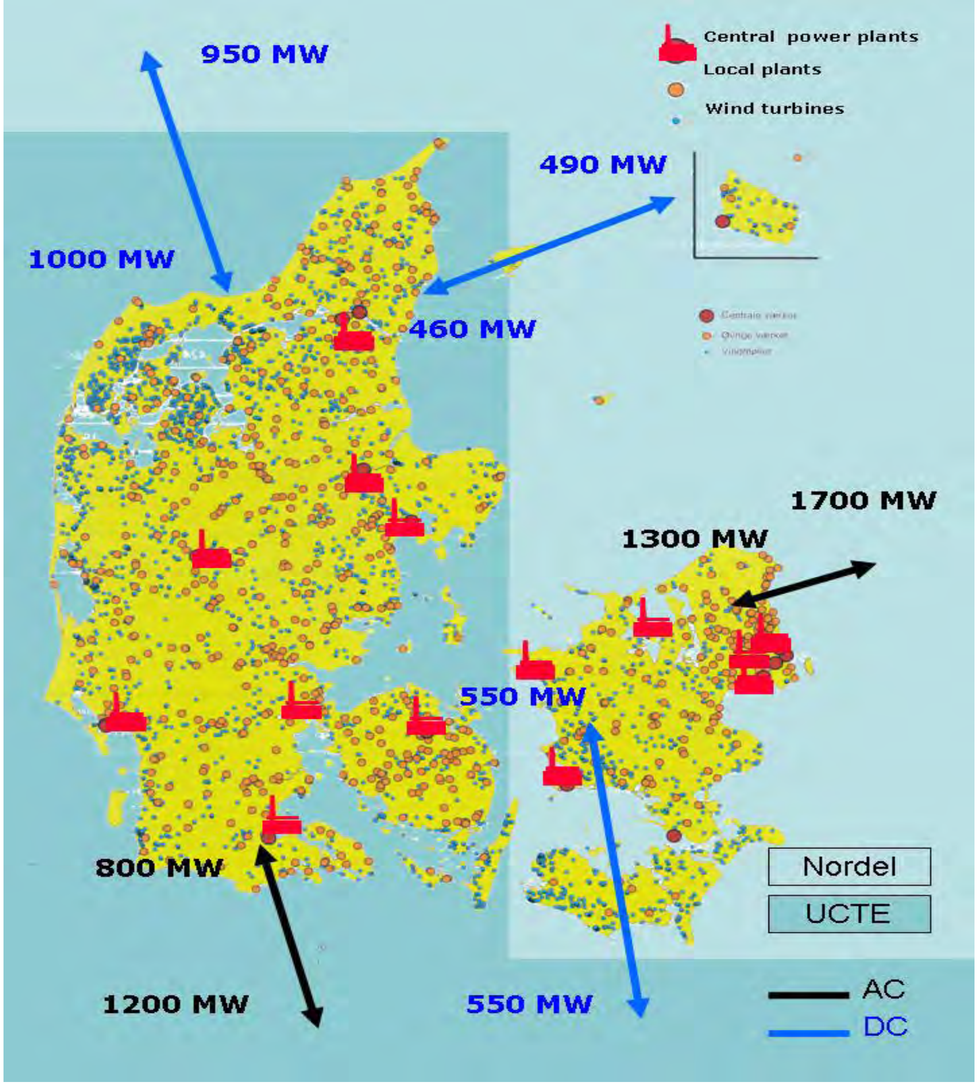


Fig. 1 Denmark within two Synchronous Areas

Being a link between the hydro-based Nordel system in the north and the thermal based UCTE system in the south, Denmark faces high energy transits [2]. The neighboring German power system is, especially in its north, also characterized by high wind power infeed [2], which will remarkably increase due to ambitious plans concerning the implementation of offshore wind parks. Thus, to secure also a future reliable energy supply at reasonable prices a careful and co-coordinated transmission system planning is required as well as the intelligent utilization of possibilities offered by the liberalized electricity market.

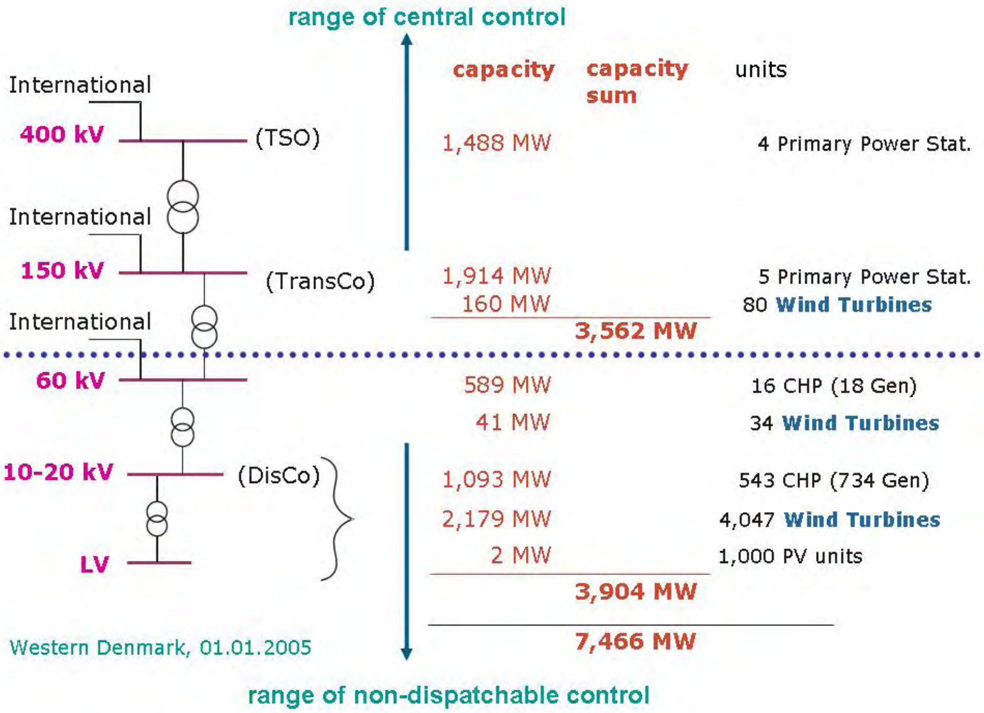


Fig. 2. Production Capacities per Voltage Level, Western Denmark, 1.1.2005

TABLE I

KEY FIGURES OF THE DANISH POWER SYSTEM (31.12.2005)

	West DK Power [MW]	East DK Power [MW]	West DK Energy [GWh]	East DK Energy [GWh]
Production, Total:	7,510	5,145		
Primary power plants	3,402	3,837	10,588	8,360
Local CHP	1,715	642	5,981	2,537
Wind Power	2,393	748	5,022	1,592
Consumption, Total:			21,006	14,385
Minimum Load	1,266	879		
Maximum Load	3,698	2,619		
Exchange Capacity: Export UCTE	1,200	550		
Import UCTE	800	550		
Export Nordel	1,440	1,700		
Import Nordel	1,460	1,300		

In the years to come production capacity within Europe has to be upgraded due to end of power plants` lifetime or due to political reasons like e.g. the German nuclear phase out. The question arises, where which kind of unit will be located best, and how prices, profits and the socioeconomic benefits of all countries involved in the common market will develop.

Energinet.dk is responsible for optimizing the respective Danish socio-economic surplus. This task is challenging, because the concern of electricity and gas producers is to optimize their companies` profits, which might lead to different solutions. To solve this task the Nordic transmission system operators actually try to identify indicators which point out the necessity of upgrading the system with respect to power and energy balances. This can be achieved by expanding the grids and thereby trade capacities on the one hand or by building new power plants on the other hand. Incentives for producers have to be found to build the right kind of units in the right location, taking into account that producers will not invest in new power plants, if this spoils their overall profit due to reduced spot prices being a consequence of this investment. However, if a TSO would wait until producers build new power plants, this might not be optimal with respect to grid costs and though not optimal for society. Additionally the danger of insufficient available balance power has to be avoided.

II. ASPECTS CONCERNING THE ENERGY MARKET

To optimize the overall usage of resources, to reach acceptable prices for the consumers and to be able to find a good socio-economic solution, it is essential to provide market access for all production units, even the small ones [3,4]. The market structure has to enable the discrimination free participation in the market. This idea is followed at the different Nordic energy market places.

A. THE NORDIC AND DANISH POWER MARKETS

The Nordic Power Market consists of two main markets - the Nordic Power Exchange (NPX) - which itself is divided into three market places - and the TSO`s real time power market, Fig. 3. The first part of the NPX is a market for financial contracts like futures and forwards covering periods from 3 years to hours ahead. The second part consists of the market places for physical contracts: the day ahead spot market (Elspot) and the hour ahead market (Elbas). Additionally the NPX works as clearing house for bilateral contracts (Elclearing).

The TSOs run two additional market places: one regulating power market for trading balance power and one system power market for trading system services. The TSOs exchange power within the operating hour based on trading on these markets, balancing load and generation in every minute of the day.

The power traded on these markets is produced internationally or within Denmark. The Danish producers sell their energy to a production balance responsible market player (P-BRMP), who sells it either directly to the NordPool spot market NPX or announces the capacity to the system operator`s (Energinet.dk) regulating power market. Energinet.dk transfers the regulation power bids to the Nordic TSO`s Operational Information System (NOIS). There a merit order list which is visible to all TSO's is composed of these bids. Actual regulation measures are based on this list.

The system operator has the overall physical balance responsibility for the electricity system. He settles - based on measurements - the physical imbalances which have occurred financially with the respective responsible players.

The market player responsible for consumption balance purchases electricity in the market - either directly at the NPX or bilaterally from a producer. He delivers to the electricity supplier and the end-customers and sends action-plans to the system operator.

The electricity supplier is a broker - signing supply contracts to customers and making agreements with balance responsible market player. "Must Supply"-companies supply end-customers who do not want to use their market access. Finally the grid company responsible for measuring delivers energy measurement data for all legal partners within the electricity market. The data are used for settlement of money flows. This structure is shown in Fig. 4.

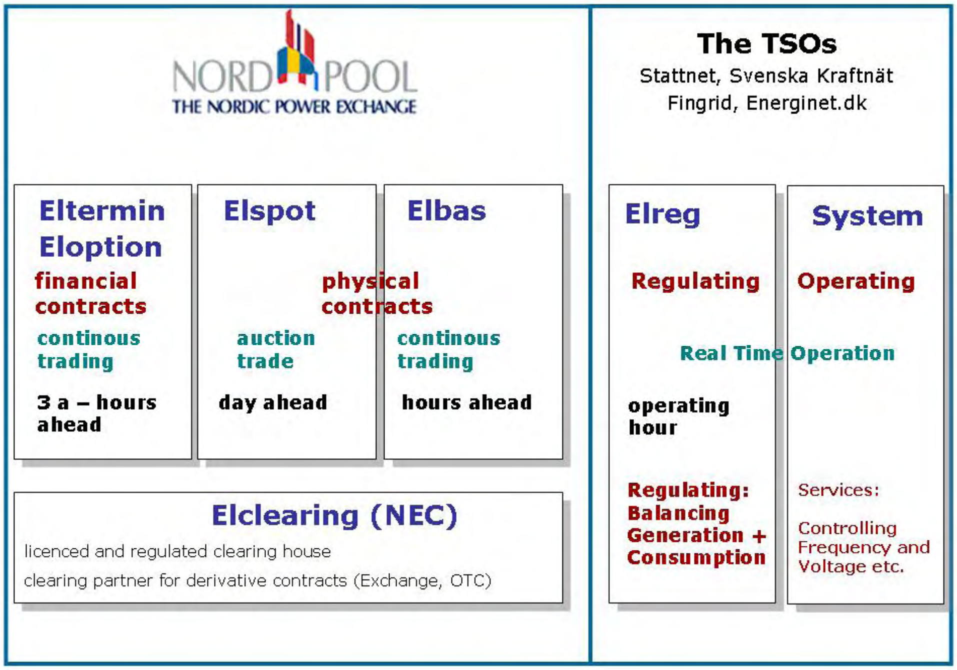


Fig. 3. Structure of the Nordic Power Markets

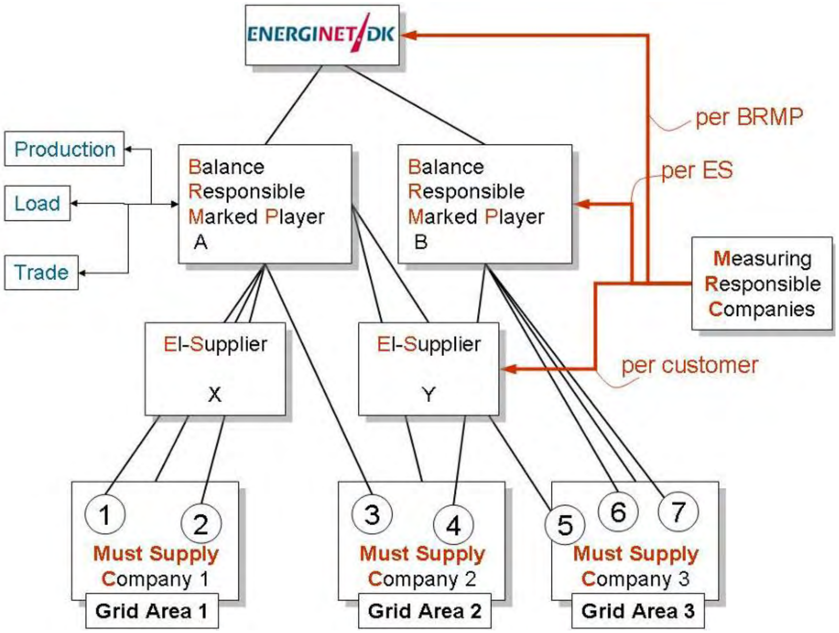


Fig. 4. Structure of the Danish Power Markets

B. LOCAL PRODUCTION ON THE SPOT MARKET

To stabilize the market, a change of operational conditions for CHP units has been implemented. Before the year 2005 there were several hours during a year, where energy was - due to a production surplus during hours with high wind production - sold for a price of zero to foreign customers, which is socio-economically not optimal. It was decided to let CHP units participate in the spot market, to reduce the number of these hours.

Since the first of January 2005 all local CHP-units above 10 MW must operate on market conditions instead of producing according to fixed time tariffs. Before the year 2005 a three tariff system was used. These units comprise a production volume of about 1,200 MW, Fig. 5. Effective from the year 2007 the limit will be lowered to 5 MW, but already today nearly all units are participating in the spot market. For units with a capacity below 5 MW no statuary provisions exist.

When the CHP units are starting to work on market terms, they are facing new tasks: they have to determine their marginal costs, i.e. the costs which are representing short term operation. These costs are a result of the estimation of next day`s heat demand and the necessary number of operational hours to cover this demand. These costs usually have values between 13 € and 26 € per MWh. The next day´s spot prices are also predicted, so that the respective surplus energy can be bid into the market during hours promising the highest profit.

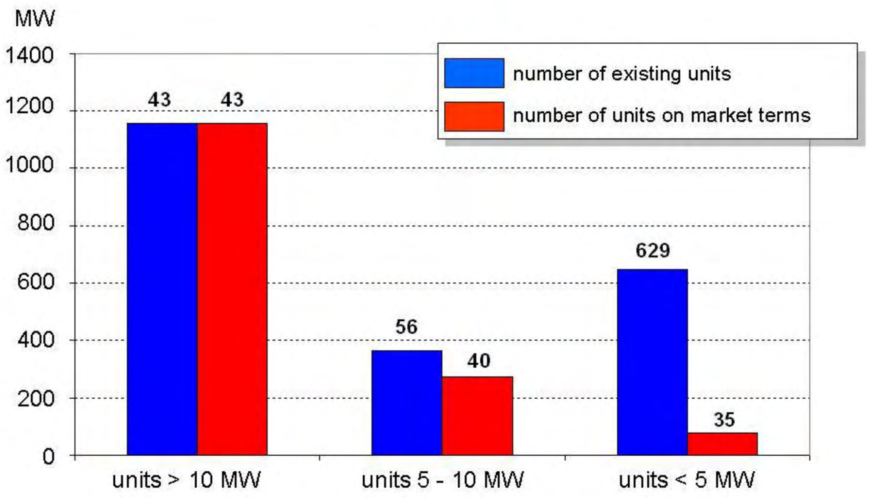


Fig. 5. Number of Danish CHP Units on Market Terms, Status October 2006

The responsible P-BRMP bids the power into the NPX spot market. With CHP running on market terms the P-BRMP has a new price level in his marginal cost curve, representing these units. After receiving the market scheduling plan from NPX, the CHP-units are scheduled according to cover the hours with the highest prices, i.e. asynchronous to wind production- hours, which usually are characterized by low spot prices. These schedules are then sent to the TSO who has to know where the producing units are located. In case of unforeseen events in real time operation the P-BRMP will send a new schedule to the transmission system operator.

Scheduling CHP units with respect to market prices is possible, because they are equipped with heat buffers, which enable decoupling heat and electricity production and run according to optimal price structure.

CHP-units do not only operate according to electricity prices, but also to heat prices. Both prices depend on each other and the producer optimizes the operation mode correspondingly. This price-structure (Fig. 6) causes that the CHP - units will run in case the price for electricity is above 320 DKK/MWh. If the electricity price is between 189 and 320 DKK/MWh the natural gas fired peak load heat boiler is cheapest and will be activated. With electricity prices below 189 DKK/MWh it will be best to use the electric boiler [5]. The tax for electric boilers has recently been lowered, so that today it is economic efficient to use electricity for heat production for a certain time.

Due to the new CHP-step in a P-BRMP`s production curve there are more hours during a year where energy is sold for a price bigger than zero, thereby reducing price difference between peak prices and off-peak prices for Danish consumers. Thus, there is less energy sent abroad for a price of zero, thereby increasing the Danish socio-economic benefit. Besides, hours with possible congestions on transborder-lines are also reduced, and the respective trade capacity is available on the market. An example of a resulting production curve - measured just a few days after the application of the new rules - is shown in Fig. 7.

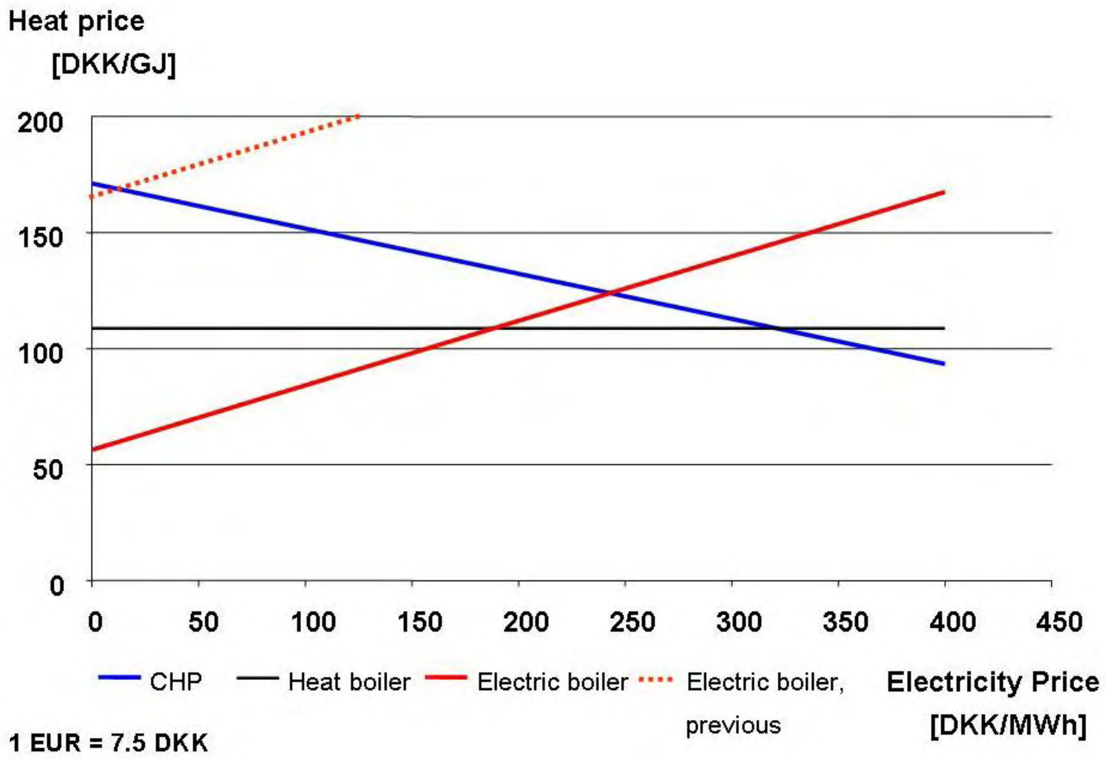


Fig.6. **Interdependency of Heat- and Electricity Prices [5]**

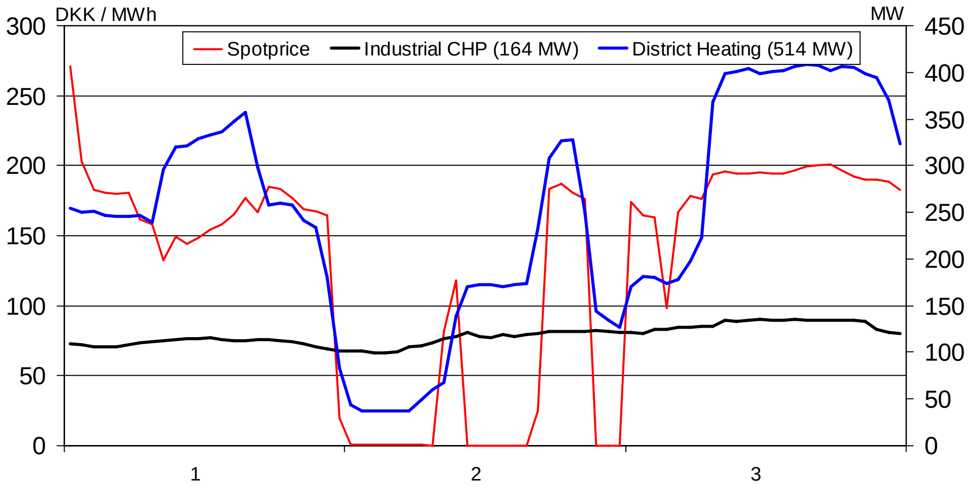


Fig. 7. Operation of CHP units on the Power Market (7,5DKK = 1 €)

The industrial CHP units show a rather constant production, while the district heating units, which are equipped with a heat buffer enabling them to decouple heat and electricity production temporarily, follow the spotprice signal. During hours with a spotprice of zero, which appears during periods of high wind and low load, the electricity production of CHP units is reduced, thereby relieving the grid and improving security of supply. Before the year 2005 the production of CHP units was running after heat demand and showed no interaction with the spot price.

C. LOCAL PRODUCTION ON THE REGULATING AND RESERVE POWER MARKET

The Danish TSO has the task of balancing the power 24 hours a day. Fluctuations of loads as well as fluctuations of sources have to be equalized. The increasing amount of dispersed generation posed new challenges on the TSO with respect to his balancing task, as most of the units are located in the distribution grid and cannot be directly controlled today. Therefore the use of market price signals for system control has been implemented, aiming at facilitating the optimal dynamic allocation of resources.

In Denmark balancing power can be bought from national as well as from international sources. The international exchange of regulating power is governed by an agreement with the Nordic countries [6]. Foreign resources seem to be more volatile than domestic resources, see Fig. 8. Especially in summer their availability can remarkably be reduced due to energy transits or network maintaining activities. Reserving access to foreign up-regulating capacity from Norway and Sweden would reduce transfer capacity in the spot market and is therefore not a preferable solution. Thus, an increase of domestic sources is desirable. Calculations have shown that the necessary amount of upward and downward regulating power, which has to be bought outside of Denmark after activating domestic central units, can remarkably be reduced by integrating CHP units also into the regulating power market.

CHP units acting on market signals and bidding into the reserve and the regulating power market offer a chance to increase the nationally available regulating power, thereby increasing the security of supply by reducing the dependency on international power or on the availability of transit lines.

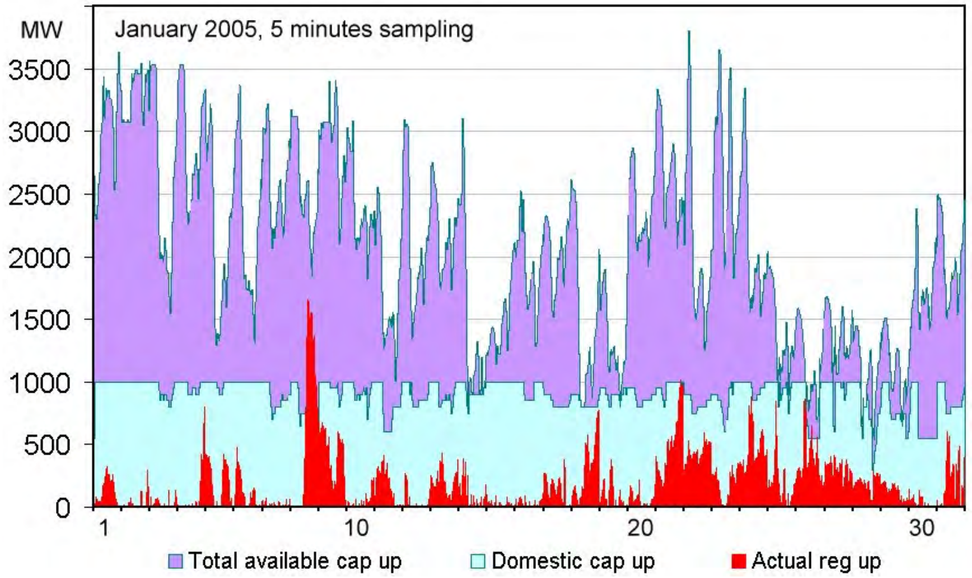


Fig. 8. Example for the Need for Upward Regulating Power

The conditions on bidding into these markets require minimum bids of 10 MW and the ability of being activated within 15 minutes. The bids can be changed until 30 minutes before real time.

Today`s experience, which is after the first two years of implementing these measures, shows, that between the year 2005 and October 2006 the amount of active CHP units on the regulating power market has increased from 7 to 55 small scale units, whereas the amount of active CHP units on the reserve power market has increased from four to 50 within the same time frame. For both markets bilateral agreements between the producer and the TSO are made. The reserve power contracts assure the compensation of the provision of regulating power, for the case it would be needed. In case this power is activated for regulation, an extra compensation is paid. It is also possible exclusively to bid into the regulation power market, i.e. not being paid for availability, but only for service. Practically up-regulating power can be activated by stopping electric boilers, which are in operation. This measure corresponds to the activation of electricity production (up-regulating power). In contrast, electric boilers can be started if they are not in operation, which corresponds to the down-regulation of power.

However, the necessary amount of spinning reserves has to be adapted due to the use of dispersed generation. Further studies considering the probabilistic nature of different sources have to be made.

D. DEMAND RESPONSE

The increasing share of wind energy results in an increasing need for balance tools, which also may be located on the demand side. Demand response is defined as a short-term change in electricity consumption as a reaction to a market price signal. This enables the customers either to shift the time of consuming, or to shift the energy resource and thereby influence the slope of the demand curve [4].

A study made by NORDEL [7] identifies demand response as both an alternative and a prerequisite for investments into new production capacity and recommends that all Nordic TSOs prepare action plans for developing demand response.

Thus, not only supply, but also electricity consumption should follow price signals. The former philosophy of influencing the consumers` behavior by means of time-tariffs or campaigns is substituted by new market products, which illustrate the market value of consumers` reaction and capitalize market gains. The system operator acts as a catalyst promoting the consumers` price flexibility.

Thereby the utilization of cheap wind energy instead of valuable coal or oil shall be achieved. During Energinet.dk`s demonstration projects [8] it has turned out for some big customers like e.g. an iron foundry to be economically efficient to install a parallel electricity based consumption system which is used during times of extremely low prices for wind energy instead of the gas- or oil-based system with higher operation costs.

E. RESIDUAL MARKET

A study made by Energinet.dk [9] investigates the effect of a further implementation of wind energy on the market. The result shows that new products have to be implemented to serve the so called residual markets: which is one market on the demand side and another one on the production side.

Within this study, the approach of defining the volume of the residual markets is based on a fictitious western Danish 100% thermal system with coal fired base-load and gas-fired peak-load units. The system is modeled in the simulation tool SIVAEL (simulation of district heating and electricity), and the consequences of increased installation of wind power are analyzed by means of model simulations. SIVAEL solves the week-scheduling problem on an hourly basis and finds the optimum load dispatch with regard to start-stop, planned overhauls and forced outages. Optimum occurs when the total variable costs are at a minimum.

For the investigations the share of wind power is gradually increased from 0% to 100% coverage of the annual energy consumption. The results show that the system can absorb about 30% wind power with no surplus electricity. The surplus grows substantially when the share of wind power exceeds about 50%. This so called "demand side of the residual market" has to be served by new products of new market players - e.g. heat pumps or electric boilers or other electricity consuming devices which are not depending on the time of their usage. This idea is followed e.g. with the concepts of demand response or with supplementing CHP units with electric heat boilers, which are also available for the regulating power market, as it was mentioned above.

On the other hand, there is also a residual market for production, Fig. 9. Depending on the share of wind energy this market itself is decreasing, but the need for fast regulating peak units is increasing simultaneously. This information is interesting for producers, who have to invest in production capacity and who have to choose the right kind of power plant, optimizing the possible profit for their companies.

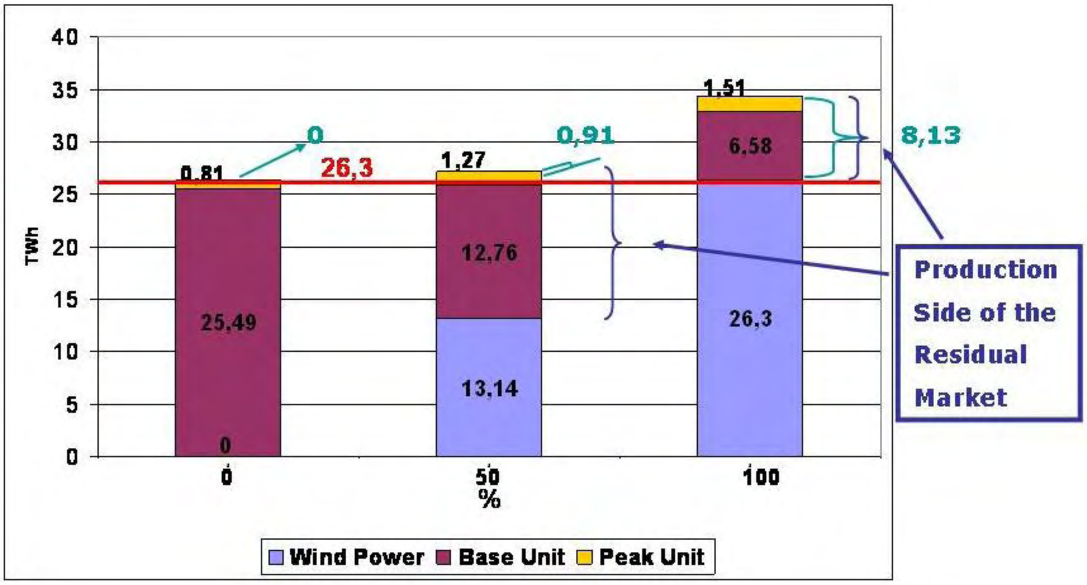


Fig. 9. Energy Production, Consumption and Overflow depending on the share of wind energy.

III. HANDLING UNCERTAINTY AS A TSO

A. NECESSARY ANALYSES

In a liberalized market not only market analyses, but, as a matter of course, also several other kinds of analyses concerning further areas are necessary to provide a secure infrastructure and a functioning market. Chapter II focused mainly on the market aspects. The further areas are at least of the same importance and are closely linked to each other. The Danish TSO, like other TSOs, therefore executes several kinds of analyses and tries to find optimal solutions or new approaches with respect to new tasks which appear due to changing framework conditions. The open view into future developments concerning e.g. society, owner structures, techniques, legal framework conditions and resulting price developments is of major importance.

Usual analyses with respect to short and medium term developments concern five main areas:

- Market: (e.g. congestion analyses; exchange of power and energy; prices; strategic market behavior, i.e. execution of market power).
- System Planning (e.g. medium to long term planning: i.e. new transmission lines, sufficiency of power, energy and network; development and testing of a new system architecture integrating local grids and consumers into system operation)
- Loadflow and stability analyses: (e.g. stationary and dynamic analyses of the power system)
- Environment: (e.g. requirements according to the Kyoto protocol, emission quotas of CO2, SO2 and NOx)
- Natural Gas Transmission System (e.g. planning of infrastructure)

B. DEVELOPING MODELING TOOLS

For each of these areas several modeling tools are used to cover all relevant aspects. Due to the rather unique composition and structure of the Danish power system with a large amount of CHP units and wind turbines and strong electric international connections some of these tools are self developed, as e.g. the partly above mentioned market analyzing and system planning tools SIVAEL and MARS. SIVAEL simulates the optimal scheduling of power and CHP production including wind power and foreign exchange, taking into account the heat buffering characteristics of the units. This tool is also used for environmental analyses.

The market modeling tool MARS simulates the producers` strategic behavior with respect to execution of market power, which is modeled by a quantity dependent mark-up. The consumer and producer surpluses, prices development and the socio economic benefit can be analyzed depending on different scenario settings. The model tool is using game theory assuming that every producer tries to maximize his own profit. Demand and supply curves are modeled for each hour considering price-dependent and price independent types of production (nuclear, conventional, hydro and wind). A market equilibrium is found by the maximization of the socio-economic surplus. The model covers the whole Nordic area and is divided into 5 price areas.

Despite there are a lot of commercial tools available on the market today it remains necessary to develop and adapt tools fitting the characteristics of the respective system and framework conditions. The above mentioned examples give an impression of today's complexity of a TSOs tasks and the way to handle them.

IV. SUMMARY

Running a system with a high share of dispersed generation requires measures of different nature. These include technology, technical guidelines as well as a suitable market structure. Strong interconnections to neighboring countries are essential for the well functioning of the system and the market as well.

The Danish transmission system operator uses the opportunities of the liberalized market to optimize the national power balance at reasonable prices. Measures on the production side, as e.g. CHP units operating on market terms bidding into different markets instead of being governed by a static three tariff system as well as measures on the demand side, as e.g. demand response are considered and described in the paper.

To ensure also in future reliable electricity and gas supply it is of major importance to simulate variants of future developments. Thus different kinds of analyses are made trying among others to identify indicators for system upgrade necessity or find future markets which have to be prepared. The overall target is to optimize the respective socio-economic surplus.

V. ACKNOWLEDGMENT

The authors gratefully acknowledge the contributions of our colleagues Søren Dupont Kristensen and Jens Pedersen for their work on the original version of this document.

VII. REFERENCES

[1] L. Söder, L. Hofmann, C.S. Nielsen, A. Orths, H. Holttinen: "A comparison of wind integration experiences in some high penetration areas,", Nordic Wind Power Conference, Espoo, Finland, May 2005.

[2] P. B. Eriksen; Th. Ackermann; H. Abildgaard et. al.: "System Operation with High Wind Penetration", *IEEE Power and Energy Magazine, vol 3 No. 5, pp 65-74, Nov. 2005.*

[3] P. B. Eriksen, A. G. Orths, V. Akhmatov, "Integrating dispersed generation into the Danish power system - Present situation and future prospects," Proceedings of the 2006 IEEE PES General Meeting, paper 06GM0520 Montreal, Canada June 2006.

[4] V. Akhmatov; A. Orths; P.B. Eriksen: "Secure operation of the Danish Power System with a High Penetration of Dispersed Generation", Proceedings of the CRIS Workshop DiGeSec, Magdeburg, Germany, December 2006.

[5] Systemplan 2006, (in Danish) available: http://www.energinet.dk

[6] System Operation Agreement, 2006-06-13, Available: http://www.Nordel.org.

[7] "Enhancing Efficient Functioning of the Nordic Electricity market", Nordel, Februar 2005. Available: http://www.Nordel.org.

[8] K. Behnke, S. Dupont Kristensen: "Nordel - Danish Action Plan for Demand response", Elkraft/ eltra, Nov. 2004 (intern document)

[9] J. Pedersen: "System and Market Changes in a Scenario of Increased Wind Power Production " *in Proc. 2005 Copenhagen Offshore Wind International conference and Exhibition, October 2005, Copenhagen, Denmark.*

VII. BIOGRAPHIES

Antje G. Orths (M'2001) graduated in electrical engineering at the Technical University of Berlin, Germany. In 1999 she joined the Otto-von-Guericke-University Magdeburg, Germany, where she received her Ph.D in 2003. Afterwards she was leading the group Critical Infrastructures at the Fraunhofer Institute for Factory Operation and Automation IFF Magdeburg. In 2005 she joined the Planning Department (Analysis and Methods) of Energinet.dk, the Danish TSO for natural Gas and Electricity. Her special fields of interests include electric power networks and systems, electricity markets, modeling of dispersed energy resources, network planning and optimization problems. She is member of the IEEE-PES, VDE-ETG and CRIS.

Peter Børre Eriksen holds a MSc. from the Technical University of Denmark. Today he is head of Analysis and Methods of Energinet.dk, the national Danish Transmission System Operator (TSO) for electricity and natural gas, which was found in January 2005. In 1980, after a career in environmental consulting, he changed to energy production planning for the Danish utility ELSAM. Later he joined Eltra, the former Western Danish TSO in 1998, where he was leading the Research and Development Department from 2000 until 2005. His main interests include the modeling and analysis of power and natural gas systems.

Vladislav Akhmatov is since 2003 with the Planning Department (Analysis and Methods) of Energinet.dk, the Danish TSO for natural gas and electricity. Before he worked for the Danish electric power company NESA A/S. He has developed detailed wind turbine models for different power system simulation tools and carried out respective analyses. In 2002 he received the Angelo's Award and in 2006 the Electro Award of the Danish Engineers' Society for his work with wind power in Denmark.

6. DISTRIBUTED GENERATION: TOWARDS AN EFFECTIVE CONTRIBUTION TO POWER SYSTEM SECURITY (PAPER 07GM0679)

B Meyer, Senior Member IEEE

Abstract**—**With a continuously increasing penetration in power system, the impact of dispersed generation is getting higher and higher. This paper deals with the contribution of DG to power system security. It focuses more precisely on its behavior in case of severe frequency disturbances and shows how distributed generation can provide an active contribution to power system security.

The UCTE represents the continental European TSOs and defines system security rules, among which the required amount of reserves or general load shedding management rules.

On the one hand, the paper deals with the decoupling protections in EU countries whose specifications may induce different frequency behaviors across the various interconnected power systems. In case of severe frequency deviation across the European grid, unwanted tripping of DG may occur at a large scale, even if this kind of generation has the ability to remain connected during such disturbances. Such a behavior may jeopardize the whole system security by decreasing the amount of available power for frequency support. As an example, the outage of European grid on November 2006 led to the tripping of a significant DG capacity in the western part of the UCTE (e.g. in Spain with the loss of 2 800 MW of wind power) as frequency dropped at 49 Hz.

On the other hand, the paper presents the requirements and the existing frequency control systems for wind farms. Due to the dramatic increase in installed wind power capacity, this may become a key issue for frequency control. DG could thus contribute to frequency support and power system security.

Index Terms**—**Ancillary services, dispersed generation, power system security, wind energy, decoupling protections

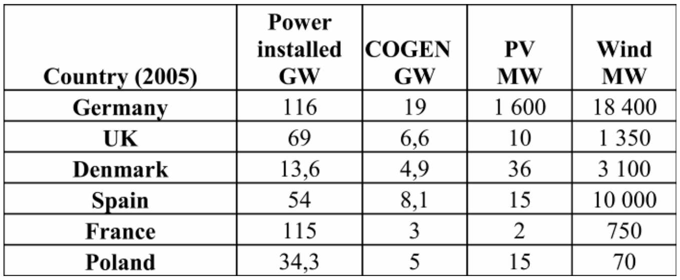
I. INTRODUCTION

The penetration of dispersed (or distributed) generation (DG) resources ranging from a few kW to multi MW sizes is increasing worldwide. The incorporation of DG units in the grid raises new questions regarding power quality, supply reliability and safety.

DG is defined by CIGRE Working Group 37-23 IX as a generation not centrally planned (by the utility), not centrally dispatched, normally smaller than 50-100 MW and usually connected to distribution power systems (networks to which customers are connected, typically ranging from 230 V/400 V to 145 kV).

Wind power, cogeneration, PV, small hydro and waste/biomass are considered as DG. Table 1 shows the DG installed in Europe according to 0.

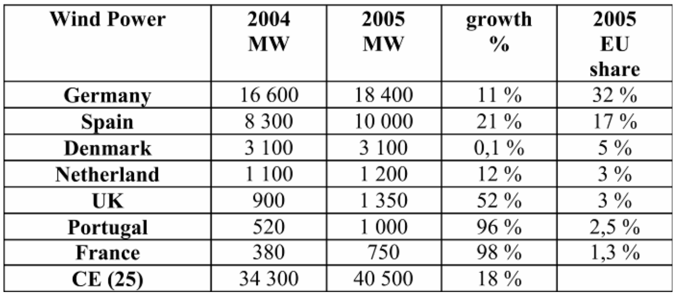
TABLE 1 : DG INSTALLED IN EUROPE 0



Country (2005)	Power installed GW	COGEN GW	PV MW	Wind MW
Germany	116	19	1 600	18 400
UK	69	6,6	10	1 350
Denmark	13,6	4,9	36	3 100
Spain	54	8,1	15	10 000
France	115	3	2	750
Poland	34,3	5	15	70

The rates of development of the different forms of DG vary. At present the fastest one is wind energy with some 40 GW installed in Europe (2005) and a still increasing growth rate in some countries (up to 100% more each year).

TABLE 2 : WIND POWER IN EUROPE (EWEA)



Wind Power	2004 MW	2005 MW	growth %	2005 EU share
Germany	16 600	18 400	11 %	32 %
Spain	8 300	10 000	21 %	17 %
Denmark	3 100	3 100	0,1 %	5 %
Netherland	1 100	1 200	12 %	3 %
UK	900	1 350	52 %	3 %
Portugal	520	1 000	96 %	2,5 %
France	380	750	98 %	1,3 %
CE (25)	34 300	40 500	18 %	

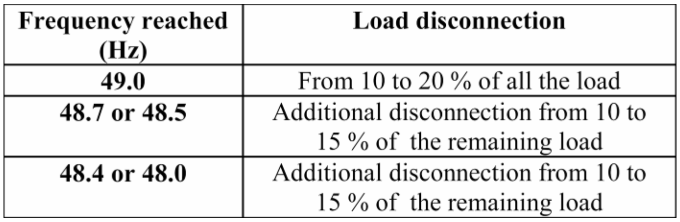
With a significant penetration of DG, power flows in distribution network are altered. The change in real and reactive power flows caused by DG has important technical and economic implications for the power system. To date, most countries have developed their own standards and practices to deal with these issues. In general, the approach adopted has been to ensure that DG integration does not reduce the quality of supply offered to other customers. As a consequence, despite the growth rate of DG in Europe, there is no real harmonization of grid connection rules yet. Furthermore, national grid connection rules are continuously updated because of the increase in DG penetration and the rapid development of new technology. This is specially true for wind energy. As a consequence this increasing amount of DG has to be taken into account for power system security. This is the reason why more and more grid code are defining requirements for low voltage ride through capabilities of wind turbines.

In this paper, the contribution of DG to power system security is discussed. More precisely, the frequency behavior of DG and its potential contribution to frequency support is assessed. Up to now, even though this generation is able to operate in abnormal conditions, unwanted disconnections may be observed due to protections tripping. This paper presents some possible reasons for unexpected tripping in case of frequency deviation, and possible improvements to remain connected and provide an active support to frequency control.

II. UCTE RULES

The UCTE (Union for the Coordination of Transmission of Electricity) is the association of the TSOs (Transmission System Operators) operating within the synchronous system of mainland Europe. This organization helps to coordinate the national transmission grids that serve a total of 500 million of users across 23 countries. To help maintaining security and quality of the electricity supply, each TSO has to provide some ancillary services according to the recommendations of the UCTE. Among these services, frequency control maintains the balance between generation and consumption by keeping in reserve a certain amount of active power from some generators. The frequency, which is the same across an interconnected system, is a measure of the balance between production and consumption. Several controls are usually used to adjust the system frequency 0. Within the UCTE, the primary frequency control reserve is the production capacity that is automatically activated and fully deployed within 30 seconds after a sudden change in frequency. The primary frequency control reserve is 3,000 MW for the whole UCTE. This value has been chosen to respond to realistic incidents that could occur in the continental European grid. If the security of the system cannot be maintain anymore with the sole reserves, the TSOs use automatic load shedding according to the frequency reached. Load shedding starts at 49 Hz in order to stop any frequency drop before reaching the point of no return, which is the critical threshold of disconnection of production units (fixed at 47.5 Hz by the UCTE). Table 3 shows the load-shedding plans recommended by the UCTE (usually, the considered loads are those connected to distribution network apart from priority loads).

TABLE 3 : UCTE RECOMMENDED LOAD SHEDDING PLAN



Frequency reached (Hz)	Load disconnection
49.0	From 10 to 20 % of all the load
48.7 or 48.5	Additional disconnection from 10 to 15 % of the remaining load
48.4 or 48.0	Additional disconnection from 10 to 15 % of the remaining load

Therefore, there is a common set of rules concerning the load disconnection across continental Europe. In case of a sudden frequency change, the whole European power system will see the deviation and will react in a coordinated way. However, due to the differences in the grid connection rules, dispersed generation may not behave in the same way across Europe.

III. DECOUPLING PROTECTION SYSTEMS

In most of the European countries, the rules forbid islanded operation of DG on distribution networks in order to guarantee the quality level of the electricity supply, and more specifically to prevent DG units from:

- supplying power to customers under abnormal voltage and/or abnormal frequency conditions;
- causing false couplings when isolated networks are reconnected to the main network of the distribution company.

More specifically, generating plants connected to distribution networks should be equipped with decoupling protection systems in order to:

- ensure that the protection and automatic control systems fitted by the Distribution System Operator (DSO) in the network are able to operate properly;
- prevent operation of isolated networks under no-fault conditions, thus preventing the DG units to supply power to other users under abnormal voltage and frequency values and avoiding false couplings when these networks are reconnected to the main distribution network;
- instantly disconnect DG plants in the event of a fault occurring during the special operating conditions which apply when live work is being carried out on the MV-overhead network.

These decoupling protection systems must be coordinated with the Distribution System Operator’s (DSO) protection scheme and should be able to detect the following situations:

- islanded operation without fault;
- phase-to-ground faults;
- phase-to-phase faults for MV networks and faults between conductors (phase and/or neutral) for LV networks;
- risk of false couplings;
- faults on the HV network (transmission). Indeed, when the sum of the maximum active power of all the generating plants connected to a HV/MV substation becomes significant (for instance larger than 12 MW), the DSO should take appropriate measures to ensure the safety of people and equipment in case of faults occurring on the HV side.

The DSO specifies to the producer the performance which is expected from the decoupling protection.

Presently, decoupling protections are mainly based on over- and under voltage, over and under frequency criteria and in some cases on “inter-tripping”, i.e. on the use of an automatic control linked with the protections implemented at the substation level (such as the feeder protection or other protections, which may lead to the islanded operation of DG units on some parts of the distribution grid).

A. OPERATING PRINCIPLES

The decoupling protections comprise a group of relays with a certain number of functions among which :

- “maximum zero-sequence voltage” function;
- “minimum phase-to-phase voltage” functions or three “minimum phase-to-neutral voltage” functions (one for each of the three network phases);
- “maximum phase-to-phase voltage” function;
- “minimum (and maximum) frequency” function;
- “maximum (or minimum) active power return” function;
- “inter-tripping” function.

When a frequency or a voltage threshold is reached, a decoupling order is transmitted to the decoupling switch of the DG.

Relays and functions actually implemented in a DG plant depend on the decoupling protection type. Moreover, some (frequency and/or voltage) functions may be instantaneous or delayed.

For a particular DG plant, the choice of the decoupling protection type results from a study made by the DSO which takes into account the generating plant power and the network (LV or MV) to which the generating plant is connected.

IV. COMPARISON OF DECOUPLING PROTECTIONS FOR DG ACROSS SOME EUROPEAN COUNTRIES

A. FRANCE

Technical rules for the grid connection are specified in legislative documents. In February 2000, following the publication of the French law on electricity 0, new government decrees concerning the technical specifications for the connection of “installations” to the distribution 0 and transmission 0 networks were issued. These texts are complemented by technical reference guides that have been prepared by the Transmission and Distribution System operators (DSO 0 and TSO grid codes 0).

Presently, different types of decoupling protections are defined for use with DG plants. Depending on the network voltage (LV or MV), the type of network (lines or underground cables) and the feeder, frequency relays can be set to be triggered for a frequency outside a wide (47.5-51 Hz) or a narrow (49.5-50.5 Hz) range.

There has been approximately 6 300 MW of decentralized production installed at the end of 2005. For a significant part, the threshold is set to 49.5 Hz-50.5 Hz.

Now, new wind farms, which are connected to the distribution grid (20 kV), are connected through underground cables to dedicated feeders for which the threshold is set to 47.5 Hz-51 Hz.

However, the installations with the decoupling protection using the wide range (47.5–51 Hz) can sometimes be unexpectedly disconnected, either because of the prime mover’s physical characteristics, or because of the settings of the internal protections in the installation.

B. GERMANY

In Germany, the reference document for the connection to the distribution grid is the : « Distribution Code 2003 - Rules on access to distribution networks » (2003) 0. More specifically, the DSOs refer also to different technical guides 0.

The DSO determines the threshold values in the 48 – 52 Hz range, in regards to the nominal voltage / frequency of the network. The producer are free to set stricter values inside these limits.

C. SPAIN

In Spain, the Ministerial Order September, 5th 1985 "Administrative and technical specifications for grid connection and required performance of hydraulic power plants up to 5000 kVA and electrical self-generation" 0 gives the conditions for the connection of small power plant.

All the DG connected to the distribution network should be equipped with frequency relays that can be set to detect frequency outside 49 to 51 Hz.

V. RISKS OF DECOUPLING PROTECTIONS TRIPPING DURING SEVERE GRID DISTURBANCES

The DSO of each country specifies the settings of the decoupling protections according to the network protection scheme. In case of a major frequency deviation, the decoupling protections will react differently across European countries leading to possible unwanted disconnections. Thus the risk of losing a significant part of dispersed generation following a frequency problem exists today. In case of a significant frequency drop, this loss may lead to an aggravation of the disturbance.As an example, during the Italian black out of September 2003, the sudden decrease of frequency resulted in the loss of 1 700 MW at a frequency of 49 Hz (see below). In the same way, the outage of European grid on November 2006 led to the tripping of a significant DG capacity in the western part of the UCTE (e.g. in Spain with the loss of 2 800 MW of wind power) as frequency dropped at 49 Hz.

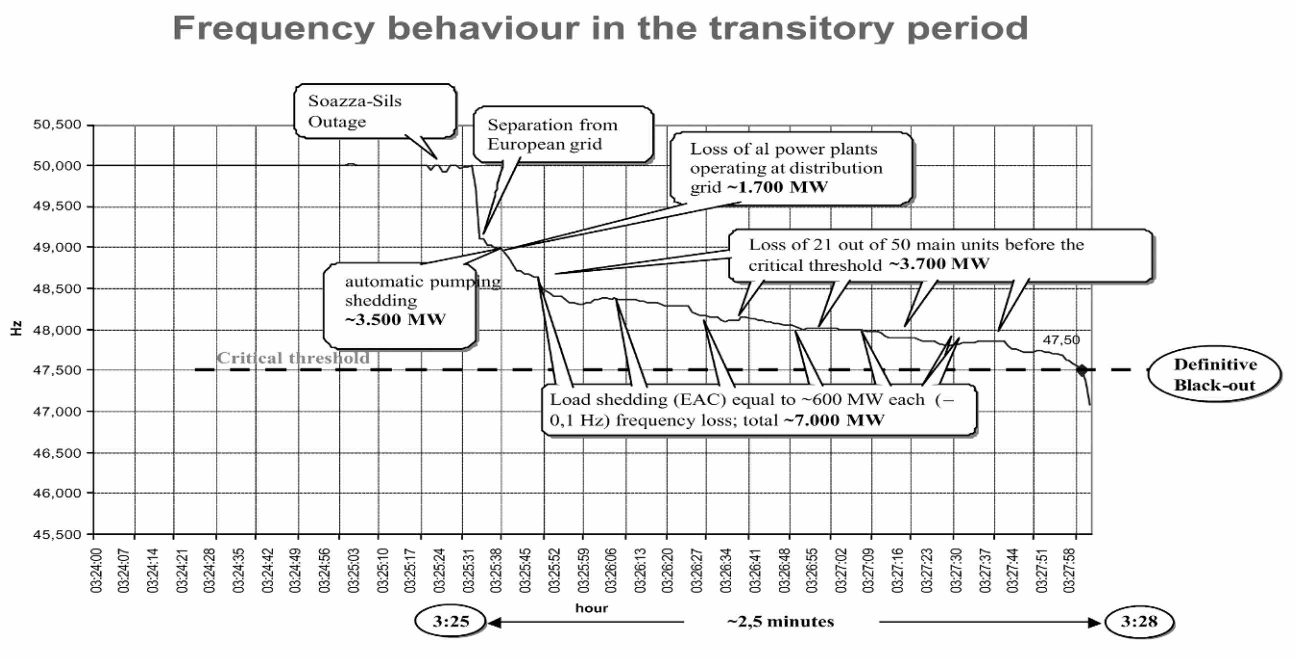


Figure 1 Frequency Behavior of Italian Grid before Black-Out 0

A concerted modification of the connection rules could be discussed to lower this risk. This situation is not optimal considering that, depending on the sources, DG could be used to provide some frequency support, since DG has the ability to remain connected during such grid disturbances if not disconnected by decoupling protections.

The design of decoupling protections may therefore be improved so as to distinguish a real islanding situation (disconnection expected) from a large-scale frequency disturbance. In the second case, the power system security requires the ability to keep as much generation as possible connected to the grid.

To do so, it is for example possible to change the threshold values of decoupling protection. A compromise would have to be drawn between security in case of severe disturbances (low probability), and risks related to islanded operations (higher probability).

Another solution would possibly rely on the use of more sophisticated protections, based on other criteria (e.g. frequency or voltage rate of change, grid impedance…), or taking into account a pre-defined reference frequency vs. time characteristic.

Up to now, the DG could not be centrally dispatched and thus could not participate in load following and frequency support. High penetration rate emphasized the need for advanced generation management, in order to allow participation to frequency control. That is why the following section describes some possible solutions for frequency control, applied to wind power production, which is today dramatically increasing.

VI. WIND FARMS PRODUCTION MANAGEMENT BY CONTROL SYSTEMS

For DG that has the ability to remain connected to the grid during major system frequency disturbances, further advanced control functions may be considered ensuring an effective contribution to frequency support.

A. NEW GRID CODES REQUIREMENTS ON FREQUENCY CONTROL

Nowadays, many grid codes define new requirements on wind farms control. These power plants may be asked to contribute to frequency control, as required for other technologies.

Thus, in Ireland and Denmark, wind power plants are expected to change their active power output in case of frequency variations.

The power/frequency curve described in the Irish grid code is reproduced on Figure 2 with the set-points defined as described on Table 4.

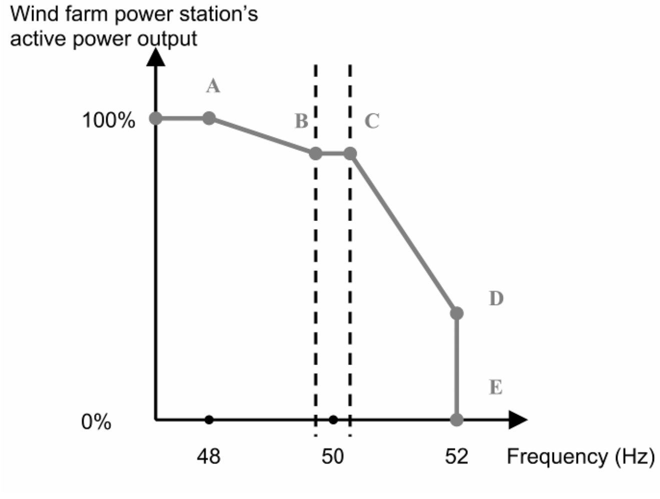


Figure 2 : Active Power vs. Frequency Curve for Wind Farms, According to the Irish Distribution Code 0

TABLE 4 : SET POINTS OF WIND FARM IN IRISH GRID CODE 0

	***Frequency** (Hz)*		***Available Active Power** (%)*	
			MEC ≥ 10 MW	5 MW ≤ **MEC** <10 MW
F_A	47.0-51.0	P_A	50-100	100
F_B	49.5-51.0	P_B	50-100	100
F_C		P_C		
F_D	50.5-52.0	P_D	20-100	20-100
F_E		P_E	0	0

MEC: Maximum Export Capacity

The power-frequency response curve is specified by the TSO.

Since the maximum generation is limited by the available wind resource, wind turbines must work at reduced frequency in nominal conditions, so as to be able to contribute to upward frequency regulation.

Furthermore, the Danish grid code 0 defines some other sophisticated control strategies for wind farms connected on transmission grid (above 100 kV). Among them, the so-called “balance regulation” allows the constitution of a spinning reserve through a decrease in active power output.

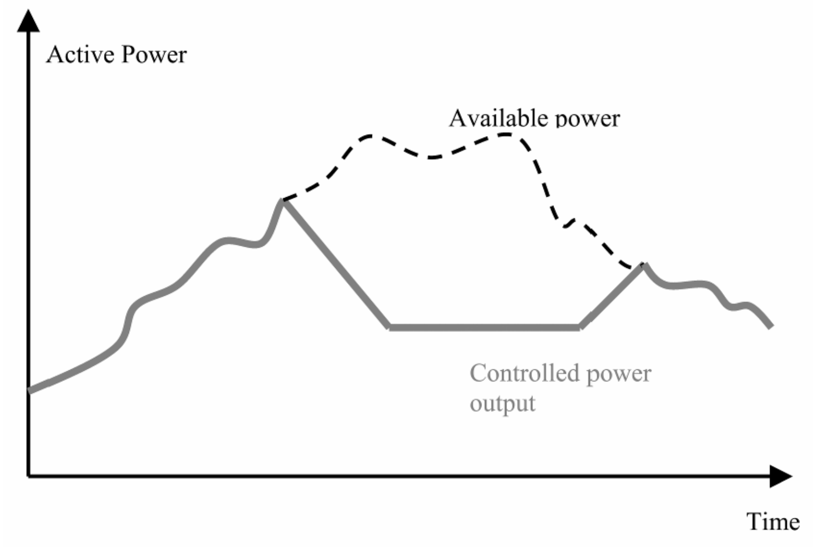


Figure 3. Balanced Regulation [“&]

It would be thus possible to contribute to primary frequency control by regulating frequency upwards as well as downwards.

B. EXISTING CONTROL SYSTEMS FOR WIND FARMS AND POSSIBLE CONTRIBUTION TO FREQUENCY REGULATION IN CASE OF DISTURBANCE

Many systems, which are currently being implemented for wind farm control, take into account requirements related to grid integration.

As an example, the German TSO E.oN has developed a “generation management” system 0 which aims at relieving constraints on transmission grid. A reduction signal may be sent to participating power plants based on renewable energy sources (1 100 MW of installed capacity in E.oN zone) all over a region. In Spain, the TSO REE is also able to ask for a power output reduction in order to preserve system security 0.

Nevertheless, this kind of regulation was not designed for primary frequency control. For example, concerning E.oN congestion management, the requirement is a reduction of the power output in the range of 10 % of the grid connection capacity per minute (according to the high and extra-high voltage grid code).

Therefore, frequency regulation may more likely be implemented at the wind farm controller level. This is for example the case at the offshore wind farm of Horns Rev in Denmark, whose frequency regulation conforms to the requirements of the Danish grid code.

This frequency control is implemented on the wind farm's turbines and their monitoring and control, as described in Figure 3.

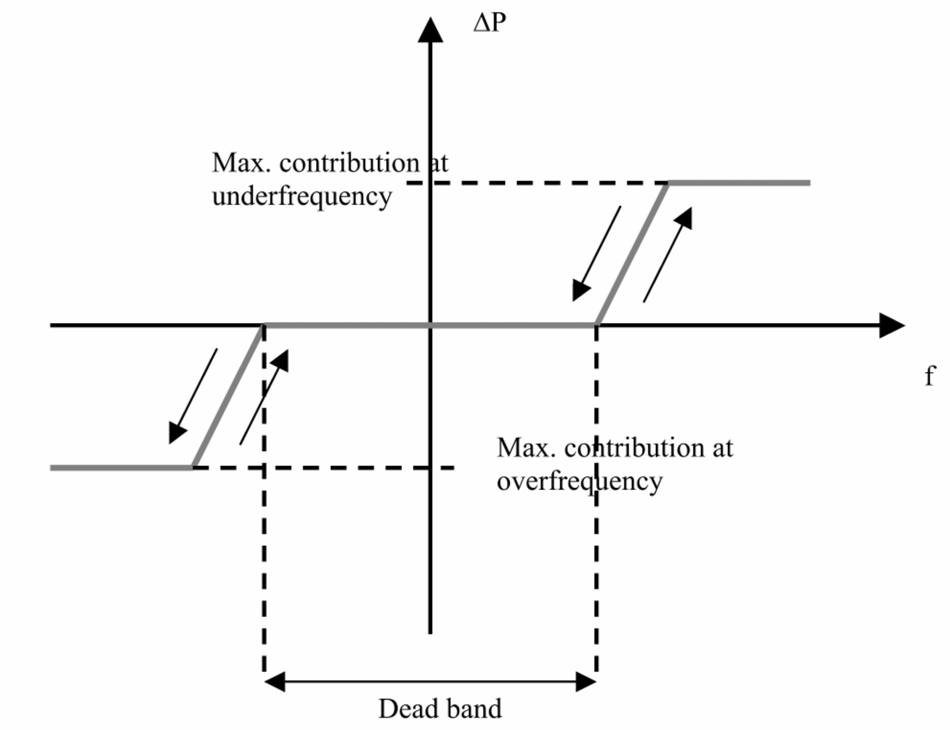


Figure 3 : Power/frequency curve of turbines at Horns Rev 0

VII. CONCLUSIONS

In this paper, the frequency behavior of DG is discussed. In particular, it can be seen that on one side, there is a common set of rules concerning the load disconnection across Europe but, on the other side, there is a lack of harmonization on the frequency behavior of DG, especially concerning the decoupling protections. Generally, it is the DSO that specifies the settings of the decoupling protections according to the network protection scheme. In case of a major frequency deviation, the decoupling protections will then react differently across European countries leading to possible unwanted disconnections. Thus the risk of losing a significant part of dispersed generation following a frequency problem exists today. A concerted modification of the interconnection rules would have to be discussed to lower this risk. Moreover, instead of disconnecting in case of frequency problem, DG can provide an active contribution to power system security by ensuring a frequency control. Indeed many grid codes (Ireland and Denmark) are presently defining new requirements on wind farms control. Wind farms are asked to contribute to frequency control, as required for other technologies: they are expected to change their active power output in case of frequency variations. Different improvements in grid connection rules and DG's technical specifications are then under way in Europe, all aiming to favor DG integration to the grid and taking advantage of its presence to ensure an active contribution to power system security.

VIII. ACKNOWLEDGMENT

The author gratefully acknowledges the contributions of B. Prestat, F. Dufourd, J. Duval, C. Duvauchelle, L. Capely and R. Hurel for their work on the original version of this document.

IX. REFERENCES

[1] CIGRE WG C6.01, “Development of dispersed generation and consequences for power systems”, July 2003.

[2] UCTE, “UCTE Operation Handbook”, v2.5E, 20 Jul. 2004. Available: http://www.ucte.org/pdf/ohb/Operation_Handbook_20.07.2004.pdf

[3] B.Meyer, Y. Bamberger, I. Bel, “Integration of Distributed Energy Resources”, IEEE 2006 General Meeting, Montreal, Canada, 18-22 June 2006

[4] R. Belhomme, C. Corenwinder, EDF R&D, “Wind power integration in the French distribution grid -Regulations and network requirements”, Proceedings of NWPC’04 Nordic Wind Power Conference, Chalmers University, Göteborg, Sweden, March 1-2, 200

[5] http://www.industrie.gouv.fr

[6] “Loi No. 2000-108 du 10 février 2000 relative à la modernisation et au développement du service public de l’électricité”, Journal officiel de la République Française, No. 35, pp. 2143-2159, February 2000. Available : http://www.industrie.gouv.fr/

[7] “Directive 96/92/EC of the European Parliament and of the Council of 19 December 1996 concerning common rules for the internal market in electricity”, Official Journal of the European Union, No. L 027 ,pp. 0020 – 0029, January 30, 1997.

[8] Ministère de l'économie, des finances et de l'industrie, “ Décret n° 2003-229 du 13 mars 2003 relatif aux prescriptions techniques générales de conception et de fonctionnement auxquelles doivent satisfaire les installations en vue de leur raccordement aux réseaux publics de distribution”, Journal Officiel de la République Française, No. 64, pp. 4589-4592, March 2003. Available : http://www.legifrance.gouv.fr .

[9] Ministère de l'économie, des finances et de l'industrie, “Décret n° 2003-588 du 27 juin 2003 relatif aux prescriptions techniques générales de conception et de fonctionnement auxquelles doivent satisfaire les installations en vue de leur raccordement au réseau public de transport de l'électricité”, Journal Officiel de la République Française, No. 151, pp. 11110-11113, July 2003. Available : http://www.legifrance.gouv.fr

[10] http://www.edfdistribution.fr/

[11] http://www.rte-france.com/

[12]“Distribution Code 2003 - Rules on access to distribution networks” (2003), VDN Verband der Netzbetreiber, 2003, available : http://www.vdn-berlin.de/

[13] “Eigenerzeugungsanlagen am Mittelspannungsnetz” and “Erzeugungsanlagen am Niederspannungsnetz”, VDN/VDEW, 1998

[14] Ministerial Order September, 5th 1985 “Administrative and technical specifications for grid connection and required performance of hydraulic power plants up to 5000 kVA and electrical self-generation”

[15] “Interim Report of the Investigation Committee on the 28 September 2003 Blackout in Italy”, UCTE, October 2003, available: www.aei.it

[16] “Distribution code”, Distribution System Operator ESB Network (Ireland), February 2006, available on http://www.esb.ie/

[17] “Wind turbines connected to grids with voltages above 100 kV” and “Wind turbines connected to grids with voltages below 100 kV”, Danish TSO Eltra and Elkraft, 2004, available: www.wt-certification.dk

[18] P.Sorensen et al., “Modeling of wind farm controllers”, EWEC 2006 February 27 - March 2nd, Athens

[19] "Netzsicherheit und erneubare Energien im Einklang: Erzeugungsmanagement bei E.ON Netz", E.ON Netz, 2006, available : www.eon-netz.com

[20] G.Gonzalez et al., REE and Iberdrola, "Experience integrating and operating wind power in the peninsular spanish power system. Point of view of the transmission system operator and a wind power producer", CIGRE 2006, Paris, August 2006

[21] M. Rasmussen, "Grid Compliance and how Vestas turbines can meet the new grid Code demands", presentation by Vestas at the New Generation Technologies and the GB Grid Codes Forum, 2004, available : www.ofgem.gov.uk

X. BIOGRAPHIES

Bruno Meyer holds degrees in physics from Unicamp (B.Sc.), Sao Paulo (M.Sc.) and Edinburgh (Ph.D.). He is presently Director of Power Systems Technology and Economics at EDF R&D. He joined EDF in 1985 where he has held several positions in the R&D Division as well as in the Marketing and Commerce Divisions. He is a Senior Member of IEEE, and is Region 8 Representative for IEEE PES. He is also an Eminent Member of Cigré.

Received January 27 2007-01-27

7. IMPACT OF MICROGRIDS ON SERVICE QUALITY; (PAPER 07GM1062)

Evangelos Dialynas and Nikos D. Hatziargyriou, National Technical University Athens, Athens, Greece

Abstract**--** Microgrids comprise Low Voltage distribution systems with distributed energy sources, such as micro-turbines, fuel cells, PVs, etc., together with storage devices, i.e. flywheels, energy capacitors and batteries, and controllable loads, offering considerable control capabilities over the network operation. These systems are interconnected to the Medium Voltage Distribution network, but they can be also operated isolated from the main grid, in case of faults in the upstream network. One of the key benefits of Microgrids is the potential to increase service quality by providing generation redundancy, where most needed. In this paper the effects of Microgrids in increasing the service quality are assessed by calculating a set of reliability indices on a typical LV network with and without DG sources connected and coordinated in islanded operation.

I. INTRODUCTION

Microgrids comprise Low Voltage distribution systems with distributed energy sources, such as micro-turbines, fuel cells, PVs, etc., together with storage devices, i.e. flywheels, energy capacitors and batteries, and controllable loads, offering considerable control capabilities over the network operation [1]. These systems are interconnected to the Medium Voltage Distribution network, but they can be also operated isolated from the main grid, in case of faults in the upstream network. From the customer point of view, Microgrids provide both thermal and electricity needs, and in addition enhance local reliability, reduce emissions, improve power quality by supporting voltage and reducing voltage dips, and potentially lower costs of energy supply.

The reliability of the electricity supply has become a key factor for economic wealth. The network design practices, established by the vertically integrated utilities, dominantly shaped the service quality profiles seen by end customers. Satisfying and responding to customer requirements is one of the key features of the emerging deregulated electricity markets. Because the quality of electricity supply service perceived by the end customer is mainly influenced by the performance of the distribution network, there is growing emphasis, particularly in Europe, on performance driven regulation of distribution businesses. The allowable revenue for the network operators is a function not only of the operating and capital costs incurred by the network owner in providing the service, but will also depend on the quality of customer service.

Some of the established indices used to measure the quality of service seen by the end customer are frequency of outages and their duration. The average number of interruptions per customer per year and the total annual duration of interruptions per individual customer are often used as the indicators of performance of electricity systems in the regulatory context.

Present distribution networks are designed such that performance of the medium and low voltage networks have a dominant impact on the quality of service seen by the end customers, while faults in HV distribution and transmission networks do not normally affect the continuity of supply of customers connected to MV and LV networks. MV voltage networks are generally build following so called N-1 security criterion, meaning that an interruption caused by a fault of a single MV network component, should be restored much more quickly, by switching (manually or automatically, depending on the size of the load lost) the lost load onto a sound part of the network. This clearly requires some redundancy in MV networks. Similarly, HV networks are often built with respect to N-2 security criterion. In the majority of EU countries, more than 80% of the customer interruptions and the customer minutes lost have their cause at one of MV and LV levels. The significant impact that these networks have on the number of duration of interruptions is primarily driven by the radial design of these networks, driven by the traditional network design principles. Following this design principle there is no redundancy in LV networks and the duration of outage caused by a fault in the LV network is determined by the repair time of the faulty component. Clearly, relatively small amount of loads (such as individual domestic dwellings) are provided with the lowest level of service quality.

One of the key benefits of Microgrids is the potential to increase service quality by providing generation redundancy, where most needed. The capability of Microgrids to operate in islanded mode can potentially relieve the effects of faults in the upstream networks. This capability requires sophisticated protection, control and communication infrastructures, in order to be able to isolate external faults and provide stable autonomous operation. In this paper, the effects of Microgrids in increasing the service quality are assessed by describing an efficient computational methodology that calculates a set of reliability indices on a typical LV network with and without DG sources connected and coordinated in islanded operation.

II. MONTE-CARLO SEQUENTIAL SIMULATION APPROACH

The Monte–Carlo sequential simulation approach is a stochastic simulation procedure and can be used for calculating the operational and reliability indices of a power system by simulating its actual behavior [2], [3]. The problem is treated as a series of real experiments conducted in simulated time steps of one hour, which is considered adequate for a power system reliability analysis since the number of system changes within that time period is generally small. A series of system scenarios is obtained by hourly random drawings on the status of each system component and determining the hourly load demand. The operational and reliability indices are calculated for each hour with the process repeated for the remaining hours in the year (8760 hours). The annual reliability indices are calculated from the year's accumulation of data generated by the simulation process. The year continues to be simulated with new sets of random events until obtaining statistical convergence of the indices. The sequential simulation approach steps through time chronologically, by recognizing that the status of a system component is not independent of its status in adjacent hours. Any event occurring within a particular time step is considered to occur at the end of the time step and the system state and statistical counters are updated accordingly. This approach can model any issues of concern that involve time correlations and can be used to calculate frequency and duration reliability indices. One very important advantage of the sequential simulation is the simplification of a particular system state simulation by considering information obtained from the analysis of the previous system states. This can only be applied when the system states change very little from one time step to the next. Such an assumption can be made for the power transmission and distribution systems that do not suffer large changes very often.

A computational method has been developed at NTUA for the reliability assessment of power systems applying the above principles of the Monte - Carlo sequential simulation approach [3]. This method is used as the basic method for developing the improved and efficient methodology being described in this paper. The following main features were incorporated in the improved methodology:

- The pseudo-random numbers are generated applying the multiplicative congruent method. The antithetic sampling technique is also used for variance reduction.
- The classical two-state Markovian model is generally used to represent the system component operation while actual or equivalent generating units may be represented by a multiple state model in order to recognise their derated states. Common-cause transmission and distribution line outages may be also considered.
- The generation system includes a number of plants while each plant consists of a number of single generating units.
- The generating units are considered to be taken out for scheduled maintenance during certain time periods of the year and their appropriate data are specified.
- A generation rescheduling technique is applied after the occurrence of a generating unit outage for modifying the output of appropriate generating units in order to compensate for loss of generation.
- The production cost of the generation system is calculated by using the respective fuel consumption functions with regard to the power output of the appropriate generating units.

The prime objective of the above computational method is to calculate appropriate indices that quantify the operational and reliability performance of a power system. The following indices are considered to be the most important system and load-point indices while they have the corresponding units and acronyms in parentheses:

- Loss of load expectation (LOLE) in hours/year.
- Loss of energy expectation (LOEE) in kWh/year.
- Expected demand not supplied (EDNS) in kW/year.
- Frequency of loss of load (FLOL) in occ./year.
- Average duration of interruptions (DINT) in hours/occ.

It must be noticed that the above units of the reliability indices have been adopted appropriately in order to apply for low voltage distribution networks where Microgrids are used.

III. INTERRUPTION COST FUNCTIONS OF POWER SYSTEM CUSTOMERS

The analysis of the interruption costs for the different categories of customers is an important issue associated closely with justifying new facilities, quality and reliability of electrical power systems. The ability to assess the power supply reliability has been well established [4] – [6]. This assessment is a very difficult task to conduct directly and, alternatively, the costs and losses incurred by the customers as a result of a power supply interruption can be quantified more easily. These unreliability costs are not identical to the reliability worth but they can be considered as their representative and realistic measures since they constitute a lower bound.

The customer survey approach has been utilized as the basic approach to investigate the direct short-term impacts and costs incurred by the electric power utility customers as a result of random supply interruptions [4]. The basis of this approach is that customers are in the best position to understand and assess how the costs due to supply interruptions impact their activities that depend upon electricity. A customer survey approach was designed, carried out and utilized by the Energy Systems Laboratory of the National Technical University of Athens (NTUA) in order to conduct an interruption cost assessment study of all the different sectors of power customers in Greece [5], [6]]. This study presents the results that were obtained for the industrial and commercial sectors during the last three years. These results mainly include the interruption cost data and their variation according to the various characteristics of the interruption events and the power customers.

Two types of interruption costs are reported and they are known as the average cost per interruption (€/int) and the cost normalised by annual peak demand (€/kW) which is known as ‘aggregated averages’. The aggregated average interruption cost is calculated as the ratio of the sum of interruption costs and the sum of the respective peak load demand for all customers. The approach of aggregated averages is used to offset the impact of small numbers for large or small customers, and the impact of small number of respondents who reported large or small costs. The estimates of the interruption cost are obtained from the direct cost assessment of the information being included in the respective cost questions of the questionnaires for each interruption duration being assumed. Therefore, interruption cost functions are determined for each customer category in a discrete form. Such functions have been reported assuming seven interruption durations (momentary, 3 minutes, 20 minutes, 1 hour, 2 hours, 4 hours, 1 day).

IV. RELIABILITY MODELLING AND EVALUATION OF MICROGRIDS

An improved and efficient computational methodology was developed for the reliability and cost assessment of microgrids that integrate distributed generation (DG) sources of various technologies [7]. The operation of DG sources is simulated by the classical two-state Markovian model while their operational performance is quantified by taking into account the events which occur when they fail to produce their available output capacity due to their existing limitations (failure events, maintenance). Failure events on the components of the distribution network are not considered since the respective feeder is disconnected from the system causing the loss of supply to all respective customers and the disconnection of all relevant DG sources.

It is assumed that a number of wind parks are installed at various geographical sites and each wind park consists of a certain number of groups of identical wind generating units. These wind parks are connected to the appropriate system nodes applying the existing connection rules. The average hourly wind speed of a geographical site is represented by an appropriate normal distribution which means that the values of the mean and standard deviation need to be given as input data for each hour of the year (8760 points). For simplicity reasons, the standard deviation may be assumed constant (e.g. 5%). The actual wind speed value for a particular simulated time period is determined using appropriate random numbers. The available power output of a wind generating unit at any time period is calculated by using its appropriate curve expressing the power output in respect to the wind speed of the respective geographical site.

The total wind power generation of the system at any simulation time period of the year is not allowed to exceed a certain fraction of the respective system load demand. This fraction expresses the wind penetration constraint (margin) being assumed in order to retain acceptable service reliability, security and efficient operation of the system supply source. If the total wind power generation of the system is higher than the limiting value, this generation level is necessary to be reduced. In this case, it is considered that an appropriate order will be given by the system control centre to each wind park to reduce its total power output by a certain amount so that the wind penetration margin is satisfied. This amount of power output is calculated assuming that the same percentage of the total power output is applied for each park. As a result, a certain number of wind generating units in each wind park are assumed to be either disconnected from the system or decrease their power output using appropriate procedures that take into account the technical characteristics of the respective units.

It is assumed that a number of photovoltaic parks are installed at different geographical sites and are connected to appropriate system nodes applying the existing connection rules. Each photovoltaic system consists of a certain number of groups of identical photovoltaic units. The average hourly solar radiation in a geographical site is represented by the normal distribution (or other more suitable distribution) while its actual value for a particular simulated time period is determined by using appropriate random numbers. Additional appropriate models have been developed and incorporated for modeling all necessary characteristics (slope, ground reflectance, temperature modification factor, soiling factor, etc.) for calculating the power output of each photovoltaic unit applying the solar radiation data of the respective geographical site.

The available power of the system supply source at any simulated time period is represented by an appropriate normal distribution which means that the values of the mean and standard deviation need to be given as input data. Its actual value for a certain time period is determined using appropriate random numbers.

An appropriate algorithm was developed for simulating the dispatch procedures of system supply source and DG units in order to supply the respective load demand in each simulation time period. The available DG units (not being in a repair or maintenance state) are only taken into account. The available power output of photovoltaic systems and wind generating units (applying the existing penetration margin) are assumed to supply the system load demand as a first priority since it is assumed that their operating cost is zero. The remaining load demand is usually allocated to the system supply source since its operating cost is expected to be lower than that of the microturbines and fuel cells. However, when its operational cost is greater than the respective cost of the available microturbines or fuel cells, these units are called on to operate first during the respective time periods. Finally, when the system supply source is inadequate to supply the remaining load demand and additional power generation is required due to failures being occurred, microturbines and fuel cells are called on to operate in order to supply the remaining load demand according to their operating cost.

The available spinning reserve of the system for each simulation time period is calculated by taking into account the operational features of system generation during the previous time period. For this purpose two criteria are used. Criterion 1 assumes that the spinning reserve is equal to a certain percentage of the total wind power generation in order to compensate sudden losses of this output in case of very fast wind speed changes. Criterion 2 assumes that the spinning reserve is equal to a certain percentage of total system load demand in order to compensate for a sudden loss of system supply source (reliability criterion). The actual value for the spinning reserve is calculated as the greatest value being obtained by using the two criteria.

The system reliability worth is quantified by calculating a set of appropriate indices that take into account the interruption cost functions of the various customers' categories of the system. An efficient algorithm is incorporated into the developed methodology having the following main steps:

- For each contingency that leads to a load curtailment at each system node the magnitude of load curtailment and the duration of contingency are calculated.
- The expected interruption cost to customers ECOST (in €/yr) that are connected at each system node can be obtained using its composite interruption cost function. This function is determined by taking into account the respective functions of all the customer categories being connected to the node.
- The expected system interruption cost IC (in €/yr) can be calculated by adding the respective indices ECOST for all system nodes. The interrupted energy assessment rate IEARN in Euro/kWh at each node can be calculated as the ratio of indices ECOST and LOEE for the node.
- The system index of IEARS (in Euro/kWh) can be obtained by adding the products of index IEARN of each node and its fraction of system load being taken.

Using the above described computational methodology, the following additional system indices are calculated which have the corresponding units and acronyms in parentheses**:**

a) Six indices quantifying the system generation capability:

- Expected total energy supplied by the system supply source (EGSM) in MWh/year
- Expected total energy supplied by the generating units of various DG sources (EGWS) in MWh/year.
- Expected energy supplied by wind generating units (EGWT) in MWh/year.
- Expected energy supplied by photovoltaic generating units (EGPV) in MWh/year.
- Expected energy supplied by fuel cells (EGFC) in MWh/year.
- Expected energy supplied by microturbines (EGMT) in MWh/year.

b) Five indices quantifying the operational performance of the overall generation capability of DG sources, each type of DG sources and each individual DG source site by taking into account the events that may occur (failures, maintenance). These indices have the respective acronyms (WT – wind, PV – photovoltaic, FC – fuel cells, MT – microturbines, DG - overall):

- Expected energy not supplied during the events being occurred (ENSWS, ENSWM) in kWh/year.
- Expected annual duration of the events being occurred (DNSWS) in hours/year.
- Expected load demand not supplied during the events being occurred (PNSWS) in kW/occ.
- Frequency of events being occurred (FNSWS) in occ./year.

c) Three indices quantifying the available spinning reserve by applying the respective criterion:

- Available spinning reserve (AVSPRES) as a percentage of the respective load demand.
- Percentage of applying Criterion 1 for evaluating spinning reserve (FWIND).
- Percentage of applying Criterion 2 for evaluating spinning reserve (FLOAD).

d) Two indices for system reliability worth:

- Interruption Cost (IC) in Euro/kWh.
- Interrupted energy assessment rate of the system (IEARS) in Euro/kWh.

It must be noticed that the above units of the reliability indices have been adopted appropriately in order to apply for low voltage distribution networks where Microgrids are used.

V. ASSESSMENT STUDIES

The developed computational methodology was applied for conducting reliability assessment studies on a typical LV power distribution network operating as a Microgrid. The system peak load demand is equal to 190 kW. The network topology consists of three feeders supplying commercial, residential and industrial customers. A certain number of DG sources exists using various technologies. One wind turbine exists with generating capacity equal to 15 kW and two photovoltaic parks are installed at two different system sites with five generating units having various power output capacities and total generating capacity being equal to 13 kW. Additionally, there are one microturbine and one fuel cell with generating capacity equal to 30 kW each. An annual average operating cost function of the system is assumed. The coefficient for the operating cost for the microturbines and fuel cells are assumed to be equal A=0.01, B=5.16, C=46.1 for microturbines and A=0.01, B=3.04, C=130 for fuel cells.

This system provides a good example for illustrating the different operating features of DG sources. Base case study (Case 1) assumes that the capacity of the system supply source follows a normal distribution with an average value equal to 100% of the system peak load demand and a standard deviation equal to 5%. No wind penetration margin and no criteria for spinning reserve are applied. The following eight alternative case studies are also considered:

Case 2: As in case 1 but the average value of the capacity of the system supply source is decreased to 90% of the system peak load demand.
Case 3: As in case 1 but the average value of the capacity of the system supply source is decreased to 80% of the system peak load demand.
Case 4: As in case 1 but the average value of the capacity of the system supply source is decreased to 70% of the system peak load demand.
Case 5: As in case 3 but the power output of wind generating units is increased by 15 kW (100%).
Case 6: As in case 3 but the power output of photovoltaic parks is increased by 13 kW (100%).
Case 7: As in case 3 but the power output of microturbines is increased by 15 kW (50%).
Case 8: As in case 3 but the power output of fuel cells is increased by 15 kW (50%).
Case 9: As in case 1 but the output of wind generating units is increased by 30 kW (200%) and a wind penetration margin equal to 15% is applied. The available spinning reserve is calculated assuming a percentage equal to 100% of total wind power generation according to Criterion 1 and a percentage equal to 10% of the system load demand according to Criterion 2.

The results being obtained for the above nine case studies are presented in the Table A1 of the Appendix. A considerable number of comments can be drawn from these case studies and the most important ones are the following:

- The decrease of the average value of the system supply source capacity decreases the system reliability performance as indicated by the respective results for cases 1, 2, 3 and 4. Additionally, the expected energy produced by microturbines and fuel cells increases. The expected energy produced by renewable energy sources remains the same since it depends only on their technical features and the characteristics of the respective geographical sites at which they are installed.
- The addition of wind generating units always improves the system reliability indices since there is more available power generation to supply the load demand. Furthermore, the energy supplied by wind generating units increases while the energy supplied by the system supply source decreases significantly.
- The addition of photovoltaic parks, microturbines and fuel cells improves the system reliability indices, since there is more available power generation to supply the load demand and increases the system generation indices due to the respective sources.

- When a wind penetration margin is applied and as its respective level decreases the system reliability performance and the expected energy produced by wind generating units also decrease while the energy supplied by the system supply source increases significantly.

VI. CONCLUSIONS

One of the most important aspects of the competitive electrical energy market is the operation of independent power producers that can be connected at any system voltage level. The increased use of renewable sources and more advanced technologies may significantly affect the operational characteristics and inevitably the reliability performance of power systems. This paper presents the results obtained from reliability assessment studies conducted for a power distribution system which is based on a typical LV system with multiple feeders. It is shown that the system adequacy is critically dependent on the reliability performance of the system supply source. In addition, a sufficiently large generation capacity of DG sources organized as a Microgrid can improve the system reliability indices in emergency conditions when additional power generation is required to supply the load demand.

VII. REFERENCES

[1] "MICROGRIDS – Large Scale Integration of Micro-Generation to Low Voltage Grids", EU Contract ENK5-CT-2002-00610, Technical Annex, May 2002, also at http://microgrids.power.ece.ntua.gr

[2] Billinton R., Allan R.N.,. "Reliability Evaluation of Power Systems", Plenum Press, New York, 1984.

[3] Dialynas, E. N., Koskolos, N. C, "Comparison of Contingency Enumeration and Monte - Carlo Simulation Approaches Applied to the Reliability Evaluation of Composite Power Systems", European Journal of Diagnosis and Safety in Automation, Hermes, Vol. 5, 1995, pp. 25 - 48.

[4] Tollefson G., Billinton R., Wacker G., Chan E., Aweya J., "Canadian Customer Survey to Assess Power System Reliability Worth", IEEE Transactions, PWRS-9, 443-450, 1994.

[5] Dialynas, E. N., Megalokonomos S.M., Dali V.C., "Interruption Cost Analysis for the Electrical Power Customers in Greece", CIRED 2001.

[6] Megalokonomos S.M., Dialynas, E. N., Dali V.C., "Interruption Cost Analysis for the Agricultural Electrical Power Customers in Greece", MedPower 2002, Athens, 2002.

[7] Jenkins, N., Allan, R., Crossley, P., Kirschen, D., Strbac, G., "Embedded Generation", IEE Publications, London, 2000.

VIII. BIOGRAPHIES

Evangelos Dialynas received the diploma in Electrical Engineering from NTUA in 1975 and the MSc. and PhD degrees from the University of Manchester, UK, in 1977 and 1979, respectively. He is presently Professor of electrical power systems at the School of Electrical and Computer Engineering of NTUA. His research interests are reliability modeling and evaluation, power system probabilistic assessment and power system operation. He is member of the Technical Chamber of Greece, senior IEEE member and distinguished member of CIGRE.

Nikos D. Hatziargyriou was born in Athens, Greece. He is professor at the Power Division of the Electrical and Computer Engineering School of NTUA. His research interests include dispersed and renewable generation, artificial intelligence techniques in power systems, modeling and digital techniques for power system analysis and control. He is a senior IEEE member, member of CIGRE SCC6 and member of the Technical Chamber of Greece.

APPENDIX

TABLE A1. SYSTEM RELIABILITY INDICES

Case Study Index	1	2	3	4	5	6	7	8	9
LOLE	16.160	16.165	16.255	17.974	14.971	16.042	14.593	14.582	16.497
LOEE	745.436	745.453	746.042	756.799	558.013	681.338	523.804	531.617	653.657
EDNS	36.18	36.17	36.06	33.59	28.80	33.11	27.18	27.42	31.05
FLOL	2.277	2.281	2.341	3.499	2.202	2.324	2.179	2.162	2.267
D	7.097	7.087	6.944	5.137	6.717	6.903	6.697	6.745	7.277
EGSM	660.778	660.755	660.319	657.177	553.576	638.615	650.371	653.709	643.038
EGWS	177.878	177.901	178.335	181.467	285.267	200.105	188.506	185.161	195.710
EGWT	107.418	107.418	107.418	107.418	214.997	107.424	107.116	107.376	124.823
EGPV	20.952	20.952	20.952	20.952	20.952	42.804	20.950	20.949	20.949
EGFC	23.061	23.061	23.078	23.251	22.824	23.077	23.022	30.405	23.271
EGMT	26.446	26.468	26.886	29.845	26.493	26.798	37.417	26.430	26.670
ENSWS-WT	6673.85	6673.85	6673.85	6673.85	13178.88	6673.85	6673.85	6673.85	12022.5
ENSWM-WT	4698.42	4698.42	4698.42	4698.42	9394.52	4698.42	4698.42	4698.42	7618.65
DNSWS-WT	491.642	491.642	491.642	491.642	941.906	491.642	491.642	491.642	1427.33
PNSWS-WT	13.587	13.587	13.587	13.587	13.754	13.587	13.587	13.587	7.975
FNSWS-WT	5.037	5.037	5.037	5.037	9.267	5.037	5.037	5.037	13.487
ENSWS-PV	852.65	852.65	852.65	852.65	852.65	860.786	852.65	852.65	852.65
ENSWM-PV	46.81	46.81	46.81	46.81	46.81	46.79	46.81	46.81	46.81
DNSWS-PV	1573.68	1573.686	1573.686	1573.686	1573.686	1581.40	1573.686	1573.68	1573.68
PNSWS-PV	0.517	0.517	0.517	0.517	0.517	0.518	0.517	0.517	0.517
FNSWS-PV	18.699	18.699	18.699	18.699	18.699	18.589	18.699	18.699	18.699
ENSWS-FC	9161.73	9161.73	9161.73	9161.73	8966.88	9122.40	9008.37	13234.3	8850.75
ENSWM-FC	2155.68	2155.68	2155.68	2155.68	2153.52	2160.0	2157.84	3237.84	2157.84
DNSWS-FC	305.391	305.391	305.391	305.391	298.896	304.080	300.279	581.312	292.05
PNSWS-FC	30.0	30.0	30.0	30.0	30.0	30.0	30.0	22.63	30.0
FNSWS-FC	5.615	5.615	5.615	5.615	5.424	5.555	5.478	10.491	5.587
ENSWS-MT	9292.92	9292.92	9292.92	9292.92	8381.19	8934.99	13373.78	9097.89	8761.5
ENSWM-MT	2157.84	2157.84	2157.84	2157.84	2160.0	2155.68	3234.6	2157.84	2160.0
DNSWS-MT	309.764	309.764	309.764	309.764	279.373	297.833	528.16	303.263	292.05
PNSWS-MT	30.0	30.0	30.0	30.0	30.0	30.0	22.7	30.0	30.0
FNSWS-MT	5.549	5.549	5.549	5.549	5.242	5.475	10.418	5.466	5.373
ENSWS-DG	25981.1	25981.15	25981.15	25981.15	31379.51	25580.28	30212.39	29909.0	30494.5
ENSWM-DG	9058.74	9058.749	9058.749	9058.749	13754.9	9059.256	10125.94	10133.0	11983.3
DNSWS-DG	2445.01	2445.014	2445.014	2445.014	2771.774	2440.424	2657.977	2654.75	3148.5
PNSWS-DG	10.693	10.693	10.693	10.693	11.314	10.516	11.382	11.284	9.608
FNSWS-DG	28.550	28.550	28.550	28.550	30.358	28.402	31.152	31.220	31.907
AVSPRES	-	-	-	-	-	-	-	-	14.88
FWIND	-	-	-	-	-	-	-	-	99.35
FLOAD	-	-	-	-	-	-	-	-	0.65
IC	1401.31	1401.33	1402.08	1415.95	1042.70	1273.67	965.64	979.39	1203.06
IEARS	1.880	1.880	1.879	1.871	1.869	1.899	1.844	1.842	1.841

8. IMPROVEMENT OF THE POWER SYSTEM RELIABILITY BY PREDICTION OF WIND POWER GENERATION (PAPER 07GM0397)

Kurt Rohrig[1], Bernhard Lange

Abstract: The integration of wind farms into the electricity grid has become an important challenge for the utilization and control of electric power systems, because of the fluctuating and intermittent behaviour of wind power generation. Wind power predictions improve the economical and technical integration of large capacities of wind energy into the existing electricity grid. Trading, balancing, grid operation and safety increase the importance of forecasting electrical outputs from wind farms. Thus wind power forecast systems have to be integrated into the control room of the transmission system operator (TSO). Very high requirements of reliability and safety make this integration especially challenging.

The pooling of several large offshore wind farms into clusters in the GW range will make new options feasible for an optimized integration of wind power. The geographically distributed onshore wind farms will be aggregated to clusters, for the purpose of operating these wind farms as one large (virtual) wind power plant. For this purpose, a new structure, the wind farm cluster will be introduced. All wind farms, which are directly or indirectly connected to one transmission network node will be associated to one wind farm cluster. The wind farm cluster manager (WCM) assists the TSO by operating the cluster according to the requirements of the power transmission system. Non-controllable wind farms within a wind farm cluster are supported by controllable ones.

Index terms -- Distributed generation, renewable energy, system services, forecasting, wind farm operat design, optimisation, modelling

I. INTRODUCTION

By the end of September 2006, more than 18,000 Wind Turbines (WTs) with an installed capacity of 19,500 MW generated approx. 22 TWh/year and supplied about 6.5% of the German electricity consumption [1], [2]. The targets of several countries of the European Union to increase the share of renewable energy production of the consumption to up to 40% [3] require a peak load contribution of 60%. This generation mix, dominated by Renewable Energy Sources (RES) leads to a continuous surplus in low demand periods (in the night). For wind power, these future scenarios expect temporal load coverage of more than 100 % [4]. Without new control options, these situations will effect system stability and run the risk of blackouts. To operate electricity systems with this high share of RES requires new operational strategies based on precise wind power forecasts and active contribution of Distributed Energy Resources (DER) to system reliability [5]. Without advanced and coordinated generation management, unexpected load flows will also appear frequently across borders, which requires an interoperability of the national grids.

The increasing penetration of wind energy in Germany, particularly in regions with low load has frequently direct impact on grid operation and congestion management. Special attention is to be put on the incorporation of the instantaneous and expected wind feed-in in the load flow calculations. The currently used forecast tools supply only one value per hour for wind power production for the entire control zone and/or the grid area. For the consideration of the wind feed-in for the load flow calculation however the exact values of in- and out-feed at each node of the high and extra-high voltage grid are

---

Dr. Kurt Rohrig is Head of the R & D Division Information and Energy Economy, Institut für Solare Energieversorgungstechnik, Kassel, Germany (k.rohrig@iset.uni-kassel.de)

Dr. Bernhard Lange is head of Information and Prediction Systems of the R & D Division Information and Energy Economy, Institut für Solare Energieversorgungstechnik, Kassel, Germany (blange@iset.uni-kassel.de) required. Deviations between real and predicted wind power feed-in, particularly in high wind periods can cause extreme variations of the load flow and require a re-valuation of the entire grid condition.

Today, the network operators avoid congestions by curtailing wind power. This so called wind generation management will be improved by the use of tailored forecast systems – adapted to grid calculation tools.

II. TOOLS AND INFORMATION TO ASSIST MAINS OPERATION

Wind power forecast is an integral part of the electricity supply system in Germany. The Wind Power Management System (WPMS), developed by ISET, is used operationally by all German transmission system operators [6], [7]. The system consists of three parts:

- The determination of the instantaneous value of wind power feed-in, which performs an up-scaling of current measured power values at representative wind farms to the total wind power production in a grid area.
- The day-ahead forecast of the wind power production by means of artificial neural networks (ANN). This is based on input from a numerical weather prediction (NWP) model.
- The short-term forecast, which additionally employs online wind power measurements to continuously produce an improved forecast for up to 8 hours ahead.

For the determination of the instantaneous value and the short-term wind power forecast, representative wind farms or wind farm groups have to be determined and equipped with online measurement technology. For the day-ahead forecast, only historical time series of measured power output of the representative wind farms are needed. For these locations, forecasted meteorological data obtained from a numerical weather prediction (NWP) model are used as input [8], [9]. The resolution of the forecast and the forecast horizon depends on the NWP data used. In Germany, currently an hourly resolution and a forecast horizon of 3 days are in operation.

Artificial neural networks (ANN) are used to forecast the wind power generated by a wind farm from the predicted meteorological data of the NWP model. The ANNs are trained with NWP data and simultaneously measured wind farm power data from the past, in order to ‘learn’ the dependence of the power output on predicted wind speed and additional meteorological parameters (figure 1). The advantage of artificial neural networks over other calculation procedures is that it ‘learns’ connections and ‘conjectures’ results, also in the case of incomplete or contradictory input data [10]. Furthermore, the ANN can easily use additional meteorological data like air pressure or temperature to improve the accuracy of the forecasts. The deviation (Root Mean Square Error RMSE in percent of the installed capacity) between the (day ahead) predicted and actually occurring power for the control areas of the German TSOs in the operational forecast system currently is about 6% of the installed capacity. The forecast error for the total German grid amounts to about 5%.

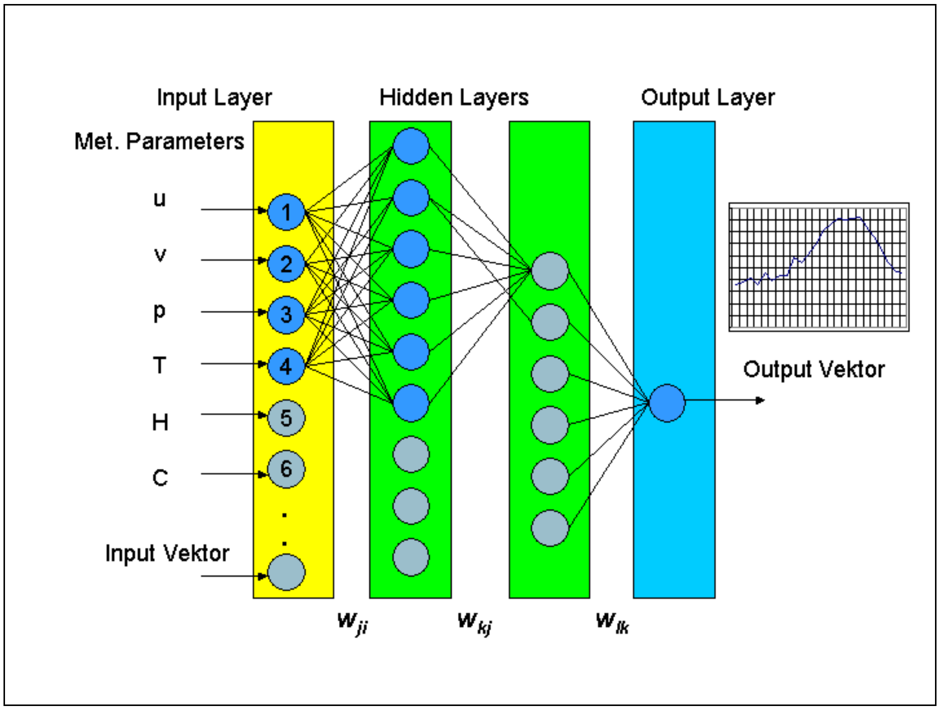


Fig. 1: Sketch of an artificial neural network (ANN) used for the wind power forecast

In addition to the forecast of the total output of the WTs for the next days, short-term (15-minutes to 8 hours) forecasts are the basis for an efficient and save power system management. Apart from the meteorological values such as wind speed, air pressure, temperature etc., online power measurements of representative wind farms are an important input for the short-term forecasts.

III. RECENT ADVANCES IN WIND POWER FORECASTING

Improved representation of the atmospheric boundary layer

The selection of the input parameters for the ANN is of crucial importance for the performance of the forecast. Wind velocity and wind direction are, of course, the most important parameters for the wind power forecast. However, with the neural network approach it is easily possible to incorporate additional parameters. The set of meteorological parameters used for the forecast has been improved to take into account the influence of atmospheric stability, especially for new turbines with high towers. This let to an important improvement in forecast accuracy. Most important was the inclusion of the predicted wind speed at 100 m height. As can be seen in figure 2 for the example of one German TSO control zone, the forecast error (RMSE in percent of installed capacity) was reduced by more than 20%. Two different numerical weather prediction models were used as input for the forecast, showing very similar results.

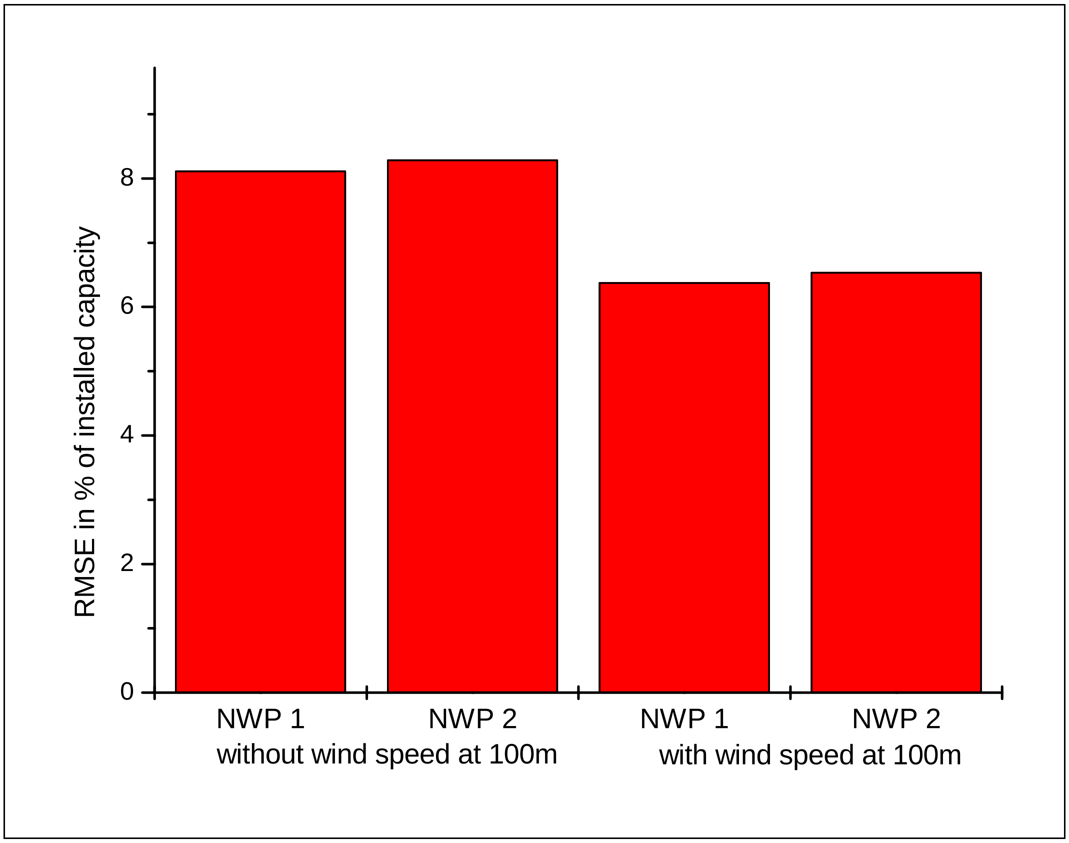


Fig. 2: Comparison of the wind power forecast accuracy for a control zone using forecasted wind speeds at 10 m and 100 m height as input parameter

Multi-model approach for forecasting methods

Day-ahead wind power forecasting by ANN as one method of artificial intelligence (AI) is used operationally by German TSOs. To improve the forecast ability, other types of AI-models were investigated in a comparative study. In detail these are mixture-of-experts (ME), nearest-neighbour search (NNS) combined with particle swarm optimization (PSO) and support vector machines (SVM). Additionally we build an ensemble from all models.

The ANN consists of nonlinear functions g which are combined by a series of weighted linear filters [11]. Here a neural network with one hidden layer was used, constituting the weight matrices A and a.

$$\hat{P}_t = g\left[\sum_{j=1}^{m} a_j g\left(\sum_{k=1}^{m} A_{jk} w_{kt}\right)\right] \qquad (1)$$

The vector w_{kt} contains the input data from the numerical weather prediction model, i.e. k values of meteorological parameters at time t. $\hat{P}_t$ denotes the output value, i.e. the predicted power output of a wind farm at the time t.

The ME model is a construction of different ‘expert’ neural networks to tackle different regions of the data, and then uses an extra ‘gating’ network, which also sees the input values and weights the different experts corresponding to the input values [12].

The NNS [13] uses those observations in a historical NWP data set closest in input space to the actual input values to form the output. The used NNS method is based upon the construction of a common time delay vector of weather data from several prediction locations of the NWP and upon an iterative algorithm consisting of the NNS and a superior PSO for the selection of optimal input weather data [14].

The SVM maps the input data vectors w_t into a high-dimensional feature space by calculating convolutions of inner products using some so-called support vectors w_i of the input space.

$$f(w_t) = sign\left[\sum_{\text{support vectors}} P_i \alpha_i K(w_i, w_t) - b \right] \quad (2)$$

In general, support vector machines are learning machines using a convolution of an inner product K allowing the construction of non-linear decision functions in the input space, which are equivalent to linear decision functions in the feature space. In this feature space, an optimal separating hyper plane is constructed [15].

A comparative study between the different forecasting methods has been performed using power output measurements of 10 wind farms in the E.ON control zone and corresponding NWP prediction data for these points from the German weather service DWD. Data from September 2000 to July 2003 have been used. Figure 3 shows the comparison of the mean RMSE for the 10 wind farms. It can be seen that the support vector machine yields the best results in this case. Also, a simple ensemble approach has been tested by averaging the outputs of the models studied. As can be seen in figure 3, even this simple ensemble improves the forecast accuracy compared to the results of the single ensemble members.

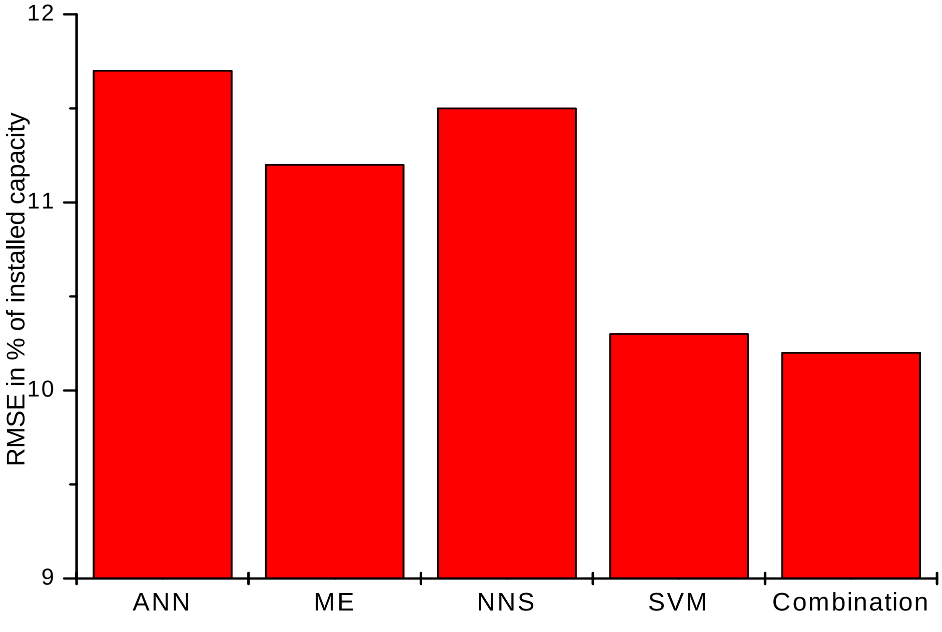


Fig. 3: Comparison of the mean RMSE of a wind power forecast for a group of single wind farms obtained with different AI methods and with a combination of all methods

Multi-model approach for numerical weather forecast models

An investigation points out the influence of merging different NWP models on the accuracy of the wind power forecast. Three different NWP models have been used for a day-ahead wind power forecast for Germany. All models have been used with the WPMS (based on the ANN method). The training of the networks has been performed with data of more than one year. A concurrent data set of seven months (April – October) has been used for the comparison.

The RMSE in percent of the installed capacity of the three models are shown in figure 4. It can be seen that the differences between the models are small. Additionally, a simple combination of the three models has been tested by averaging their forecasts. It can be seen that even this simple approach improves the forecast accuracy very significantly compared to the results of the single models. The resulting RMSE for the combined model for Germany is 4,7%.

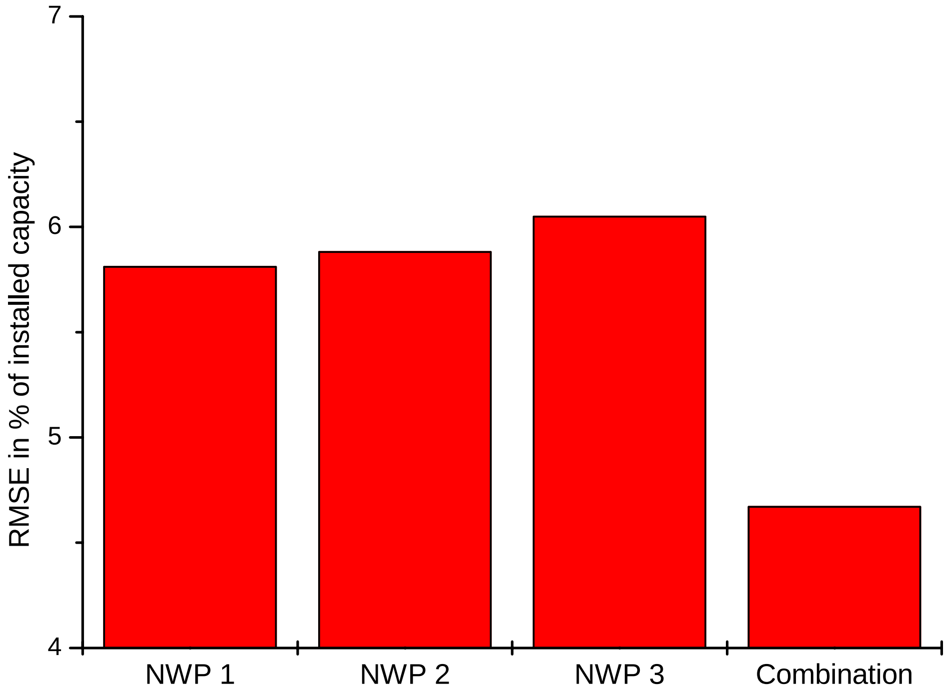


Fig. 4: Comparison of the mean RMSE of a wind power forecast for Germany obtained with the WPMS with input data from three different NWP models and with a combination of these models

Prediction of the forecast uncertainty

In addition to the wind power forecast itself, it is important to have knowledge of uncertainties of this forecast. A statistical method has been used to predict not only the power output, but also an upper and lower limit for the forecast accuracy for each time step (figure 5). The statistical method is based on the determination of the forecast uncertainty for each representative wind farm depending on wind speed and wind direction. The total uncertainty is then calculated from the uncertainty estimations of all representative wind farms.

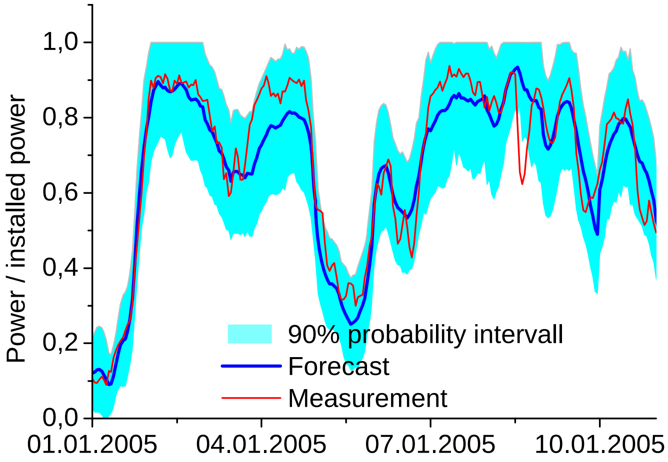


Fig. 5: Example time series of the forecasted power output and its 90% probability interval compared with real production values

IV. EXTENDED OPERATIONAL CONTROL FOR LARGE WIND FARMS

According to the German Federal Government's planning, the share of renewable energies in German electricity consumption should increase to 12,5 % by 2010 and to 20 % by 2020, of which the majority will be expected as wind energy. The conventional power production in the electrical power system will be reduced at times with high wind power feed-in. Today, conventional power plants are needed to supply ancillary services for grid management. In the future, wind farms will have to provide a part of these ancillary services, such as the supply of reactive and balancing power. Modern WTs have extended functions capable to contribute to operational grid management [16], e.g.:

- Reactive power feed-in (desired value of default reactive power or default power factor) depending on the WTs ability of reactive power provision and the wind conditions.
- Generation Management (limitation of maximum active power feed-in), which controls and regulates the power feed-in to the grid connection node.

A single WT operates as an autonomous system, but for additional functions a high-level Power Management System (PMS) is necessary. The PMS operates and manages a wind farm, which may consist of several single wind turbines. By using this PMS, the following management strategies can be applied:

- Reactive power provision (desired value of default reactive power or default power factor) with a usual setting range like conventional-power-station, independent of the wind conditions
- Schedule setting to follow a given schedule for the wind farm depending on the wind (power)

V. WIND FARM CLUSTER MANAGEMENT

The pooling of several large wind farms into clusters will make new options feasible for an optimised integration of intermittent generation into electricity supply systems. The geographically distributed onshore wind farms will be aggregated to clusters, for the purpose of operating these wind farms as one large (virtual) wind power plant [17]. For this purpose, a new structure, the wind farm cluster, will be introduced. All wind farms, which are directly or indirectly connected to one transmission network node, will be associated to one wind farm cluster. The WCM aids the TSO by operating the cluster according to the requirements of the power transmission system. Non-controllable wind farms within a wind farm cluster are supported by controllable ones. The following operational control strategies to support a reliable grid operation are feasible:

1. Reduction of gradients to minimize ramp rates
2. Supply of reactive power with a usual setting range like a conventional-power-station
3. Generation Management which controls and regulates the feed-in for the whole wind farm cluster
4. Supply of negative and positive reserve power for the balancing between wind power prediction and wind power generation
5. Congestion Management by limitation of wind power output
6. Generation schedule of wind power feed-in to achieve a reliable scheduling

The first four strategies have aspects relating both to operation control for single wind farms and to energy management of a whole cluster. For example, even if a wind farm is able to supply balancing power, by taking advantage of the smoothing effect in a cluster of distributed wind farms the reliability, which is needed for balancing power, is increasing substantially. However, it is still depending on the wind forecast and its uncertainties. Some of these strategies use the same basic functions e.g. the limitation of power output. The control strategies can be realised by using the four WCM operating modes:

1. Active Power Limitation (which combines the strategies “Reduction of gradients”, “Generation Management” and “Congestion Management”)
2. Supply of Reactive Power
3. Supply of Balancing Power
4. Scheduling

The WCM can be located in the TSO’s grid control centre. The existing control-system could be used to manage the data flow. The WCM receives the measured values from the wind farms. The desired values will be sent from the WCM to the several PMS’s.

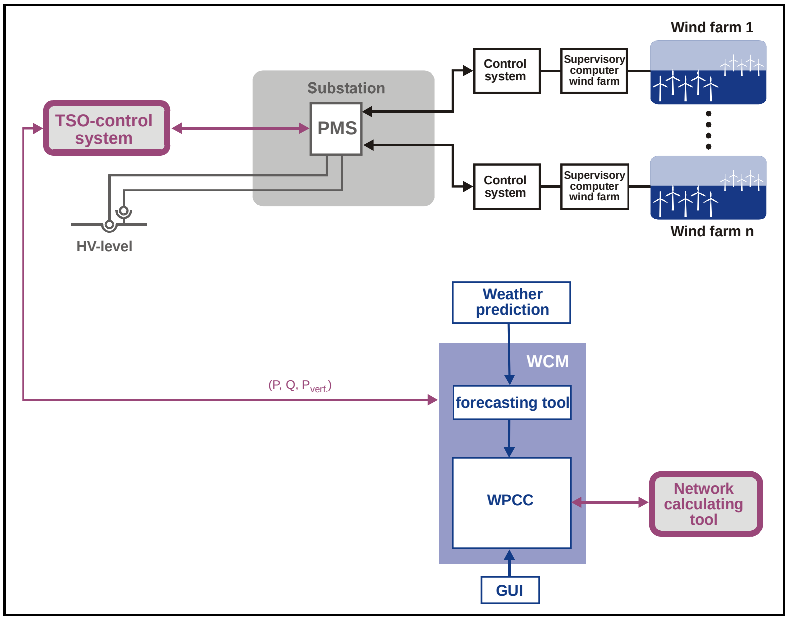


Fig. 6: Data flow between WCM, PMS and the TSO control system

For the operation modes different planning intervals need to be considered. At the previous day (after receiving the meterological weather forecast) a day-ahead-prediction is computed. By using the forecast as a provisional wind generation schedule, the TSO can calculate the power flow in his grid and thus detect possible congestions. The tool also provides a confidence interval for the forecast uncertainty [18]. This allows a first estimation of the balancing power needed for the cluster.

If necessary, the WCM executes calculations to implement the TSO's requirements for the cluster, e.g. if the TSO wants the whole cluster to follow a given schedule, the WCM computes generation schedules for each single wind farm, to ensure that the aggregation of all wind farms in the cluster achieves the requirements for the cluster.

Assuming a 100 % accuracy of wind power prediction will be achieved, this schedule could be followed by the wind farms. The day-ahead prediction is used as an initial estimation of wind power generation. During operation, a short-term prediction using current measured data to obtain a more accurate forecast in the range of 4 hours is executed. The WCM gets the current feed-in-values from the TSO's control system every 15 minutes. With this information it predicts the future generation for the next point in time up to a time horizon of four hours and then re-computes the generation schedule for every single wind farm under consideration of the cluster constraints.

Active Power Limitation

By the operation mode "Active Power Limitation" the WCM ensures that the active power output for the whole cluster is kept under a certain limit. In this case the active power feed-in of the wind farms has to be reduced.

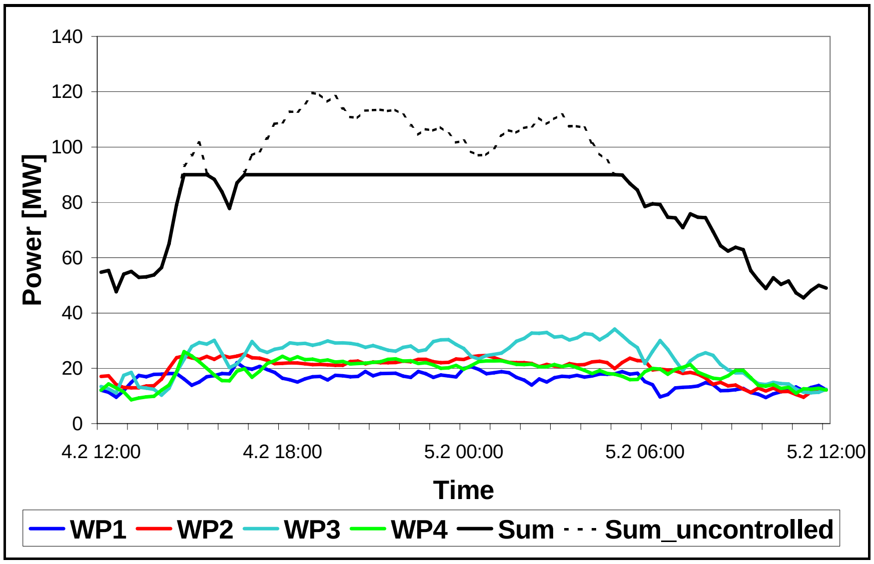


Fig. 7: Active power limitation in a cluster with four wind farms

Figure 7 shows an example with four wind farms ("WP1" – "WP4") and a total power limitation for the cluster of 90 MW. Without limitation of active power, the predicted maximum cluster feed-in in this example is about 120 MW ("Sum_uncontrolled"). If this would lead to congestion, the TSO has to limit the wind power feed-in of the whole cluster during a specific time period. The WCM now computes a schedule for all four wind farms, so that the sum of the output does not exceed the required value of 90 MW ("Sum").

Supply of Reactive Power

The operation mode “Supply of Reactive Power” can be used to provide a desired value of reactive power. In this case for each wind farm the information is needed, whether and to what extent reactive power can be supplied. For wind farms, which cannot supply a variable amount of reactive power, a forecast of its reactive power demand or generation is needed. With this information the WCM is able to determine the respective reactive power of each wind farm and to transfer the set points to the PMS.

If the wind farm is not directly connected to the power transmission system, the supply of reactive power for onshore wind farms is difficult. The WCM operates the wind farms according to the requirements of the power transmission system, but in this case the regulation of the reactive power is done by the respective Distribution System Operator. Thus the supply of reactive power by the WCM is only sensible for wind farms, which are directly connected to the transmission system. This is usually the case for offshore and large onshore wind farms.

Supply of Balancing Power

By the operating mode “Supply of Balancing Power” the WCM shall provide negative and positive reserve power for the balancing between wind power prediction and wind power generation in the whole TSO control area. In the future, in order to provide balancing power for load variations or power plant failures, WTs have to meet the TSOs pre-qualification rules for balancing power.

The supply of negative balancing power can be easily done by curtailing the output of the wind farm. To supply positive balancing power, the wind farm can be curtailed first and provide the difference between the curtailed and the un-curtailed wind power output as positive balancing power. In this operating mode the active power feed-in of the wind farms is reduced.

Because it is not possible to compute a wind power prediction with an accuracy of 100 %, a confidence interval to estimate the error between actual and predicted feed-in is necessary. The lower level of the confidence interval is the value for wind generation, which will be available with high probability. Since the requirement for availability of balancing power is very high, instead of the forecasted value the lower level of the confidence interval must be taken as reference level for supply of balancing power. If the cluster now curtails its feed-in below this level, the difference between computed feed-in and lower level of the confidence interval can be provided as positive balancing power. However, it has to be pointed out that it is still necessary to analyse whether it is possible that wind farms can provide balancing power with respect to the TSOs pre-qualification rules and the high requirements especially in view of availability and reliability.

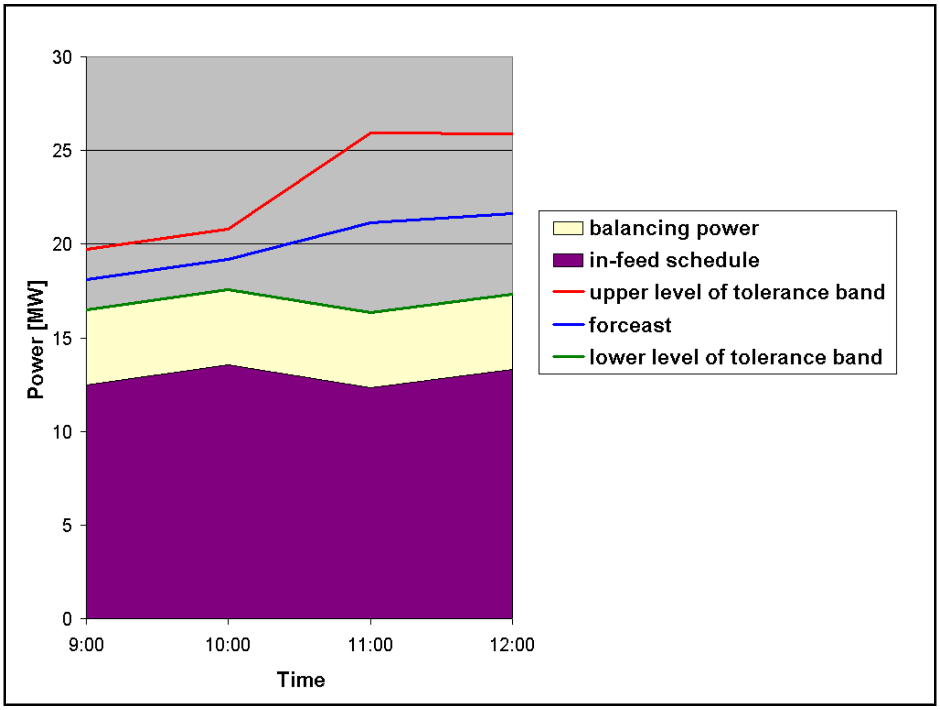


Fig. 8: Example for wind farm with balancing power after short term prediction

Figure 8 shows an example for a computed wind generation schedule based on the 4 hour short term prediction with a provided positive balancing power of 4 MW. The computed feed-in power can be provided at the same time as negative balancing power. The schedule for the cluster feed-in is then used as set point in the operating mode "Active Power Limitation". If the balancing power is not needed, the cluster runs through its computed schedule. If balancing power is needed, the feed-in of the cluster can be increased or decreased according to the need of positive or negative balancing power.

Scheduling

Aim of this operation mode is to follow a given schedule for wind farm clusters. This is done by taking advantage of the smoothing effect. The schedule must consider the given weather situation and particularly the wind conditions, e.g. the schedule can't be higher than the predicted wind power generation.

VI. CONCLUSIONS

As the wind power capacity grows fast in Germany and many other countries, forecast accuracy becomes increasingly important. However, it can also be expected that the increase in forecasting accuracy can be maintained in the future. A number of improvements such as the development of operational ensemble model systems, new generation of NWP models with more frequent updates of the weather predictions and methods for the combination of different forecasting methods are expected. Especially for short-term wind power forecasting, the additional use of online wind measurement data [19] has the potential for a new role of forecasts in mains control. Forecast accuracy is only one of the challenges for wind power forecasting systems of the future. Additionally, the scope of systems will have to be extended to meet future challenges:

- Wind power forecast in the offshore environment has the potential to become more reliable than on land, if specific offshore forecast models are developed.

- Improved forecasts for short time horizons will be needed for grid reliability.
- Prediction of the probability distribution of the forecasting error and reduction of events with large errors give the opportunity to reduce the reserve capacity for balancing wind power forecast errors.
- Forecasts in high spatial resolution for each grid node of the high voltage grid will be needed for high wind power penetration to tackle the problem of congestion management.

Considering the increasing number of wind farms in electrical power systems and the upcoming erection of offshore wind farms, an intelligent management tool for wind power generation becomes more important. Besides new operational controls for single wind farms, a high-level energy-management is also necessary.

By pooling of wind farms to so called wind farm clusters, the WCM, developed in a German research and development project, is able to co-ordinate the geographically distributed wind farms and represent it as one (virtual) wind power plant for the system operators purposes. The developed WCM simplifies the controlling of large number of WTs in electrical power system as one unit.

VII. ACKNOWLEDGEMENT

This work has been partially funded by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (projects No. 0329915A and 0329924C).

VIII. REFERENCES

[1] REISI – Renewable Energy Information System on Internet http://reisi.iset.uni-kassel.de.

[2] Wind Energy Report Germany, ISET, Königstor 59, 34131 Kassel, Germany. 2005, 2004, 2003, 2002.

[3] Wind Energy: A Vision for Europe in 2030, Advisory Council of the European Wind Energy Technology Platform

[4] dena: Energiewirtschaftliche Planungen für die Netzintegration von Windenergie in Deutschland. Berlin 2005

[5] M. Wolff, R. Mackensen, G. Füller, B. Lange, K. Rohrig, F. Fischer, L. Hofmann, S. Heier, B. Valov: Advanced Operating Control for Wind Farm Clusters. Sixth International Workshop on Large-Scale Integration of Wind Power and Transmission Systems for Offshore Wind Farms, Delft, 2006 (published on CD)

[6] F. Schlögl, K. Rohrig, A. Badelin: Practical implementation of the equal distribution mechanism of wind power costs by the German TSOs. European Wind Energy Conference 2006, Athens (published on internet)

[7] Lange, B., K. Rohrig, B. Ernst, F. Schlögl, R. Jursa, J. Moradi: Wind power forecasting in Germany - Recent advances and future challenges. Zeitschrift für Energiewirtschaft, vol. 30 (2006) issue 2, pp 115-120

[8] Ernst, K. Rohrig: Online-Monitoring and Prediction of Wind Power in German Transmission Operating Centres. First Joint Action Symposium on “Wind Forecasting Techniques”, December 2002, Norrköping, Schweden

[9] F. Schlögl: Online-Erfassung und Prognose der Windenergie im praktischen Einsatz

[10] K. Rohrig: Rechenmodelle und Informationssystems zur Integration großer Windleistungen in die elektrische Energieversorgung, PhD study at the University of Kassel, 2004

[11] N. Gershenfeld: The Nature of Mathematical Modeling, Cambridge University Press,1999.

[12] M. Bishop: Neural Networks for Pattern Recognition, Oxford University Press, 1995.

[13] T. Hastie, R. Tibshirani, J. Friedman: The Elements of Statistical Learning, Data Mining Inference, and Prediction, Springer, 2001.

[14] R. Jursa, B. Lange, K. Rohrig: Advanced Wind Power Prediction with Artificial Intelligence

Methods, First International ICSC Symposium on Artificial Intelligence in Energy Systems and Power, Island of Madeira, Portugal, Feb. 7 – Feb. 10, 2006.
[15] N. Vapnik, The Nature of Statistical Learning Theory, Second Edition, Springer, 2000.
[16] K. Rohrig, F. Schlögl, R. Jursa, M. Wolff, F. Fischer, S. Hartge, B. Valov, S. Heier, „Advanced Control Strategies to Integration German Offshore Wind Potential into Electrical Energy Supply“, 5th International Workshop on Large-Scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms, Glasgow, Great Britain, 2005
[17] K. Rohrig, B. Lange, „Application of Wind Power Prediction Tools for Power System Operations“, presented at the 2006 IEEE Power Engineering Society General Meeting, Montreal, Canada, 2006
[18] Zimmer, A. Ewert, H.J. Haubrich, “Tailored System Modelling for Congestion Detection in EHV Grids”, VII Symposium of Specialists in Electric Operational and Expansion Planning (SEPOSE), Curitiba, Brasilia, 2000
[19] Hahn, M. Durstewitz, R. Döpfer: ISET Wind Energy Measurement Network, European Wind Energy Conference 2006, Athens (published on internet)

IX. BIOGRAPHIES

Dr. Kurt Rohrig is head of ISET’s R&D Division Information and Energy Economy. Dr. Rohrig worked with ISET since 1991 and has been the scientist-in-charge for projects handling the real time calculation and prediction of wind power for large supply areas – operated in co-operation with large power transmission utilities. The computer models and approaches, developed in frame of his work are in operation at all German transmission system operators with high wind power penetration. He is member of IEEE PES and representative of ISET in CIGRE C6. Furthermore, Dr. Rohrig is head of the thematic network “Energy and Communication” which consists of 12 partners of industry, universities and research institutes.

Dr. Bernhard Lange is head of Information and Prediction Systems of the R&D Division Information and Energy Economy at ISET. He is a physicist with MSc from the University of Oldenburg. After graduating he worked in Denmark with Risø National Laboratory and Wind World A/S. 1998 to 2002 he prepared his PhD about offshore wind power meteorology at Risø National Laboratory and University of Oldenburg. His main research interests for the last 10 years are wind power meteorology and wind farm modelling.