Paper 08GM0191

IEEE POWER ENGINEERING SOCIETY
ENERGY DEVELOPMENT AND POWER GENERATION COMMITTEE

Network Security Management (NSM) focused on Dispersed Generation

Tom Hammons and Zbigniew Styczynski

Working Group European Electricity Infrastructure[1]

2008 IEEE PES General Meeting, July 20-24 2008, Pittsburgh, PA, USA
Tuesday, July 22 2008, 9:00 a.m~1:00 p.m. (Any Unforeseen Change to be Notified in Preliminary/Final Program and by Letter)

Sponsored by: International Practices for Energy Development and Power Generation

Chairs: Tom Hammons, University of Glasgow, Scotland, UK
Zbigniew Styczynski, Otto-von-Guericke-University, Magdeburg, Germany

Track: Power Reliability, Quality and Safety

INTRODUCTION

On behalf of the Energy Development and Power Generation Committee, welcome to this Panel Session Network Security Management (NSM) focused on Dispersed Generation

Progress in the use and the structure of primary energy resources requires modifications in the structure of generation and operation of the power system in the future to fulfill high requirements of secure delivery of electrical energy. The power system is one of the critical infrastructures of industrial countries and requires special consideration.

One of the aspects is that dependency of Europe on imported primary energy increases from year to year. As a countermeasure against this growing dependency, 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 to gain a sustainable electricity supply in the future. Generally, the share of renewable energy sources has to be increased until 2010 from 14% to 22% and the share of CHP has to be doubled from 9% to 18%.

The question arises, how can the power system be operated secure with such a large share of mostly not dispatched power sources? How can the reserve power be limited which is required for compensation of power fluctuations and ensuring safe network operation?

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 the 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 the import or export of power from or into the higher-level network has to follow a schedule, which can be predicted with high level of accuracy in advance.

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[1] Document prepared and edited by T J Hammons

The distribution networks will become active and have to provide contributions to such system services as 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.

For example the Danish system is characterized by a high share of wind power production as well as production from combined heat and power units.

The actual governmental plans for the implementation of additional 3,000 MW of wind power capacity by the year 2025 lead to a future situation where the installed wind power capacity reaches the level of annual peak load.

This new situation requires extended analyses, also with respect to system service. 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. H. F. Sauvain and M. J. Lalou, Switzerland, and Z. A. Styczynski and P. Komarnicki, Germany. Optimal and Secure Transmission of Stochastic Load Controlled by WACS—Swiss Case (Invited Panel Presentation Summary 08GM0596).
2. Kurt Rohrig and Bernhard Lange, ISET, Kassel, Germany. Improving Security of Power System Operation applying DG Production Forecasting Tools (Invited Panel Presentation Summary 08GM0039).
3. Jozef Paska, Warsaw University of Technology and Adam Oleksy, PSE-Operator, Poland. Reliability Issues in Power Systems with DG (Invited Panel Presentation Summary 08GM0572).
4. Rainer Krebs, E. Learch, and O. Ruhle, Siemens, Germany and S. Gal, F. Lazar and D. Paunescu, Transelectrica, Romania. Future Distribution Systems with Dispersed Generation will require Network Security Measures as Transmission Systems Today (Invited Panel Presentation Summary 08GM0501)
5. Cor J. Warmer, Maarten P. F. Hommelberg, I. G. Kamphuis and J. Koen Kok, ECN, The Netherlands. Local DER Driven Grid Support by Coordinated Operation of Devices (Invited Panel Presentation Summary 08GM1177).
6. Zita A.Vale, Hugo Morais, Marrilio Cardoso, Carlos Ramos, and H. Khodr, ISEP/IPP, Porto, Portugal. Distributed Generation Producers’ Reserve Management (Invited Panel Presentation Summary 08GM0040).
7. Antje Orths and Peter Børre Eriksen, Energinet.dk, Fredericia, Denmark. System Service in a System with High DG Penetration - A Task for DG? (Invited Panel Presentation Summary 08GM0531)
8. Zbigniew A. Styczynski and Chris O. Heyde, Otto-von-Guericke-University, Magdeburg, Germany, and Bernd Michael Buchholz and Olaf Ruhle, Siemens, Germany. Network Security Management Tool for Distribution Systems (Invited Panel Presentation Summary 08GM0038).
9. Christophe Kieny, N. Hadjsaid, B. Raison, Y. Besanger, R. Caire, and D. Roye (INPG and EDF, France), T. Tran Quoc (IDEA, France), and O. Devaux and G. Malalarange (EDF R&D, France). Distribution Grid Security Management with High DG Penetration Rate: Situation in France and some other Trends. (Invited Panel Presentation Summary 08GM0762)
10. Invited Discussers.

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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 Center 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.

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Professor Z. A. Styczynski makes the first presentation**.** It is entitled: *Optimal and Secure Transmission of Stochastic Load Controlled by WACS—Swiss Case*. The authors are: H. F. Sauvain and M. J. Lalou, Switzerland, and Z. A. Styczynski and P. Komarnicki, Germany.

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Kurt Rohrig, ISET Kassel, Germany, will give the second presentation. It is entitled: *Improving Security of Power System Operation applying DG Production Forecasting Tools*

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 of projects handling 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 German transmission system operators with high wind power penetration.

Bernhard Lange is Head of Information and Prediction Systems, 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.

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The third presentation is by Jozef Paska and Adam Oleksy, **Poland**. It is entitled: *Reliability Issues in Power Systems with DG.*

Jozef Paska is with Institute of Electrical Power Engineering of the Warsaw University of Technology, Poland (WUT). He graduated from WUT and is since 2004 the professor of electrical power engineering. He is author of more than 200 scientific papers, member of the faculty and member of the Committee of Power Engineering Problems of the Polish Academy of Sciences and editorial boards of newspapers "Electrician", "Energy Market" and "International Journal of Emerging Electric Power Systems".. His areas of interest include power system reliability and security of supply, electricity generation technologies including distributed generation and renewable energy sources utilization, electrical power engineering management and economics.

Adam Oleksy is with PSE-Operator, operator of the Polish transmission system. He graduated from Silesian Technical University (B.Sc.) and Warsaw University of Technology (M.Sc.). He is head of the group for technical analyses in Sales and Development Department of the PSE-Operator.

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R. Krebs, E. Learch, and O. Ruhle, Siemens, Germany and S. Gal, F. Lazar and D. Paunescu, Transelectrica, Romania have prepared the fourth presentation. Rainer Krebs will present it. It is entitled: *Future Distribution Systems with Dispersed Generation will require Network Security Measures as Transmission Systems Today*

Rainer Krebs graduated from University in Erlangen, Germany. 1997 he joined Siemens AG where he is currently a principal expert in the field of power systems and Director. He is a chairman of the VDE ETG Nord Bavaria and author of numerous scientific papers.

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The fifth presentation has been prepared by, Cor Warmer, Rene Kamphuis, Maarten Hommelberg and Koen Kok from ECN, Netherlands. It is entitled***:** Optimal CHP Operation for Security Improvement of Distribution Systems.* Cor Warmer will present it.

Cor Warmer graduated as a mathematical statistician in 1981 from the University of Amsterdam, Netherlands. He joined ECN in 1981 as a mathematics and statistics consultant in a scientific mainframe environment. He was involved in a large number of projects for data and object modeling. His current research includes process optimization of large energy consumption systems and optimization of power demand and supply flows in the distribution network using market based agent algorithms.

Maarten Hommelberg graduated in building services in 2005 at the University of Technology, Eindhoven, Netherlands. The graduation subject was titled "Software agents for a building management system". His first and current employer is ECN. He is currently working on optimizing power demand and supply flows in the distribution network using market based agent algorithms.

René Kamphuis graduated from Nijmegen University, Netherlands, in 1976 in chemistry. He earned a Ph.D. from Groningen University, Netherlands, in Chemical Physics. His employment experience at ECN started with a position at the computing center. From there he went to a number of software engineering positions involved in and coordinating a number of large software projects. Since 2001 he is with the unit Renewable Energy in the Built Environment. He has been involved in a number of projects concerning the application of agent technology for comfort management in buildings and dynamic distributed applications in the electricity network.

Koen Kok received Bachelor degrees in Electrical Engineering (1992) and in Computer Engineering (1992). After a short working period at the University of Groningen, Netherlands, he studied Computer Science at the same university and received his MSc in Computer Science in 1998. From 1998 to date, he is working as a Researcher and Project Co-ordinator at ECN. He is working in the interdisciplinary field between electrical engineering, systems control and ICT. His current research focus is on intelligent distributed control mechanisms for electricity grids with a high penetration of distributed generation.

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The sixth presentation has been prepared by Zita do Vale, Carlos Ramos, Jose Oliveura and Hugo Gabriel Morais from ISEP, Porto, Portugal. It is entitled: *Distributed Generation Producers' Reserve Management*. Zita Maria do Vale will present it

Zita Maria Almeida do Vale is Coordinator Professor at the Computer Engineering Department of the Institute of Engineering – Polytechnic of Porto, Portugal (ISEP/IPP). She coordinates the program on electric power system, published more the 200 scientific papers, and is involved in numerous scientific projects. Her main research areas are electricity market, distribution generation, and expert system in power system.

Carlos Ramos is Coordinator Professor at the Computer Engineering Department of the Institute of Engineering – Polytechnic of Porto, Portugal (ISEP/IPP). He is also Director of the

Knowledge Engineering and Decision Support Research Group (GECAD). He war responsible for more then 20 R&D projects, supervised 10 PhD works, and has published more than 30 papers in Scientific journals. His main areas of research are artificial intelligence and decision support systems.

Jose Marilio Oliveira Cardoso graduated from ISEP/IPP in power system and since 2005 has been a Ph.D. student of the University of Tras-os-Montes and Alto Douro, Portugal, where he is involved in the research project FENDIN (Future Energy Distribution Networks).

Hugo Gabriel Valente Morais graduated from ISEP/IPP, Porto, Portugal, in power system and since 2005 he has been a researcher at this institute where he is involved in the research project FENDIN (Future Energy Distribution Networks).

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The next presentation is entitled *System Service in a System with High DG-Penetration - A Task for DG?* It has been prepared by Antje G. Orths and Peter B. Eriksen from Energinet.dk, Frederica, Denmark. Antje Orths will present it.

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 researcher at the OvG-University, Magdeburg, Germany, where she finished her PhD, and Head of the group Critical Infrastructures at the Fraunhofer Institute "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.

Peter Børre Eriksen is Head of Analysis and Methods (Planning Department) 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. Peter Børre Eriksen is author of numerous technical papers on system modeling.

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Zbigniew Styczynski, Chris Heyde, Bernd Buchholz and Olaf Ruhle from Germany have prepared the next presentation. It is entitled: *Network Security Management Tool for 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 Saxonia Anhalt. His special field of interest includes electric power networks and systems, expert systems and optimization problems. He is senior member of IEEE PES, member of CIGRE SC C6, VDE ETG und IBN and fellow of the Conrad Adenauer Foundation.

Chris Oliver Heyde is graduated 2005 from Otto-von-Guericke University in Magdeburg, Germany, in electrical engineering. Since then he is a researcher at the Chair of Electric Power Networks and Renewable Energy Sources at this University. His primary field of interest is power system security.

Michael Buchholz is 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 the parts 4 and 7 of IEC 61850. He is the German member of the SC C6 of CIGRE “Dispersed generation in distribution systems”.

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Christophe Kieny, IDEA and EDF, France and colleagues will make the penultimate presentation. It is entitled*: Distribution Grid Security Management with High DG Penetration Rate: Situation in France and some other Trends.* Christophe Kieny will present it.

***The final presentation is entitled: Optimal and Secure Transmission of Stochastic Load Controlled by WACS—Swiss Case. It has been prepared by H. F. Sauvain and M. J. Lalou (Switzerland) and Z. A. Styczynski and P. Komarnicki, (Germany). Professor Styczynski will present it.

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PANELISTS:

1. 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
Herbert.sauvain@hefr.ch
Moncef.lalou@hefr.ch
Przemyslaw.komarnicki@iff.fraunhofer.de
Tel.: +49 391 6718866
Fax: +49 391 6712408

2. 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: +495617294358
Fax: +495617294260

3. **Mr Josef Paska, Prof. Dr**
Vice Dean of Electrical Engineering Faculty
Warsaw University of Technology
Institute of Electrical Power Engineering
Group of Electric Power Plants and Power Engineering Economy
ul. Koszykowa 75
PL-00-662 Warszawa
Poland
E-mail: jozef.paska@ien.pw.edu.pl
Tel.: +48 22 234 7366
Fax: +48 22 234 5073

Mr Adam Oleksy
PSE-Operator SA
ul. Mysia 2
PL-00-496 Warszawa
Poland
E-mail: Adam.Oleksy@pse-operator.pl
Tel.:+48 22 693 1172

4. **R. Krebs**
E. Learch
O. Ruhle
Siemens AG
Power Transmission and Distribution
Freyeslebenstr 1
PO Box 3220
91058 Erlangen
Germany
E-mail: rainer.krebs@siemens.com
Tel: +49 9131 7 33515
Fax: +49 9131 7 35017
Mobile: +49 171 302 6091

S. Gal
F. Lazar
Mobile: +40 745 340 348
Tel: +40 213 035 641
Fax: +40 213 035 740

D. Paunescu
Transelectrica
Romania Power Grid Company
16-18 Hristo Botev Blvd
Bucharest 3
030236 Romania
E-mail: flazar@transelectrica.ro

5. **Mr Cor Warmer**
ECN Energy Research Center of the Netherlands
ECN Intelligent Energy Grids
Westerduinweg 3
P.O. Box 1
NL 1755 LE Petten
E-mail: warmer@ecn.nl
Tel. :+31224564702
Fax. :+31224568966

Mr Maarten Hommelberg
ECN Eenergy Research Center of the Netherlands
ECN Intelligent Energy Grids
Westerduinweg 3
P.O. Box 1

NL 1755 LE Petten
E-mail: hommelberg@ecn.nl
Tel. :+31224564702
Fax. :+31224568966

Mr Rene Kamphuis, Dr
ECN Energy Research Center of the Netherlands
ECN Intelligent Energy Grids
Westerduinweg 3
P.O. Box 1
NL 1755 LE Petten
E-mail: kamphuis@ecn.nl
Tel. :+31224564702
Fax. :+31224568966

Mr Koen Kok
ECN Energy Research Center of the Netherlands
ECN Intelligent Energy Grids
Westerduinweg 3
P.O. Box 1
NL 1755 LE Petten
E-mail: kok@ecn.nl
Tel. :+31224564702
Fax. :+31224568966

6. **Mrs Zita Maria Almeida do Vale, Prof. Dr.**
Director of Power System Program
ISEP – Instituto Superior de Engenharia do Porto
Rua Dr. Antonio Bernardiono de Almeida, 431
PT-4200-072 Porto
Portugal
E-mail: zav@isep.ipp.pt
Tel.: +351228340500
Fax.: +351228321159

Mr Hugo Gabriel Valente Morais
ISEP – Instituto Superior de Engenharia do Porto

Mr Jose Marilio Oliveira
ISEP – Instituto Superior de Engenharia do Porto
Rua Dr. Antonio Bernardiono de Almeida, 431
PT-4200-072 Porto
Portugal
E-mail: hgvm@isep.ipp.pt
Tel.: +351228340500
Fax: +351228321159

Mr Calos Ramos, Prof. Dr.
Director of Knowledge Engineering and Decision Support Research Group
ISEP – Instituto Superior de Engenharia do Porto
Rua Dr. Antonio Bernardiono de Almeida, 431
PT-4200-072 Porto
Portugal
E-mail: cr@isep.ipp.pt
Tel.: +351228340500
Fax: +351228321159

7. **Mrs Antje Orths, Dr.**
Analysis and Methods
Energinet.Dk
Tonne Kjærsvej 65
DK-7000 Fredericia

Tel.: +45 7622 4426/4000
Fax: +45 7624 5180
E-mail: ano@energinet.dk

Mr Peter Børre Eriksen
Head of Analysis and Methods
Energinet.dk
Tonne Kjærsvej 65
DK-7000 Fredericia
Denmark
E-mail: pbe@energinet.dk
Energinet.dk
Tel.: +45 7622 4000
Fax: +45 7624 5180
www.energinet.dk

8. Mr Zbigniew Antoni Styczynski, Prof. Dr.
President Centre 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@ovgu.de
Tel.: +49 391 6718866
Fax.: +49 391 6712408

Mr Chris Heyde
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: chris.heyde@ovgu.de
Tel.: +49 391 6718866
Fax.: +49 391 6712408

Mr Bernd Michael Buchholz, Dr.
Director,
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 Olaf Ruhle.
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

9. Christophe Kieny
IDEA / G2Elab
BP 46
38402 St.Martin D'Heres Cedex
France
E-mail: christophe.kieny@G2Elab.inpg.fr
Tel: +33 4 76 82 71 94
Fax: +33 4 76 82 71 84
Mobile: +33 6 66 44 32 41

N. Hadjsaid
B. Raison
Y. Besanger
R. Caire
D. Roye
INPG and EDF
France

T. Tran Quoc
IDEA
France

O. Devaux
G. Malalarange
EDF R&D
France
IDEA and EDF
France

PANEL SESSION CHAIRS

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

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

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.

Received 23 February 2008
Paper 08GM0596

1. Optimal and Secure Transmission of Stochastic Load Controlled by WACS—Swiss Case

H. F. Sauvain and M. J. Lalou, Switzerland
Z. A. Styczynski and P. Komarnicki, Germany

Abstract--The load flow has a stochastic character due to the high penetration of renewable generation, especially wind power. Nowadays about 50 GW of wind power is installed in the UCTE power system. This causes difficulties especially in the optimal operation of the system and can lead to black outs due to problems with energy flow which is often not produced according to demand. An example occurred on November 4, 2006 when the UCTE system was divided into three parts with different frequencies. The reason for this was the uncontrolled share of power on the transit line caused by high, unpredicted wind penetration.

In the paper an objective function for a WAC (Wide Area Control) system has been defined. The Fribourg analog power system simulator, which has been used to test the flexibility of the proposed solution, will be presented too. The controllability of the system has been provided using a Phasor Measurement Unit (PMU) installed in the simulator.

Index Terms— wide area control, power system simulator, PMU, power flow controllers, transmission control

1. INTRODUCTION

In 2004, 13.1 percent of the world total primary energy supply came from renewables [5]. To avoid greenhouse gas emissions, this value will increase continuously in the future. The EU leaders have proposed a goal of a 15% share of renewables for the European Union by the year 2010 [6]. These technologies cause higher requirements of operation of the power system. The flowed energy, which cannot be balanced or broadly transmitted, could excite system brownouts or blackouts. An example of one such critical situation was on 4th November 2007 in the UCTE-System, where the high wind energy generation occurred and its transmission in the transit corridors has not been controlled and the system divided into three parts with different frequencies.

The best way to solve the increasing demand on transmission will be to build new lines, which is unfortunately in many cases not possible, e.g. from ecologic, economic or geographic conditions On the other hand, the better controlled use of existing transmission lines may help in transferring the local generated energy into the power system, too. The FACTS Technology (Flexible Alternative Current Transmission System), which has been in use for many years, is one of the possibilities for increasing transmission capacity in power system corridors. The other method to control the AC load flow is to use a phase shift transformer (PST). In principle, the FACTS or PST are operated by using the following methods:

- decreasing of the reactance of the power transmission line by using the series connected capacitor,
- increasing and decreasing of the voltage by using the shunt connected capacitors and coils,
- changing of the angle between two ends of the transmission line [1].

Nowadays, two groups of compensators belong to the typical FACTS-Systems. The first one is the Static Shunt Compensators group with SVC (Static Var Compensator) and STATCON (Static Condenser). The parts of the second group - Static Series Compensator- are TSCC (Thyristor Switched Series Capacitor), TCSC (Thyristor Controlled Series Capacitor), GCSC (GTO-Thyristor Controlled Series Capacitor), and SSSC (Static Synchronous Series Compensator)[11].

To allow for the proper operation of FACTS the present data of the power system parameters, like voltage and angle, are needed. The technology of FACTS can be improved by using the Phasor Measurement Unit. Generally, a PMU takes online measurements of voltage and current phasors, frequency and power output at a rate of 100 ms. The advantage of employing Phasor Measurement Units is that they record measurements with a universal time stamp (UTC-Time) thus enabling simultaneous measurement and comparison of different system parameters in different locations. Signal reception by GPS (Global Positioning System), GOES and, in the future, GALILEO, for example, can be employed to synchronize such measurements. PMU are widely utilized to support complex systems (e.g. wide area control system - WACS), by estimating steady states, monitoring voltages online and supporting adaptive protection algorithms.

This paper proposes a WACS-solution to optimal controlling and to increasing the transmission of stochastic load. The objective function of the method will be presented in Section II. The algorithm was implemented in the Fribourg, Switzerland, power system simulator described in Section III. The simulations and results of the investigated case will be illustrated in Section IV.

2. MODELING AND OBJECTIVE FUNCTION

The method of controlling the stochastic load transmission presented here is based on a phase angle and magnitude regulations. This adaptive control system could be realized using a phase shift transformer (PST) or a power electronic device like FACTS. In this paper the PST elements are implemented for the control of power flow. Because of the economic reasons today the practical usage of PST technique is generally more probable then the use of FACTS. The vector diagram of the phase shift transformer used in the simulation is shown in the Fig. 1.

$$\underline{U}_A = \underline{U}_{N'} - \underline{U}_{NA} = \underline{U}_{NA}(\underline{T} - 1)$$

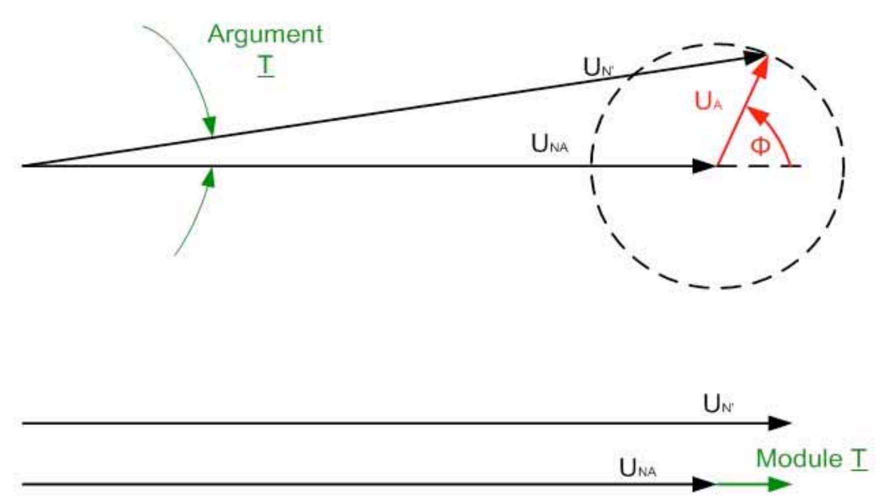

Fig. 1. Vector diagram of phase shift transformer

The possibilities of the maximal phase angle changing depend on the maximal allowable switching power of the appropriate transformers switchers. The typical values of possible angle regulation α are approximately 10 degrees [4]. Using presented method, the transmission of the stochastic load will be continuously provided on the requested level, independently on the actual angle. If the active power equation will be formulated as in (2), the influence of the α-changing can be calculated using (3).

$$P_\alpha = \frac{U_N U_{NA}}{X} sin(\alpha)$$

$$\frac{\partial P_\alpha}{\partial \alpha} = \frac{U_N U_{NA}}{X} cos\,\alpha = \sqrt{\left(\frac{U_N U_{NA}}{X}\right)^2 - P_\alpha{}^2}$$

Reference [11] shows that for larger *P* the influence of a change in α is rather small compared to the influence for the low transmitted active power. The information about the actual state of the voltage and angle from all of the interesting points will be measured and delivered by the Phasor Measurement Units. According to the IEEE C37.118 the PMUs are able to transfer the data at a rate of 10 or 25 times/second in the system where the nominal frequency is 50Hz. From this point of view, the parameter for optimal transmission of power can be calculated fast and accurately. The next section of this paper illustrates the example, which was implemented in the power system simulator, to test the flexibility of the proposed solution.

The corridor capacity depends on the configuration of the lines like allowable voltage range or individual capacities of each of the line. Generally, the corridor capacity is less than the sum of individual capacities and is limited by the worst line. The use of phase shift elements influences the line loading and, in this way, maximizes the use of the possible corridor capacity during quick changes of the load or by unscheduled load transfers that are often caused by wind generation.

To control the corridor load flow an objective function is developed. The idea is to operate under optimal power flow conditions utilizing all set point definitions of network controls as controlled variables. For this case the following function can be given:

$$f(x,u) = \sum_i (a p_i^{loss} + b\varepsilon_i + c\eta_i) + \sum_i \big[d(v_j - v_j^{ref})^2 +$$
$$+ \sum_k \left[f(\alpha_k + \beta_k + \theta_k) \right]$$

where:

- p_i^{loss} - active losses on the *i* line
- ε_i - load limitation at the line *i* to 90%
- η_i - load limitation at the line *i* to 100%
- $(v_j - v_j^{ref})$ - voltage difference limitation
- v_j^{ref} - voltage reference
- α - active power positive transit control
- β - reactive power positive transit control
- θ - currents ratio (effective to rated) optimization in the lines

and the a, b, c, d, e are the weighting factory of the criteria importance. The first part of (4) represents the cost of losses and the cost of overload situations. The second sum represents the costs related to the voltage variations.

As to investigate, an example of a possible corridor between Germany and Italy is modeled for the purpose of this WACS application. The mathematical model is implemented in the Fribourg Power System Simulator (F-PSS). Taking into account different scenarios, the usefulness of the proposed method has been investigated.

3. FRIBOURG POWER SYSTEM SIMULATOR

The Fribourg Power System Simulator (F-PSS) is a full analog power system model, which allows real time simulating of the power system operation and its control by using digital or analog control systems. The power scale of the presented system is 1 to 100000. To create the practical system behavior and different type of possible loads, the real electrical machines or generators can be directly connected to the simulator. Therefore F-PSS allows for the combining of the analog and digital models that can be implemented and useful for the tests. The used models and its control applications are programmable in the MATLAB/SIMULINK and ABB PSGuard environments. The parts of the simulator control applications are realized in LabView software.

Fig. 2 shows the F-PPS proposed for the investigations. The analog part of the load with measuring equipments is illustrated in the front of the control panel. For the presented cross-boarding case, the Italian power system was modeled as a load using a physical synchronous machine (MS in Fig. 2). Using the data from the real PMUs, which are connected to the network and delivers continuous up to date network parameters; the control algorithms of the cross-boarding area transmission can be utilized.

Fig. 2. Parts of the Fribourg Power System Simulator

In Fig. 3 a functional schema of this part of the simulator is shown.

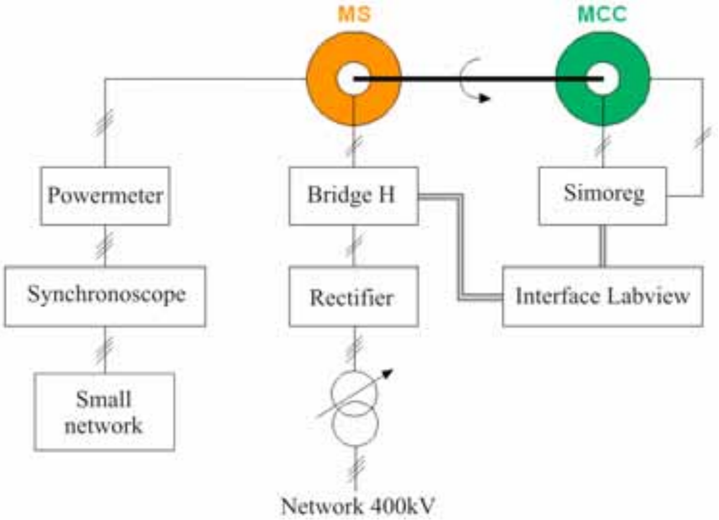

Fig. 3. Functional schema of the analog load. Scale 1/ 10000

4. SIMULATIONS – STUDY CASE

The Swiss corridor between Germany and Italy (GI-C) has been modeled in the F-PSS. The simulator used numerical calculations of the MATLAB software. Fig. 4 shows the general configuration of the arbitrary selected GI-C-corridor. The one phase shift transformer is placed between Hauterive-Payerne station and the second one is installed between Hauterive-Schiffenen network nodes.

Taking into account the other calculation done with Neplan and PowerWorld software, the investigated area was modeled as presented in Fig. 5. The implementation in the PowerWorld application enabled economic calculations of the power network behavior in the different networks conditions.

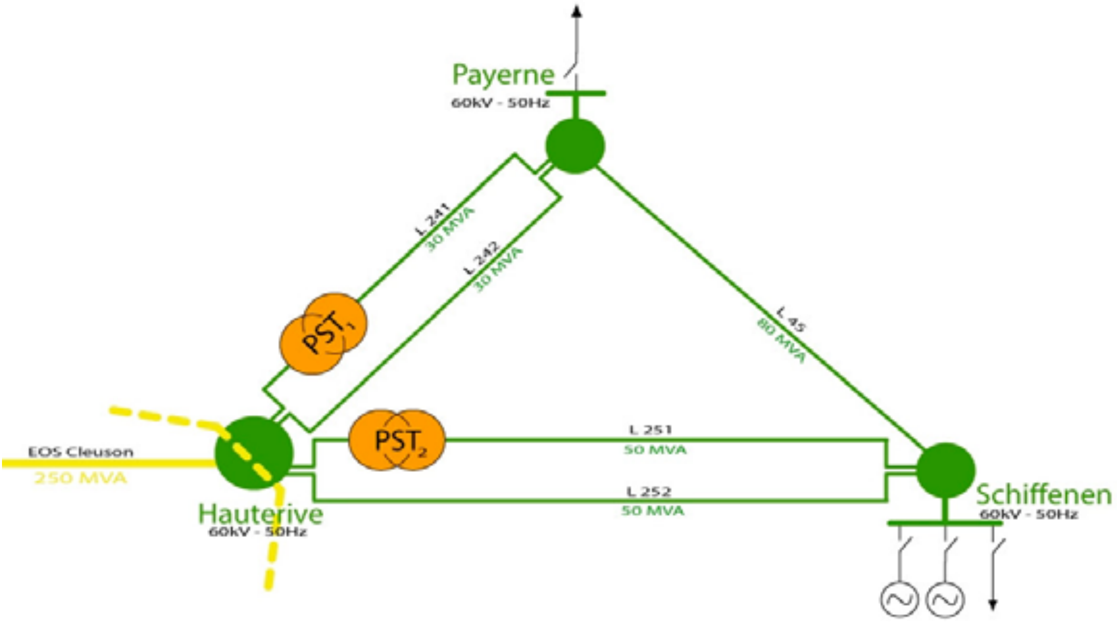

Fig. 4. Configuration of the GI-corridor in Swiss with two PSTs

Fig. 5. The arbitrarily selected corridor from Breite to Sils used for an academic WACS test

Using the complete control system, different scenarios have been implemented to investigate the benefit of using the proposed solutions. The parts of the investigations results are summarized in Table 1 and 2.

TABLE 1: COMPARISON OF THE SIMULATION WITH AND WITHOUT OF PSTS

	without PST		with PST	
Voltage and angles	U (kV)	α (°)	U (kV)	α (°)
Breite	400.90	0.00	400.90	0.00
Tavanasa	393.79	-1.59	397.81	-1.84
Bonaduz	390.52	-3.18	392.74	-3.05
Sils	389.76	-4.47	391.91	-4.33
Benken	397.4	-2.36	398.7	-2.28
Load flow	P (MW)	Q (Mvar)	P1 (MW)	Q1 (Mvar)
P_8 / Q_8	327.34	-25.92	281.55	45.45
P_{12} / Q_{12}	465.57	36.32	545.89	10.66
P_7 / Q_7	464.45	34.713	434.40	0
P_6 / Q_6	1225.8	-8.55	1230.6	1.14
P_{20} / Q_{20}	195.36	59.51	190.49	48.52

Table 1 shows that the load flow using PST is only in the positive direction - due to the condition in the objective function - and the reactive load flow are minimizing by about 40 %. The voltage differences between the nodes are smaller, when the PST is used. The active load flow is almost the same, whereby only the load flow balance changes minimally. The local parameter changes which are physically connected with the occurred power flow changes can be recognized as well.

TABLE 2
MEASUREMENT VS MATLAB CALCULATION

	Measurement		Matlab	
Voltage and angles	U (kV)	α (°)	U (kV)	α (°)
Breite	381.8	-	381.548	0.0
Tavanasa	371.8	-	371.426	-1.9
Bonaduz	364.3	-	366.096	-3.9
Sils	359.1	-	364.162	-5.6
Load flow	P (MW)	Q (Mvar)	P1 (MW)	Q1 (Mvar)
P_8 / Q_8	412.2	58.1	385.1	11.48
P_{12} / Q_{12}	574	145.8	538.6	100.50
P_7 / Q_7	543.3	107.8	537.5	98.50
P_6 / Q_6	1407.2	148.28	1413.4	121.34

From Table 2 one can see that the results of the numerical and model simulations are not similar. In particular, the load flow calculation shows some errors rate of between 10% and 30%. These are caused by the neglect of the losses in the PST and not precise losses in the lines, including the real π parameters of the lines. On the other hand, the measured parameters are saved directly, which means that high-precise Phasor Measurement Units are used [15] and the MATLAB results use different numerical calculations. To summarize, the optimal power flow in the proposed network case can be estimated.

5. CONCLUSIONS

The presented investigations have shown that it is possible to optimize the energy transfer by using a corridor in the optimal way, even for the stochastic load flow changes. The use of a new kind of wide area system control – supported by the measurements using synchronized phasor measurements- allows for the combination of technical and economic solutions depending on the objective function- dispatch of the transmission line. This is especially important for the unscheduled changes of the transits that cannot be by planned and can occur if the stochastic energy generation is dominant in the power system.

For the simulation and better comprehension of this new technique and methodology of the increasing corridor capacity, the F-PSS shows many advantages. During its simulations, the exact results that are delivered are more flexible and practical than the results of other simulation programs.

Generally, the use of the proposed method can avoid an overload of the transmission corridor, especially during big unexpected load transfers and, thus, prevents potential blackouts. For further work, investigations of the economic aspects for the use of this method are needed.

6. ACKNOWLEDGMENT

The authors express their special thanks to Mary-Laure Matthey, Jérémie Christ and Alexandre David from Fribourg for the input in this paper.

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BIOGRAPHIES

Hubert Francois Sauvain studied at the Swiss Federal Institute of Technology EPFL - Lausanne in electrical engenering. He was working for different companies before he became Professor at the College Engineering and Architecture in Fribourg (HES-SO), He is a President of the Swiss ETG society. He is also member of different boards.

Justin Lalou Justin Lalou received his Ph.D. degree in electrical engineering from the Swiss Federal Institute of Technology EPFL – Lausanne.

From 1995 to 1999, he worked at the companies Portescap and SAIA-Burgess, two Swiss motion systems manufacturers. He is currently Professor in Automatic control at the College of Engineering and Architecture in Fribourg. His center of interest is automatic control in power systems, and engineering education

Zbigniew A. Styczynski (M’94, SM’01) completed both his doctorate in 1977 and habiliation in 1985 at Wroclaw University of Technology in Poland.

He taught at the Technical University of Stuttgart in Germany from 1991 until 1999 when he was appointed to the Chair of Electric Power Networks and Renewable Energy Sources in the School of Electrical Engineering and Information Technology at Otto von Guericke University Magdeburg in Germany. He is also President of the Center for Renewable Energy, Saxony-Anhalt (Z.E.R.E. Sachsen-Anhalt e. V.) His special fields of interest include electric power networks and systems, expert systems and optimization problems

Przemyslaw Komarnicki studied at the Wroclaw University of Technology, Poland and Otto von Guericke University Magdeburg, Germany, received both his Master’s of Science degress. there in 2004.

Since April 2004 he is researcher of the Department of Process and Plant Engineering Business Unit, Fraunhofer Institute for Factory Operation and Automation, Germany Since 2004 is a Ph. D. student at 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. His special field of interest includes wide area measurement and its applications. He is member of CRIS (International Institute for Critical Infrastructures).

Received 19 February 2008
Paper 08GM0039

2. Improving Security of Power System Operation applying DG Production Forecasting Tools

Kurt Rohrig and Bernhard Lange, ISET, Kassel, Germany

Abstract: The integration of renewable energy sources (RES) into the electric energy system has become an important challenge for the utilization and control of electric power systems, because of the fluctuating and intermittent behavior of wind and solar power generation. The reliable operation of future energy supply structures with high share of distributed generation and renewable energy sources is an important and highly complex task. Supply of energy always means to find an optimal mixture of different sources. The main issues are economic effectiveness, environmental sustainability and reliability in supply. Any energy source has its own advantages and disadvantages. Over the last years the structures of electrical power supply changed noticeable. Distributed renewable energy resources supplement centralistic conventional power generation. It is obvious that Germany will only meet the ambitious greenhouse gas-reduction targets - with phasing out nuclear energy at the same time - by a major increase in renewable energy usage.
The pooling of large on- and offshore wind farms into clusters in the GW range will make new options feasible for an optimized integration of wind power. 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.
Major arguments against a massive penetration of RES are the intermittent generation, the poor predictability and the missing controllability. These arguments are disproved by adapting a virtual power plant (VPP) the Renewable Combi-Plant (RCP) which aggregates and controls large wind farms, PV plants, biogas fired CHP and pumped-storage hydro power plants making use of powerful RES prediction tools. Wind farm clusters are major members of the Renewable Combi-Plant, a VPP that aggregates and controls RES to face the demand at any time.

Index terms -- Distributed generation, renewable energy, virtual power plants, forecasting, wind farm operation, design, optimization, modeling

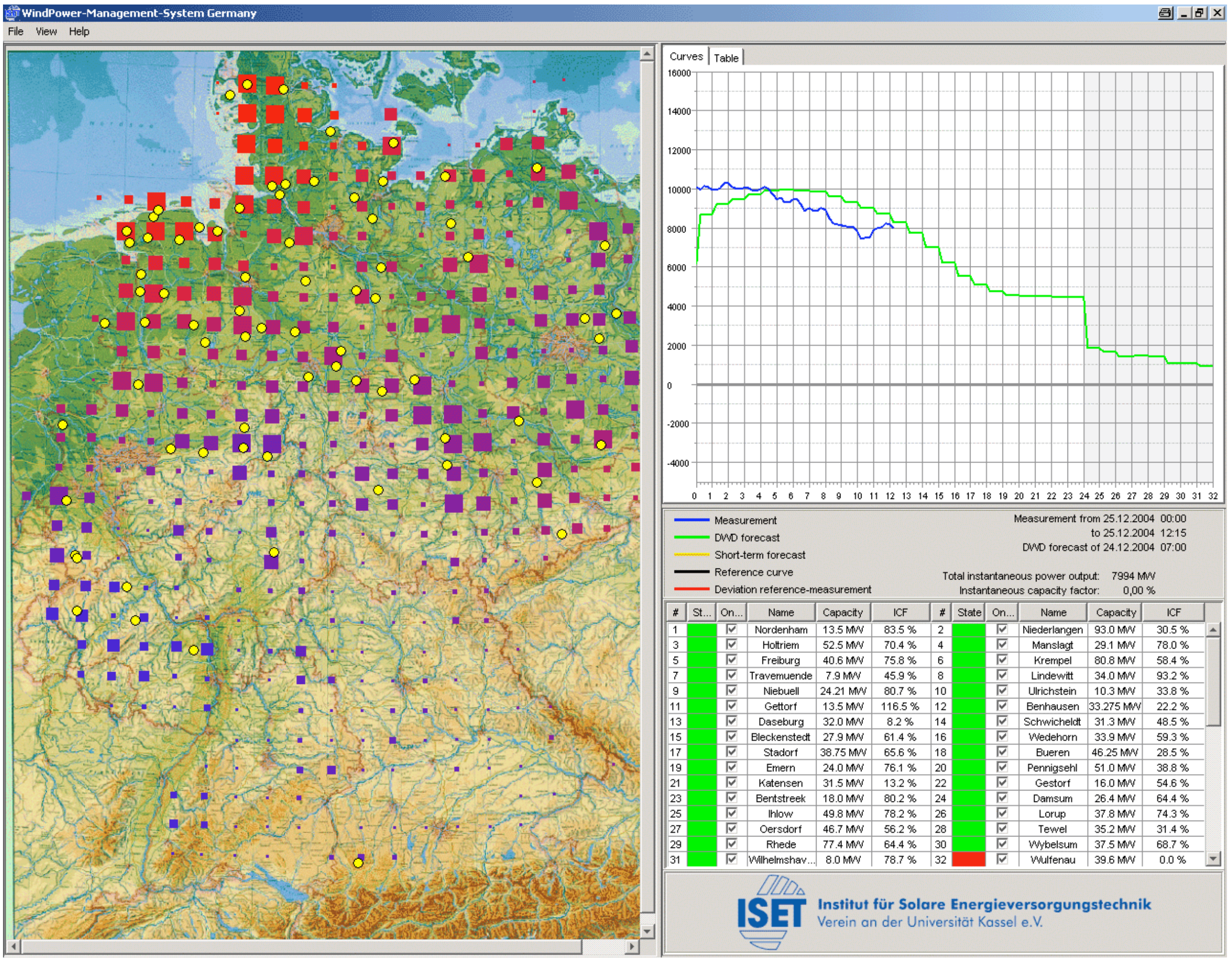
1. INTRODUCTION

By the end of October 2007, more than 18,800 Wind Turbines (WTs) with an installed capacity of 21,300 MW generated approx. 30.1 TWh electrical energy [1], [2]. Today, the electrical power generated from wind, already covers the total grid load in some grid areas temporarily. This large intermittent generation has growing influence on the security of the grid, on the operation of other power plants and on the economy of the whole German supply system. In frame of governmentally funded projects and in co-operation with the German Transmission System Operators (TSOs) E.ON Netz (ENE), Vattenfall Europe Transmission (VE-T) and RWE Transportnetz Strom (RWE), solutions for an optimized integration of the large amount of wind power into the electrical supply system have been investigated. On the basis of these solutions, a VPP of large wind farms, PV plants, biogas fired CHP and pumped storage hydro power plants was developed to demonstrate the capability of RES to assume the leading part of the electric energy supply. The members of the Renewable Combi-Plant (RCP) are existing power plants and the actual power generation is the real measured generation of these plants. To calculate the power generation schedule of the near future, the fluctuating sources solar and wind are forecasted by using artificial intelligence. The generation of the different plants is balanced against each other to face the typical energy demand of Germany. The difference between the load and the generation mix of wind farms and PV-plants is compensated by fast controllable biogas fired CHP plants and the pumped-storage hydro plant.

2. UTILIZED PREDICTION TOOLS

Mainly two different approaches are used for wind power prediction. The physical method employs physical laws to determine the relationship between weather data from a numerical weather prediction model and the power output of the wind farm. The statistical method is the mathematical modeling approach in which for example statistical methods or neural networks are used to find the relationship between weather prediction data and power output from historical data sets [3].

Based on ongoing research assignments, a very extensive and flexible wind power forecasting system, which meets the varying requirements of the users, has been developed from the Wind Power Management System (WPMS). Currently, the system is in operation at six TSOs in three European countries and is also being applied in the "Renewable Combi-Plant" and the "Wind Farm Cluster Management System". It delivers a valuable contribution to the trade in wind energy, to the economical and technical application planning of the available power plants and to ensure network stability.



Measurement from 25.12.2004 00:00
to 25.12.2004 12:15
DWD forecast of 24.12.2004 07:00

Total instantaneous power output: 7994 MW
Instantaneous capacity factor: 0,00 %

#	St...	On...	Name	Capacity	ICF	#	State	On...	Name	Capacity	ICF
1	🟩	☑	Nordenham	13.5 MW	83.5 %	2	🟩	☑	Niederlangen	93.0 MW	30.5 %
3	🟩	☑	Holtriem	52.5 MW	70.4 %	4	🟩	☑	Manslagt	29.1 MW	78.0 %
5	🟩	☑	Freiburg	40.6 MW	75.8 %	6	🟩	☑	Krempel	80.8 MW	58.4 %
7	🟩	☑	Travemuende	7.9 MW	45.9 %	8	🟩	☑	Lindewitt	34.0 MW	93.2 %
9	🟩	☑	Niebuell	24.21 MW	80.7 %	10	🟩	☑	Ulrichstein	10.3 MW	33.8 %
11	🟩	☑	Gettorf	13.5 MW	116.5 %	12	🟩	☑	Benhausen	33.275 MW	22.2 %
13	🟩	☑	Daseburg	32.0 MW	8.2 %	14	🟩	☑	Schwicheldt	31.3 MW	48.5 %
15	🟩	☑	Bleckenstedt	27.9 MW	61.4 %	16	🟩	☑	Wedehorn	33.9 MW	59.3 %
17	🟩	☑	Stadorf	38.75 MW	65.6 %	18	🟩	☑	Bueren	46.25 MW	28.5 %
19	🟩	☑	Emern	24.0 MW	76.1 %	20	🟩	☑	Pennigsehl	51.0 MW	38.8 %
21	🟩	☑	Katensen	31.5 MW	13.2 %	22	🟩	☑	Gestorf	16.0 MW	54.6 %
23	🟩	☑	Bentstreek	18.0 MW	80.2 %	24	🟩	☑	Damsum	26.4 MW	64.4 %
25	🟩	☑	Ihlow	49.8 MW	78.2 %	26	🟩	☑	Lorup	37.8 MW	74.3 %
27	🟩	☑	Oersdorf	46.7 MW	56.2 %	28	🟩	☑	Tewel	35.2 MW	31.4 %
29	🟩	☑	Rhede	77.4 MW	64.4 %	30	🟩	☑	Wybelsum	37.5 MW	68.7 %
31	🟩	☑	Wilhelmshav...	8.0 MW	78.7 %	32	🟥	☑	Wulfenau	39.6 MW	0.0 %

Fig. 1. GUI of Wind Power Management System

In order to predict the wind power from representative wind farms on the basis of the predicted meteorological data and measurements, Artificial Neural Networks (ANN) are used. The extrapolation algorithm to calculate the wind power production for larger regions comprises other important component of this system.

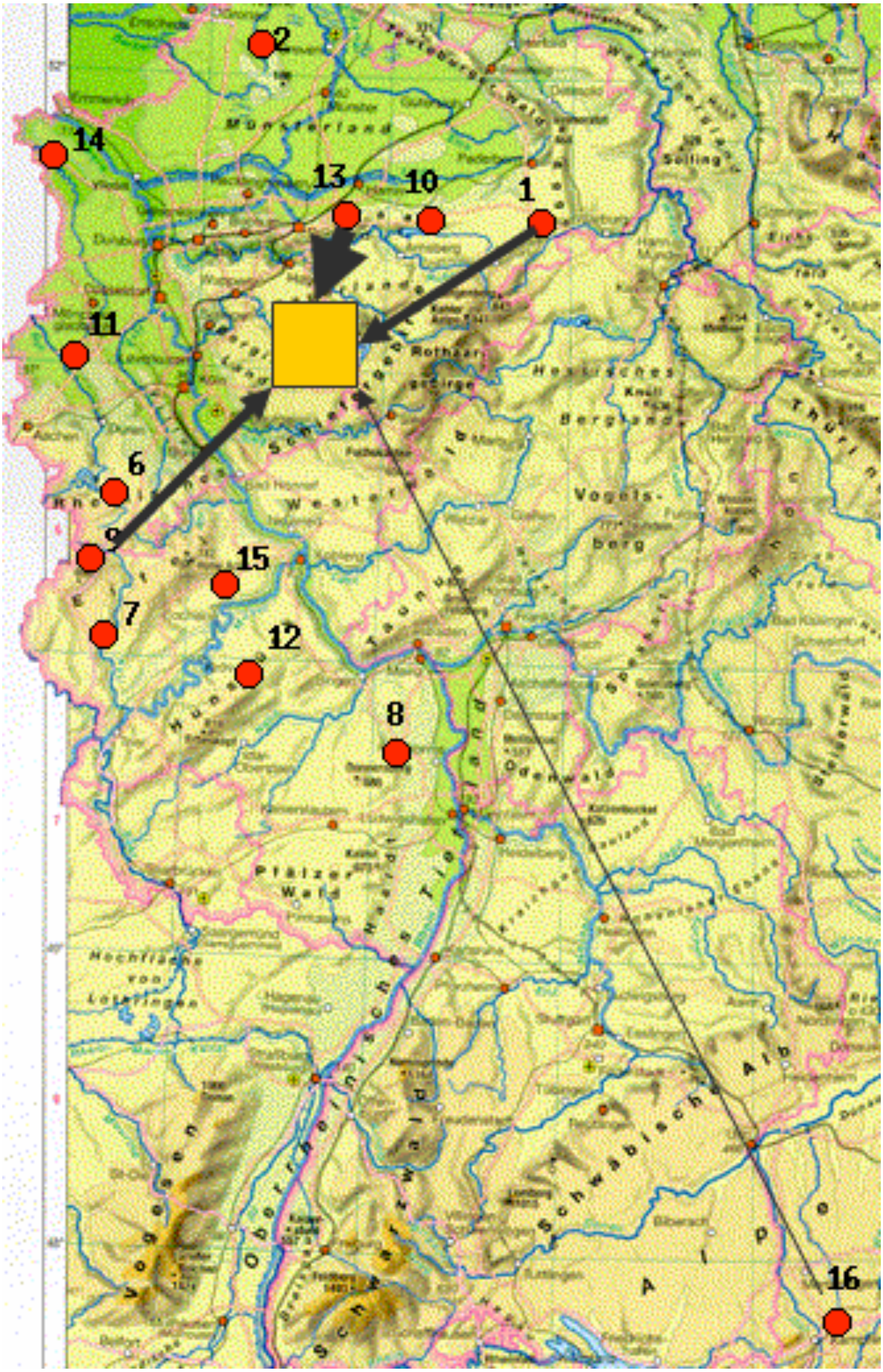


Fig. 2. Schematic view of the transformation algorithm

The instantaneous wind generation is calculated by evaluating measured production data of representative wind farms. The algorithm computes time series of the aggregated wind power for grid nodes, grid areas and control zones as well as for the whole German grid.

The WPMS delivers the temporal course of the instantaneous and expected wind power for the control zone for up to 96 hours in advance. For the day-ahead prediction, meteorological forecast data from the numerical weather prediction system (NWP) of the German weather service (DWD) are used as input to the ANN. The simultaneous data of measured power output of wind farms are used to train the ANN, which are then able to calculate the power output from weather prediction data [4]. The prediction error (RMSE in % of the installed capacity) amounts to 5.3% for the entire German system.

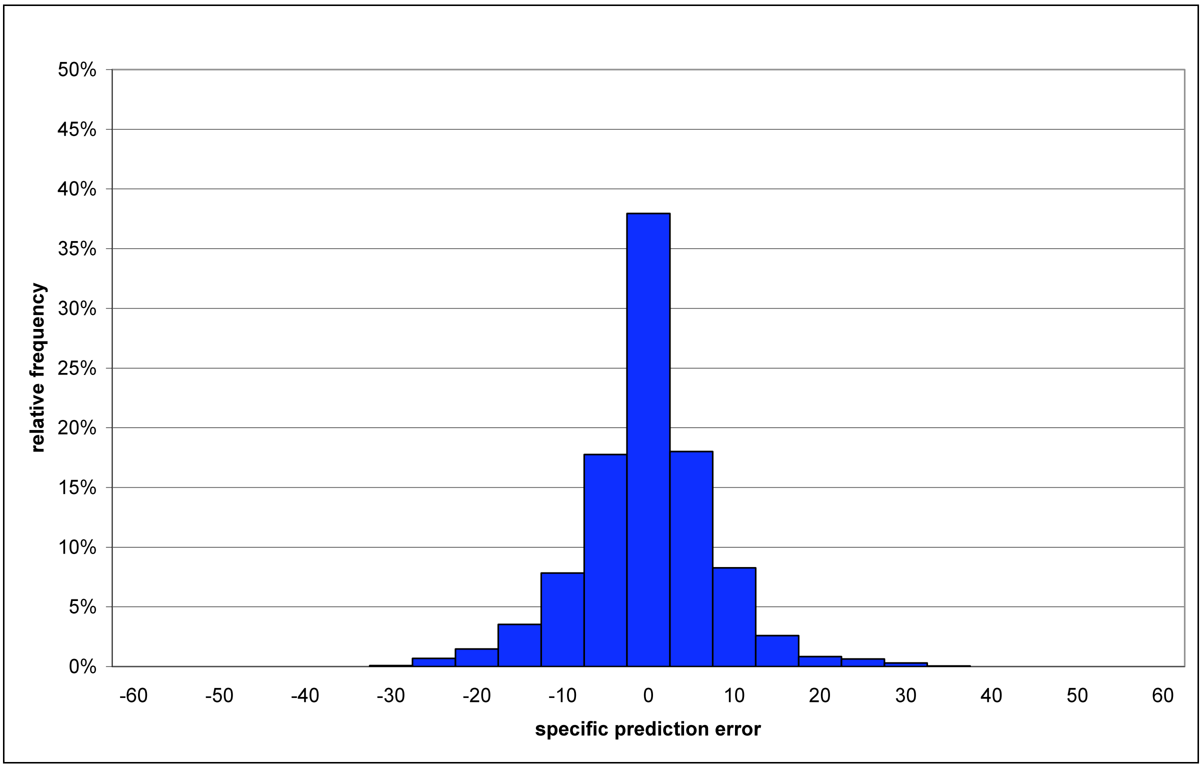


Fig. 3. Frequency distribution of prediction error of E.ON TSO control zone in 2006

Figure 3 shows the frequency distribution of the prediction errors of the day-ahead prediction of the E.ON Netz control zone in 2006. For the day-ahead forecast, the prediction error ($P_{meas} - P_{pred}$) of -10% was recognized in 7.8% of the total period (8760 hours).

In addition to the forecast of the WT production for the next days, short-term high-resolution forecasts of wind power generation in certain grid regions or for high-voltage nodes or wind farm clusters are the basis for a safe power system management. Apart from the meteorological values such as wind speed, air pressure, temperature etc., online power measurements of representative sites are an important input for the short time forecasts (15-minutes to 8 hours) [5]. To achieve a further improvement of the short-term prediction, especially at extreme weather situations (storms, turbulence) measured wind speed data of nearby measurement sites is added to the input data of the ANN.

In addition to predicted power value, the forecasting system also delivers a weather situation dependent confidence area, which is calculated from the experiences (prediction errors) of the past and from the data of the meteorological services.

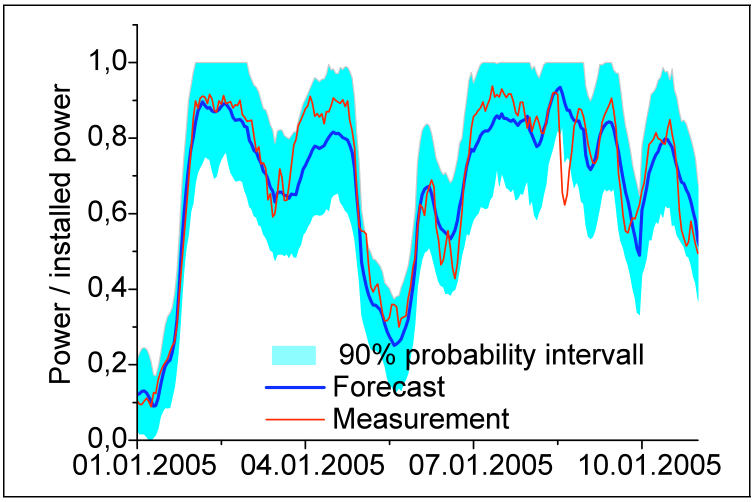


Fig. 4. Measured and predicted wind generation with associated confidence area

3. MODEL ACCURACY IMPROVEMENTS

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-neighbor search (NNS) combined with particle swarm optimization (PSO) and support vector machines (SVM).

The ANN consists of nonlinear functions g that is combined by a series of weighted linear filters [6]. 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 [7].

The NNS [8] 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 [9].

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.

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

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 [10].

A comparison between the introduced forecasting methods has been performed using power measurements of 10-wind farms form September 2000 to July 2003 in the E.ON control zone. Figure 3 shows the comparison of the methods. The support vector machine yields the best results in this case. Also, a simple ensemble approach by averaging the outputs of the models was studied. Even this simple ensemble improves the forecast accuracy compared to the results of the single ensemble members.

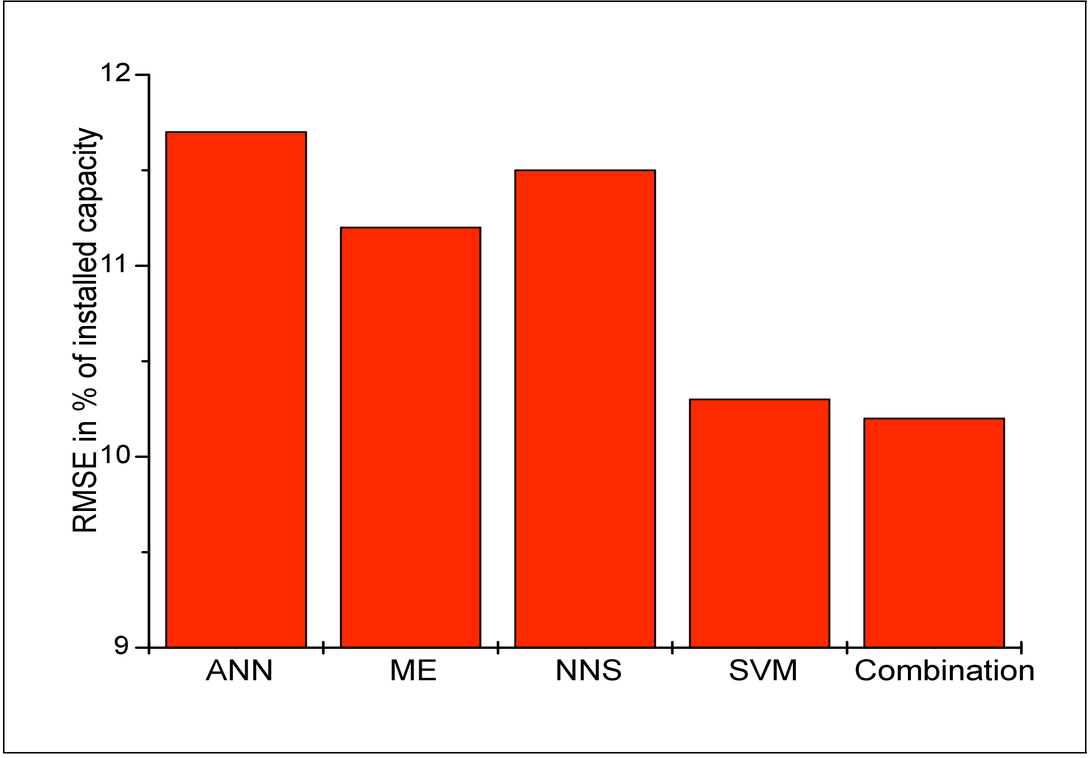


Fig. 5: Comparison of the mean RMSE of a wind power forecast obtained with different AI methods and with a combination of all methods

Beside the wind power forecasts, more detailed information on the power generation of photovoltaic (PV) plants is more and more of interest. The installed PV capacity of more than 3.500 MW in Germany influences the grid management partially. To detect the PV generation for the TSOs purposes, a model, comparable to the wind power prediction was developed. The combination of wind power and PV prediction gives the TSO a complemented picture of fluctuating in-feed in his control zone.

4. ACTIVE CONTRIBUTION OF RES TO SYSTEM RELIABILITY

Since a 100% accuracy of wind power forecasting is not realizable, the difference between the forecasted and instantaneous wind power production can only be minimized by means of advanced control strategies of wind farms. The pooling of several large wind farms to clusters will make new options feasible for an optimized control of intermittent generation. Geographically distributed wind farms will be aggregated to clusters, for the purpose of operating these wind farms as one large (virtual) wind power plant [11]. All wind farms, which are directly or indirectly connected to one transmission network node, are be associated to one wind farm cluster. The power production of a cluster will be controlled in accordance to the schedule determined by short-term forecasting. This strategy has a large impact on wind farm operation and requires matching of expected and instantaneous production on a minute-to-minute basis. The schedule compliance is achieved inside a certain confidence area determined by the forecast error. Time-variable set points are constantly generated and refreshed for a close interaction between wind farms and WCM. A continuously updated short-term prediction for wind farms and cluster regions is generated for this operation management. The following operating control strategies for wind farms and wind clusters were identified:

- Reduction of gradients to minimize ramp rates
- Supply of reactive power with a usual setting range like conventional-power-station
- Generation Management which controls and regulates the feed-in for the whole wind farm cluster
- Supply of balancing power to provide negative and positive reserve power for the balancing between wind power prediction and wind power generation
- Congestion Management by limitation of wind power output
- Scheduling of wind power feed-in to achieve a constancy in scheduling

Additional, non-controllable wind farms can be supported by controllable ones of the same cluster. So, the strategy allows hybrid clusters to meet the requirements.

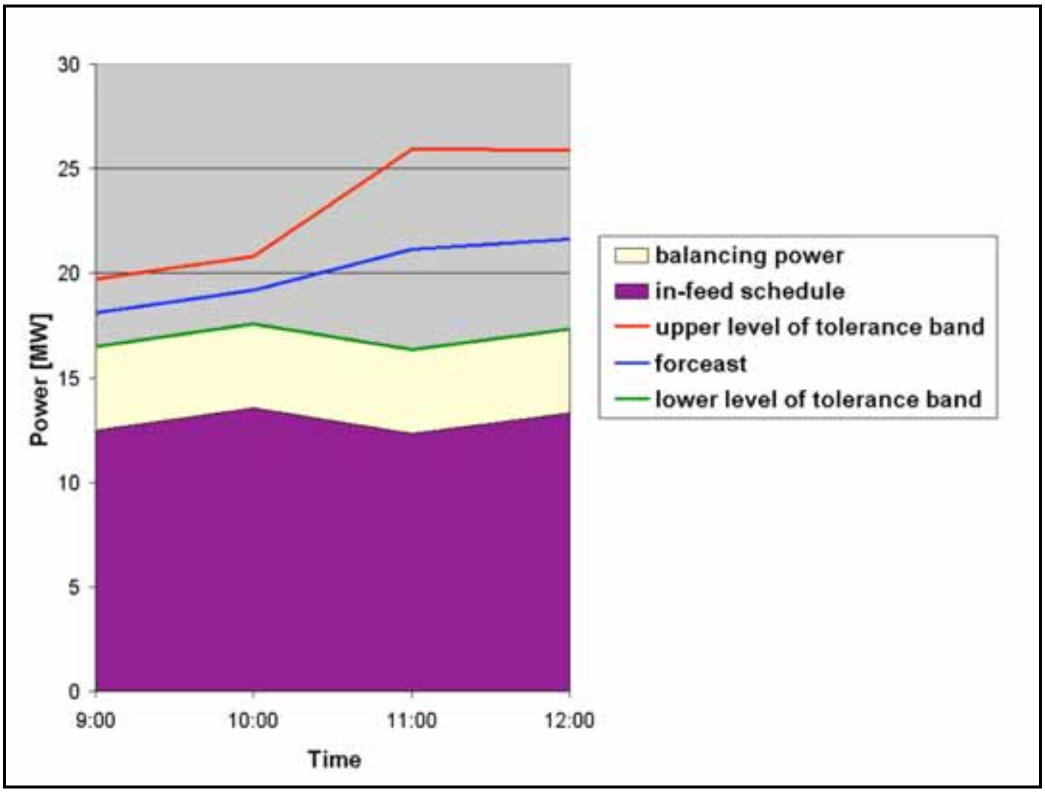


Fig. 6: Example for wind farm with balancing power after short-term prediction

The WCM will be located in the TSOs control center. The existing control-system is used to manage the data flow. The WCM receives the measured values from the wind farms. The desired values are sent from the WCM to the several wind farms.

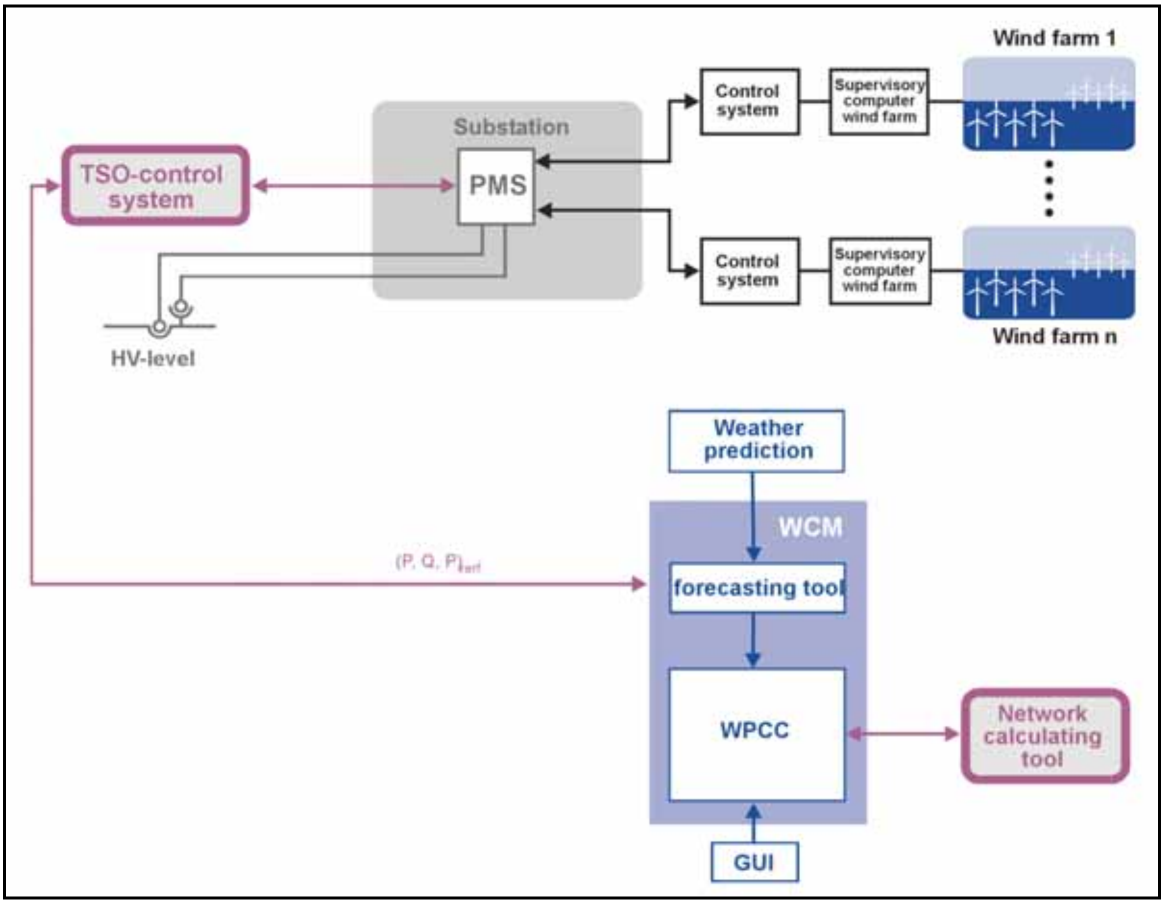


Fig. 7: Data flow between WCM, wind farm and the TSO control system

5. FULL SUPPLY OF ELECTRICITY WITH RES

The integration of RES into the electric power supply system continues to present interesting challenges to all parties involved. One of the main arguments against using renewable sources of energy is the lack of controllability due to discontinuities of generators such as wind and solar power plants. During the 2006 energy summit, the leading German manufacturers of RE plants (wind, PV, biogas) announced that they would prove in a clear and concrete way that the generation of renewable energies is reliable [12]. The goal of this project was to demonstrate that the demand for electric power could be met at any time by combining different forms of renewable energy generation. To this end, wind, solar and biogas power plants were merged in a Renewable Combi-Plant (RCP) with a total capacity of 23.1 MW. The plants were selected based on realistic future scenarios. The overall scenario simulates the energy demand and a realistic growth of regenerative energy generators in Germany at a ratio of 1:10,000. ISET's task within this project was to develop and operate the central control unit. Using a control algorithm, the system determines the optimum energy mix at any given point in time. The usage of resources from controllable biogas power plants is scheduled based on wind and solar forecasts. The project was presented at the 2007 energy summit and attracted great interest in the political and the industrial sector.

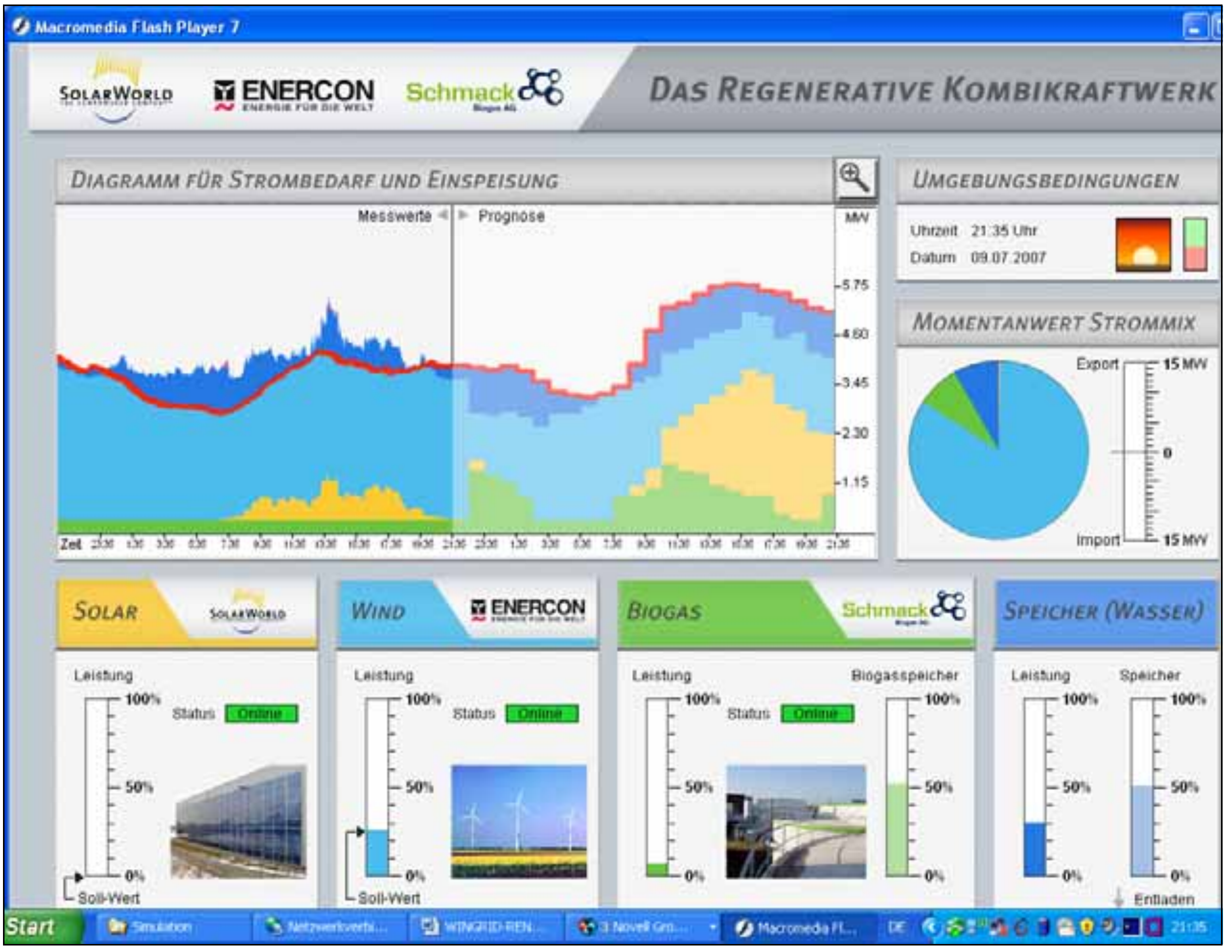


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Fig. 8: Control panel of the Renewable Combi-Plant

The RCP is in operation since May 2007 and is controlled to supply an energy mix to cover 1/1000 of the total electricity consumption at any time. The control algorithm of the system was tested with production data of wind farms and PV plants of 2006 to verify the needed production of biogas-fired CHP and pumped-storage hydro plants.

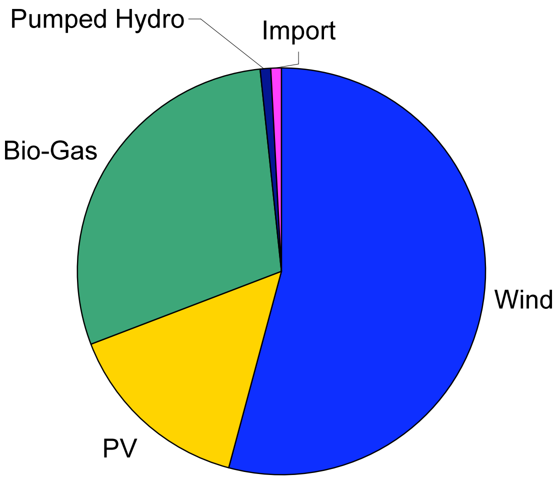

Fig. 9: Renewable energy mix of the Combi-Plant for the year 2006

Figure 9 shows the energy mix of the produced energy of the RCP in 2006. The total (simulated) generation was about 41,1 GWh, the shares of the members are 22,3 GWh (54%) wind, 6,1 GWh

(15%) PV, 12,0 GWh (29%) biogas, 0,3 GWh (1%) pumped storage and 0,4 GWh (1%) import. In addition, 3,3 GWh were exported and 6,3 GWh wind were curtailed. The values correspond to 1/10000 to the 100% RES electricity supply scenario for Germany in 2050. The control algorithm and the interfaces as well as the embedded forecast system can be easily adapted to other RES production groups.

6. CONCLUSIONS

The structural change in the power supply is characterized by adjustments of classical elements of the existing utility system as well as by the addition of innovative elements (automation, prediction tools, integration of storage technologies, active integration of the demand site etc.) for an effective utilization of RES. The continuation of this development as well as the introduction of adapted control strategies and competencies are necessary, in order to achieve constantly technological and economical optimized and justifiable solutions. With the further penetration of decentralized producers in the electrical power supply also their share of the tasks for system security and reliability needs to be increased. The combination and advanced control of intermittent RE sources wind and PV with biogas-fired CHP and pumped-storage hydro plants allows a scheduled electricity generation facing the demand at any time and prepares the way towards an energy supply without greenhouse-gas emissions.

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8. BIOGRAPHIES

Dr. Kurt Rohrig is head of ISET's Program Area Information and Energy Economy. Dr. Rohrig 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 frame of his work are in operation at all German transmission system operators with high wind power penetration. 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 Program Area 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 modeling.

Received 7 February 2008
Paper 08GM0572

3. Reliability Issues in Power Systems with DG

Józef Paska, Technical University of Warsaw, Poland
Adam Oleksy, Polish Power Transmission System Operator, Warsaw, Poland

***Abstract*--**Even, or may be particularly, in the time of disintegration, deregulation and competition in a power system, its reliability is one of the most important criteria which must be taken into consideration during planning and operation phases of its life. In many countries the increase of generating capacity takes place in small units of so-called distributed generation (DG). They use primary energy conventional sources as well as renewable energy sources (RES), and in many cases produce electricity and heat (CHP). Using of renewable energy sources is one of the crucial components of the sustainable development, giving rationale economic, ecological and social effects. Electrical energy sources can be qualified into two groups: with production dependent on unpredictable external sources of primary energy, and others. The most difficult is to analyze those, production of which depends on renewable energy sources like: hydro energy, the Sun, and wind energy. This paper presents chosen aspects of power system reliability modeling and evaluation, including distributed generation.

***Index Terms*--**electric power system reliability, distributed generation, renewable energy sources, reliability assessment methodology.

1. INTRODUCTION

After 1990 deep structural changes occurred and still occur in the electric power systems; takes place disintegration, deregulation and advancing market orientation. This is a worldwide trend. Departure from the vertically integrated structures, deregulation and market solutions in electric industry create new conditions, in which the responsibility for the satisfaction of power demands of individual customers is not and cannot be attributed to the particular electric power company. The objective of the electric power system, which is the assurance of electricity supply of the required quality to the customers at the possibly lowest cost and acceptable reliability of delivery is now the task decomposed into many components, and into many subjects.

Reliability is one of the most important criteria, which must be taken into consideration during planning and operation phases of a power system. Electric power sector almost all over the world is undergoing considerable change in regard to structure, operation and regulation. But from the reliability point of view in this “new era”, methods, algorithms and computer software capable of assessing at least the adequacy of systems much larger than in the past are needed [5], [9].

Although there are different opinions about the potential of efficiency enhancements in the energy sector and about the feasibility of CO_2 sequestration, all scenarios conclude that expansion of renewable energies offers the chance to join a path of sustainable energy. Renewable energy is thus the only dependable guarantor for a future energy supply.

Nowadays, in many countries the increase of generating capacity takes place in small units of so-called distributed power industry (distributed generation - DG), and among them in hybrid power (generating) systems (HPS) [3], [8]. They use primary energy conventional sources as well as renewable energy sources (RES), and in many cases produce electricity and heat (CHP). For example, Polish Energy Law Act [10] defines renewable energy source as unit which, in the conversion process, uses wind energy, solar energy, geothermal energy, sea wave and tidal energy, river fall energy, biomass energy, energy from landfill biogas and biogas produced in the process of sewage disposal and treatment or decomposition of plants and animal remains.

J. Paska is with Institute of Electrical Power Engineering, Warsaw University of Technology, Warsaw, POLAND.
A. Oleksy is with PSE-Operator being Polish Power Transmission System Operator, Warsaw, POLAND.

Additionally the Minister of Economy ordinance allows using of renewable sources (biomass) together with other fuels (co-firing).

2. DISTRIBUTED GENERATION AND ITS PLACE IN POWER SYSTEM

Distributed generation (also called dispersed generation, embedded generation) is a new area where up till now it is not established commonly used terminology [3-4]. There is no consensus on a precise definition as the concept encompasses many technologies and many applications in different environments. At one end, DG could include only small-scale, environmentally friendly technologies, such as photovoltaics (PV), fuel cells, micro-turbines, or small wind turbines that are installed on and designed primarily to serve a single end-user's site. At the other end, DG could encompass any generation built near to a consumers' load regardless of size or energy source. A CIGRE working group defined DG as all generation units with a maximum capacity of 50 to 100 MW, that are usually connected to the distribution network and that are neither centrally planned nor dispatched.

It is very often that definition of distributed generation is connected with definition of renewable energy sources. However, using of renewable energy sources in many cases includes distributed generation it should not narrow distributed generation down to renewable energy sources sector because it is important to underline that distributed generation uses also conventional fuels.

Distributed generation is using different kind of power generation technologies – from traditional, through CHP and renewable energy sources utilization, and fuel cells as well as energy storage. Cogeneration and renewable energy sources are often considered as DG. However, only a part of CHP and RES can be considered as DG.

Definition of distributed generation, used in this work, is presented below: small installations or power stations (50–150 MW), connected to distribution network or located on final consumers side (behind electricity meter), they often produce electricity using renewable energy sources or non-conventional fuels and also often in co-generation with heat (CHP technology) [4], [8].

Distributed generation sources could be localized in power system in different subsystems: distribution, transmission, final consumer own network; but mainly in distribution networks.

3. POWER SYSTEM RELIABILITY AND VALUE BASED RELIABILITY APPROACH (VBRA)

Reliability of the electric power system (EPS) is defined by its ability to secure the supply of electricity of acceptable quality to the customers. The reliability of subsystems, constituting the EPS, i.e. generation, transmission, distribution, can be analyzed separately. So, the reliability of the fulfillment of single function: generation, transmission, distribution and supply to the particular customers are considered. Three hierarchical levels can be also distinguished in the system [1-2], [5], [8]:

- first level (HL I) containing the equipment and units generating electricity;
- second level (HL II) containing both the units and equipment for generation and transmission of electricity;
- third level (HL III) containing whole system, including distribution.

This structure still well presents the main idea of power system functioning, but two additional aspects should be considered:

- Generation and distribution is divided into some number of independent energy companies.

- Utilization of renewable energy sources and small scale generating units located within distribution system, constituting distributed generation, increases.

First level (HL I) contains the equipment and units generating electricity and is the same as the first functional zone of EPS – the generation subsystem.

Second level (HL II) contains both the units and equipment for generation and transmission of electricity. The reliability indices of twofold type are counted: indexes for specific system nodes as well as “system” indexes for whole system or its area (on this hierarchical level).

Third level (HL III) contains whole system, including distribution.

Reliability is resultant of action of the whole electric power system in its hierarchical structure; therefore depends on reliability of generation, transmission and distribution of electricity.

The reliability assessment is made on the basis of the reliability indices accommodated to hierarchical level and task. Because of complexity of the problem for reliability indices’ calculation are used the computer programs adjusted to given tasks. These tasks are: the running and prognostic estimation of reliability for the planning needs of power system development, settling of transmission and delivery agreements and clearing of reliability in agreements.

The goals of all the actions in the field of power system reliability are:

- Maintaining of present system reliability level.
- Identification of investment projects which have the most cost effective contribution to maintain system reliability.
- Development and determination of quantified reliability measures for electric system planning.
- Assurance that future system parameters will meet predicted requirements of reliability.
- Valuation of reliability in terms of interruption service cost.

The evaluation of economic losses caused by electric power system unreliability is especially needed for analysis of alternatives of system development planning. Usefulness of an investment, which improves system reliability, may be estimated on the basis of relationship between costs and benefits. The tool for these development planning is cost – benefit analysis of power system reliability, known as value-based reliability approach (VBRA). The VBRA idea is shown in Fig. 1 [5-6].

The major components in VBRA are:

- Identification of alternatives. It means that all considered system reinforcements, both investment and in operation procedures should be listed and clearly identified.
- Assessment of capital costs and operating costs (connected with activities, which improve system reliability).
- Computation of reliability indices of power system for planned reinforcements. It should be done using adequate reliability model and efficient computer tool (e.g. GRA and/or TRELSS computer programs).
- Assessment of supply interruption costs. Both outage customer costs and utility outage costs should be taken into account.
- Ranking of alternatives, by the total costs of solution.

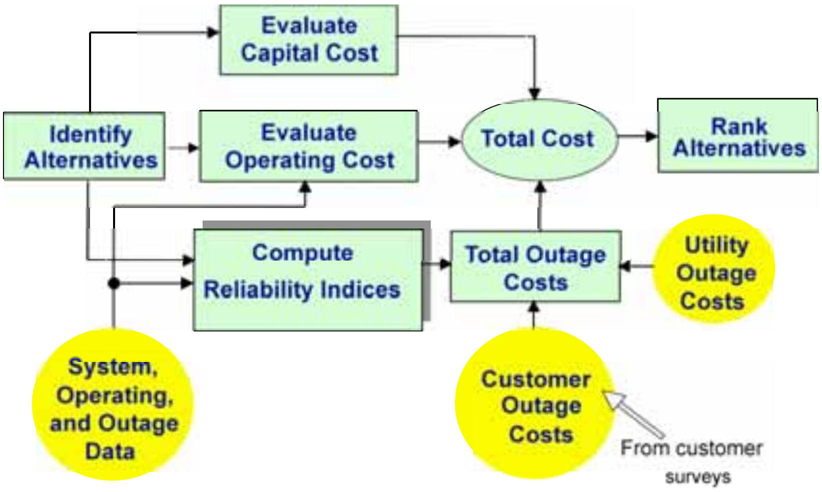

Fig. 1. General idea of Value-Based Reliability Analysis

Nowadays in power system analyses more and more common are probabilistic criteria. VBRA strategy is oriented on supplying to electric utilities the methods and tools for quantitative assessment and analysis of generation, transmission and distribution resources.

4. SOME REMARKS ON POWER SYSTEM RELIABILITY EVALUATION METHODOLOGY

Each hierarchical level of power system reliability analysis requires different approaches to evaluate relevant reliability indices.

4.1 Generation Reliability Evaluation

The first hierarchical level of the EPS is identical with the first functional zone, with the generation system. At this level the reliability of so-called simplified EPS is analyzed. The grid of this system does not introduce restriction, at normal and maintenance conditions, in the use of the available capacity of generation centers for the supply of customer units. So, the reliability of such system is the **reliability of electricity generation in EPS**, interpreted as the readiness of the electric power plants to cover the loads (**adequacy**) [1], [5].

The necessity of adjustment of generation capacity for the needs of customers gives more importance for the evaluation of generation reliability in the future, it's forecasting. The knowledge of anticipated reliability indices is the basis for the determination of the required capacity reserve in EPS allowing for the coverage of the expected system load (customers' demand together with grid losses) and for the performance of preventive and emergency repairs of the generating units.

The historical criteria of deterministic assessment of the reliability of electricity generation (capacity reserve equal to: determined percentage of the expected load, capacity of one or several biggest units, combination of two preceding options) are now more and more frequently replaced by the probabilistic criteria. The fulfillment of these probabilistic criteria is decided on the basis of the value of particular indices. The most often used reliability indices of electric power system at the level HL I are: LOLP (Loss of Load Probability), LOLE (Loss of Load Expectation), EENS/LOEE/EUE (Expected Energy Not Supplied/Loss of Energy Expectation/Expected Unserved Energy), EIR (Energy Index of Reliability).

The reliability of electricity generation can be analyzed as a problem of surpassing by the stochastic process of power demand (load) $Z(t)$ of the stochastic process of generation capacity

$P(t)$. The model of the generation reliability consists the stochastic process of power deficit $D(t)$, being the difference of those processes.

The parameters of this process are the quantitative characteristics of generation reliability. It may be those listed above and others.

Generating capacity adequacy assessment involves the creation of a capacity model and the convolution of this model with a suitable load model. A distribution function of available capacity can be used as the capacity model. This function could be evaluated by different methods.

The example of computer programs for generation reliability assessment is GRA program for the determination of distribution function of available capacity of the EPS and the generation reliability indices [5].

The subject range of the software includes generation subsystems consisting of two- and (or) multi-state generating units (number of states can not exceed 4). Generators are compiled in the groups of identical units. The number of groups and overall number of generating units in the system are limited only by the computer memory because the program evaluates resources and informs user about the resulting possibilities. The program enables to determine distribution function of available capacity by the methods: recursive, simulation, normal distribution, expansion in Edgeworth’s series (they were chosen because theirs applicability for both two- and multi-state models of generating units [1-2], [5]) and to calculate the mentioned above reliability indices of electricity generation.

The system load can be considered as the load: daily, weekly, monthly or annual. In each period the load can be:

- step, given in the marginal case by the values for every hour or half-of-hour;
- approximated by the function - exponential model of load, or polynomial of the 5th order.

The GRA program is the convenient and flexible tool for the assessment of the reliability of generation subsystem on the basis of whole set of indices, with the possibility of taking into account the multi-state reliability models of generating units.

4.2 Composite (Generation and Transmission) Power System Reliability Evaluation

During power system reliability evaluation on the second hierarchical level HL II the simple model: generating capability – load should be extended and include transmission network, i.e. capability to transfer generated power and energy.

Network reliability is determined by execution level of required tasks. The network tasks are: delivery of required power and energy with adequate quality; supplying of subjected network (including subnets with different voltage level); power leading out from power stations; utilization of international and intersystem connections for power exchange (usually periodically).

Failures occurring in the network components can introduce the limitations or absence of task execution and depend on location and connections of considered node (bus) in the system. Network tasks are realized with some probability. Troubles in realization of network tasks have different consequences, which strongly depend on type of fault and its propagation in network.

Methods of analysis and evaluation of composite power system reliability could be divided into two groups: analytical and simulation (Monte Carlo).

Analytical methods consist in calculations of reliability indices from the adequate mathematical model. Set of determined indices and their quality are the offshoot of assumed model and set of input data. The basic problems are the assumptions of simplification, which influences are frequently unknown.

By analytical approach usually the adequacy (sufficiency) of electric power system is estimated.

In the Monte Carlo based simulation methods, the basis is sampling power system states and then inferring the information from the sample.

Monte Carlo simulation consists of randomly sampling system states, testing them for acceptability and aggregating the contribution of loss of load states to the reliability till the coefficients of variation of these indices drop below pre-specified tolerances. The basic approach can be applied for each hour in a year in chronological order (sequential approach) or the hours of the study time can be considered at random (random approach). The simulation of the randomly selected system condition is done with the use of load flows, dispatch algorithms, and pre-selected operating policies. The results of the simulation are distributions of variables of interest (circuit flows, voltage levels, energy curtailment etc.). These results are used in the computation of appropriate reliability indices.

There are a number of computer programs available in the power industry to assess the reliability of the composite system. Practically all of them address only the adequacy of the system.

One of those computer programs is, developed by EPRI (Electric Power Research Institute) program TRELSS. In model applied in TRELSS the approach, consisting in creation of list of all possible system states (contingencies), choice and analysis of violation for determined conditions of system failure and calculation of reliability indices is used. For the reliability estimation is used the effective ranking of contingencies, basing on the components overloads and analysis of voltage conditions for several levels of load, load-flow calculation, linear programming for the optimization of remedial actions (change of load distribution between generating units, connection of parallel shunt, regulation with autotransformers, change of transformer taps, 3 classes of load curtailment) making for decreasing of emergency of the system. This allows determining the severity of deficit states of the system. States (contingencies) are chosen according to increasing level of severity of virtual fault, i.e. zero withdrawal, first degree of withdrawal (one component), second degree of withdrawal (two components) etc. This process will be stopped on some level of contingency depth (i.e. till 6 simultaneous disconnected components) or when probability of state will be lower as predetermined value (cut-off probability). The given state is in such way estimated only one time and the indices are calculated mathematically from the data described each state, i.e. probability, frequency, duration etc.

In TRELSS program the automatic action of so-called Protection and Control Group can be taken into account and imitate the situation, when the failure of transmission system component, because of incorrect operation of protection or circuit-breaker can make the disconnection of group of components.

TRELSS program allows to estimate the transmission reliability of nodes and areas taking into consideration the generation. The calculated indices are: frequency, duration, probability and expected values of emergency states as well as probability of not assurance of demand, expected amount of unserved energy, indices of consumer limitations.

TRELSS program is available under PC/WINDOWS, and with the help of this program large systems can be analyzed, with the size till 4500 nodes and 9900 branches (version 5.1).

TRELSS creates many output reports, divided into seven groups. Basic results of reliability calculation are included in two reports of the group VI:

- report respecting system reliability indices, consisting: severity of state of disconnection; probability and frequency of loss load; duration of loss load; expected value of unserved energy per year and per event; expected value of not met demand per year and per event; energy curtailment per year; number of states causing loss of load;
- report with consumer nodes’ reliability indices: probability and frequency of loss load, duration of loss load, expected value of unserved energy, expected value of not met demand.

TRELSS was implemented and used for the reliability investigation of Polish power system, considering generation (in system power plants) and networks 400 and 220 kV with equivalent of 110 kV network [6].

Basing on experience with application and implementation of TRELSS computer program in Polish electric power system conditions, in Warsaw University of Technology the special overlay computer program for TRELSS, named “SYSTEM TRELSS – PW” was created [7].

This program is user-friendly tool, adjusted for Polish condition and data, which allows doing the next step in application of transmission system reliability analysis.

5. IMPACT OF DISTRIBUTED GENERATION ON POWER SYSTEM RELIABILITY

Distributed generation has the potential to improve reliability of electricity service because, as noted above, it places the generation source closer to the demand centers. The combination of having many units in operation, thus reducing reliance on a small number of large generators, and the reduction in transmission and distribution, provides certain advantages over centralized generation.

In a stand-alone system, without grid support, the availability of having two plants instead of one is different and the resulting reliability characteristics will be more or less favorable depending upon the needs of the customer. With one unit, the probability of having no power is larger. With two units, the probability of half the capacity being unavailable is larger (since half the capacity will be lost if either unit is unavailable). However, in general, the resulting reliability is less than with the electricity grid because the unavailability of individual units is higher than the grid system as a whole. With distributed generation that is grid-connected, those concerns are lessened because the customer can rely on grid power when their individual unit is unavailable. As noted above, the costs of using DG for electricity only tend to be higher than with conventional electricity generation, unless cogeneration is used.

Grid interconnection is also an issue that must be considered when examining electricity systems with a high level of distributed generation. Traditionally, electricity grids were run in one direction, with electricity flowing from generators, through the grid, to consumers. Distributed generation places generators within the grid and requires the DG units and the grid to be run in parallel and coordinated. While this poses some problems for control of the grid, these problems can be addressed through digital control equipment. The issue of how to interconnect and control DG units in a grid is an active area of research and should not be an issue of concern for the problem at hand.

5.1 Power Generation from Wind

As we know, energy production in wind turbines depends mainly on wind speed in a place in which wind power plant is located. This dependency is called “power curve”.

The most commonly used probability density function to describe the wind speed is the Weibull’s function. The Weibull’s distribution is described by the following probability density function:

$$f(\upsilon) = \frac{k}{c}\left(\frac{\upsilon}{c}\right)e^{-(\upsilon/c)^k} \qquad (1)$$

where k is a shape parameter, c is a scale parameter and υ is the wind speed. Thus, the average wind speed (or the expected wind speed), $\bar{\upsilon}$, can be calculated from:

$$\bar{\upsilon} = \int_0^\infty \upsilon f(\upsilon)d\upsilon = \frac{c}{k}\Gamma\left(\frac{1}{k}\right) \qquad (2)$$

where Γ is Euler’s gamma function.

If the shape parameter equals 2, the Weibull distribution is known as the Rayleigh's distribution. For the Rayleigh's distribution ($k = 2$, and $\Gamma\left(\frac{1}{2}\right) = \sqrt{\pi}$) the scale factor, c, given by the average wind speed, can be found from: $c = \frac{2}{\sqrt{\pi}}\bar{\upsilon}$.

Correlation between probability density functions of wind speed in different locations is also concerned. Thus, wind velocities in all locations of distribution system are correlated random variables. Simulation of correlated random variables with Rayleigh's distribution is not an easy task. Recognition of probability density function of wind speed allows assessing probability density function of power generated by wind turbines in a way of analytical method or based on Monte Carlo simulation.

However, creating of analytical methods, as far as correlated random variables with the Rayleigh's distribution is concerned, is complicated, while Monte Carlo methods are easier tools. Monte Carlo simulation is used to model relations between wind speed and power generated in wind power plant.

Wind turbines – similarly as the other generators in the system – have two main functions that constitute their value in the power system:

- they generate electrical energy, their primary function that can be paraphrased as the workhorse function and expressed in GWh (units of electricity),
- they contribute to the system capability to match the power demand at every moment, to keep the lights on - the capability function that can be paraphrased as the muscle function and expressed for example in GW (power units).

Thus, a key parameter indicating the electrical energy generating value of a generator in the system is load factor (capacity factor). The load factor – the ratio of average generated power and rated power – of generator is measure for the amount of energy that can be produced per MW of generating capacity (rated capacity).

Countries experiences, especially where wind energy plays significant role, show that wind power stations have got low annual time of installed capacity utilization.

By its energy or workhorse function, a wind power plant is capable of avoiding energy to be generated by other plants in the system, for example conventional generators. Load factors (capacity factor) of typical conventional plants vary between 50 and 90%. Typical aggregated load factors (annual average) of wind power (onshore) are in the range of 20-35%, depending primarily on wind conditions, but also wind turbine design (rotor size with respect to generator size).

A question commonly addressed in studies on integration of wind energy in power systems is how much installed wind capacity statistically contributes to the guaranteed capacity at peak load. This firm capacity part of installed wind capacity is called *capacity credit*. Due to the variability of wind capacity credit of wind power plants is lower than for the other generation technologies. Capacity credit is not a term that refers to how much wind power actually replaces and should not be confused with the displacement of power from other power sources. The contribution of variable-output wind power to system security – in other words the capacity credit of wind – should be quantified by determining the capacity of conventional plants displaced by wind power, whilst maintaining the same degree of system security with unchanged loss of load probability (LOLP) in peak periods.

Despite the variations in wind conditions and system characteristics among the European countries and regions, capacity credit studies converge to similar results. For small penetrations, the relative capacity credit of wind power will be equal or close to the average production of wind power plants (load factor) during the period under consideration. It is proportional to the load factor at the time of the highest demand.

With increasing penetration levels of wind energy in the system, its relative capacity credit becomes lower. However, this done not mean that less capacity can be replaced. It means that new wind turbines on a system with high wind power penetration levels will substitute less than the first turbines in the system.

5.2 Power Generation in PV Systems

Production of electrical energy by means of photovoltaic systems depends mainly on intensity of solar radiation; thus, it is changing randomly during the day and season. So, therefore this generated power, like power from wind turbines, can be characterized using probability density function, which strictly depends on probability density function of radiation intensity.

Probability density function of radiation intensity can be estimated from statistical data; as a good reality description the following distributions are considered: lognormal distribution, beta distribution, Weibull’s distribution and others.

In this case correlation problem of solar radiation intensity between neighboring terrains does not occur. We may assume, with a big credibility degree, that probability density function of solar radiation intensity does not change significantly in examined terrain.

Probability density function of solar radiation intensity and probability density function of power produced by PV system can be estimated by means of analytical methods, easy to use thanks to linear dependence between power of solar cell and of solar radiation intensity. In reality, power produced by photovoltaic cells with area A and efficiency η is expressed as:

$$P(r) = rA\eta \qquad (3)$$

where r is intensity of solar radiation.

5.3 Power Generation in Small Hydro Power Plants

Energy production in hydroelectric power plant mainly depends on water flow, which can be characterized by many changes. To characterize energy production in hydroelectric power station, like in PV system, it is necessary to find probability density function of water flow – standard, widely used distribution (probability density function) does not exist – and then introduce probability density function of generated power.

Probability density function of water flow q can be obtained from statistical data. When we know probability density function of water flow, then probability density function of output power P can be analytically estimated, basing on the following expression:

$$P(q) = qh\eta\rho g \qquad (4)$$

where: h – effective head, η – overall efficiency of power station, ρ – water density, g – acceleration due to gravity.

Usually, for this kind of hydro stations their location depends strictly on availability of water sources place.

5.4 General Remarks

In the end, we would like to stress that energy production from wind, sun and in small hydro-turbines has variable (random) character and the only solution to describe theirs behaviors is to apply the statistical methods, statistical categories with appropriate daily, seasonal or yearly distribution of probability density function. However, practice shows that in some cases uncertainty is connected with selection of the best probabilistic model (probability density function) for description of random quantity both as concerns distribution (Rayleigh’s, Gauss’s, not-standard etc.) and its parameters (the mean, standard deviation etc.).

Power stations using renewable energy sources contribute to decrease dependency on fuels and energy import and in consequence to increase energy self-sufficiency factor. Through sources diversification they support also energy security.

Increasing renewable energy sources share, in assumption, should support reliability of energy supply to final consumers, but this assumption should be verified on each hierarchical level of electric power system.

Renewable energy sources and distributed generation can be a reason for different problems and dangers in electric power system.

6. CONCLUSIONS

Reliability of a power system decides about the quality of supply and consumers' trust, that they will get energy adequate to their requirements. It is necessary to perform a running and future assessment of power system reliability.

Even, or rather particularly, in the present situation of the liberalization of electricity markets and unbundling of generation, transmission and distribution, questions on the present and future reliability level arise, and the interest in detailed investigation of electric power system reliability issues, especially taking into account possibly the whole power system, increases.

For our energy supply to become sustainable, it needs to satisfy a large number of requirements: climate compatibility, sparing use of resources, low risks, social equity and public acceptance. At the same time it should also give a fresh boost to innovation and help to create jobs with a future. Numerous worldwide and regional studies indicate that renewable energy sources are capable of meeting these requirements. Relevant global and national scenarios for the future indicate substantial growth in the share of energy supplies that will be accounted for by renewable energy sources in the decades ahead. It is becoming increasingly clear that faster expansion of renewable energy systems is a necessary requirement for a sustainable energy future.

Properly installed and operated, DG can increase both end- user and grid reliability.

Analyzing an influence of distribution generation we can advance a hypothesis that energy production from renewable energy sources is the main reason of uncertainty.

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BIOGRAPHIES

Józef Paska (Prof., D.Sc., Ph.D., MEE) received the M.Sc. degree in electrical engineering from Warsaw University of Technology, Faculty of Electrical Engineering in 1974, Ph.D. in 1982 and D.Sc. (habilitation) in 2002.

Presently, he is Associate Professor at Institute of Electrical Power Eng. and Vice-Dean of the Electrical Engineering Faculty. Member of editorial boards of newspapers “Electrician”, “Energy Market” and “International Journal of Emerging Electric Power Systems”. His areas of interest include power system reliability and security of supply, electricity generation technologies including distributed generation and renewable energy sources utilization, electrical power engineering management and economics. Author of 5 monographs, 4 academic textbooks and over 200 journal and conference papers.

Adam Oleksy (MEE) received the B.Sc. degree in electrical engineering from Silesian Technical University, Faculty of Electrical Engineering in 1998, and M.Sc. from Warsaw University of Technology, Faculty of Electrical Engineering in 2001.

Adam Oleksy works in PSE-Operator, operator of the Polish transmission system. He is head of the group for technical analyses in Sales and Development Department of the PSE-Operator.

Paper 08GM0501
Received 02 February 2008

4. Future Distribution Systems with Dispersed Generation Will Require Network Security Measures as Transmission Systems of Today

R. Krebs, E. Lerch, O. Ruhle, Siemens, Germany
S. Gal, F. Lazar and D. Paunescu, Transelectrica, Romania

***Abstract*—**The paper describes typical developments of blackouts from simple cause to cascading outages. Possible measures to increase the system observability, combined with power electronic equipments as controlling elements, can lead to a future closed loop control of the power supply. The possible increase of the overall network security by protection security assessment (PSA) and dynamic network security assessment (DSA) will be shown. The described network and protection simulations, which are available today for the transmission sector, have to be adapted to future distribution systems with dispersed generation.

***Index Terms*—**Transmission system, distribution system, blackout prevention, dispersed generation, observability, controllability, security, PMU, DSA.

1. INTRODUCTION

The growing consumption of electrical energy in recent decades has led throughout the world to the development and physical expansion of synchronously operated AC grids as well as to higher voltage levels. In Europe, the technical and economic advantages of interconnected operation led to the linking of neighboring national grids, resulting in the creation of the synchronously operated UCTE (Union for the Co-ordination of Transmission of Electricity) system, which today supplies over 500 million people with 2300TWh.

As a result, larger, and therefore more efficient, generating plants can now be utilized while the need for reserve power has been reduced. At the same time transmission networks reached the highest possible levels of reliability and availability.

With deregulation and privatization, the load placed on the network is currently increasing. This means transport bottlenecks and deterioration in reliability. Global warming and the need to reduce CO_2 emissions will lead to a significant shakeup in the resources used and in the energy mix. Because in the past the transmission and distribution structures were adapted to the generation and load structures of the time, major structural and operational changes are now required in the systems.

Widespread failures and blackouts in America and Europe have confirmed that the interconnection of neighboring grids for operational and efficiency-related purposes also involves the risk of cascading power outages. Stability and protection are particularly problematic when the networks are working with a high level of capacity loading.

2. BLACKOUTS AND HOW THEY OCCUR

What is the difference between a blackout and a system disruption?

"A blackout is a widespread collapse in the power supply caused by a fault in the grid or in the provision of electrical power. Faults in distribution networks, on the other hand, merely lead to interruptions in local supply."

Let us assume that the transmission network is currently in a normal operating condition, all equipment is working within the limits for which it was designed, the grid is steady and well within the bounds of stability – under such circumstances large-scale disruptions are always triggered by a simple cause. This could be a short circuit, failure of a particular item of equipment or a planned power shutdown. If protection equipment now quickly and selectively disconnects the short circuit, or if the operator makes the right decisions, the grid will return to a normal operating state. If this is not the case because, as in the Italian blackout for example, synchrocheck settings in distance protection devices were wrong thus preventing "automatic reclosing", and operators did not make the right decisions to switch off pump storage, cascading power failures may be the result.

Fig. 1 shows this process in terms of the times involved. There was a good twenty minutes between the initial cause and the cascading failures: time that could have been used to return to normal operating conditions.

Once such cascading failures begin, the point of no return has been reached and when this has been passed, the grid consists of non-controllable islands in which overshoots and shortfalls lead to a frequency collapse, or reactive power problems cause a voltage collapse.

If one compares the disruption to the Italian grid on September 28, 2003 with the UCTE disturbance of November 4, 2006 [1, 2], it is recognizable that control was regained over the UCTE network before the point of no return by means of stable islanding as well as planned load shedding and generator disconnection. Normal operating conditions were restored within 30 minutes. In contrast, the Italian grid collapsed following disconnection from the UCTE network, leading to a full-scale blackout.

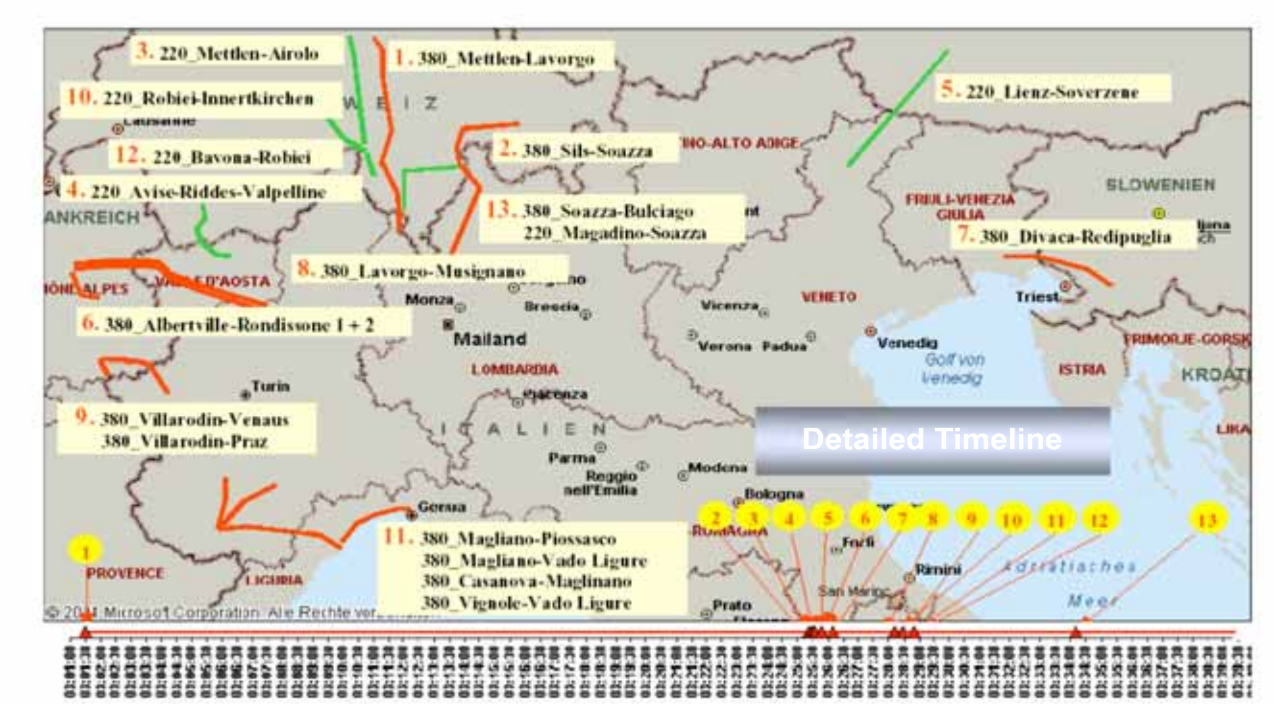


Fig. 1. Timeline of Italy Blackout September 28th 2003, 3:01 o’clock

3. OBSERVABILITY OF NETWORKS

As can be seen in Fig. 2, transmission networks are currently observed on a quasi-static basis, as a rule with asynchronous measurements, e.g. using RTUs with refresh cycles ranging from tens of seconds to a number of minutes. The measuring data, sometimes weakly correlated, is perfectly adequate for quasi-static control of the network, for example with corrective switching based on the results of the state estimator. The data is also sufficient for advance calculation of load/overload conditions prior to switching actions.

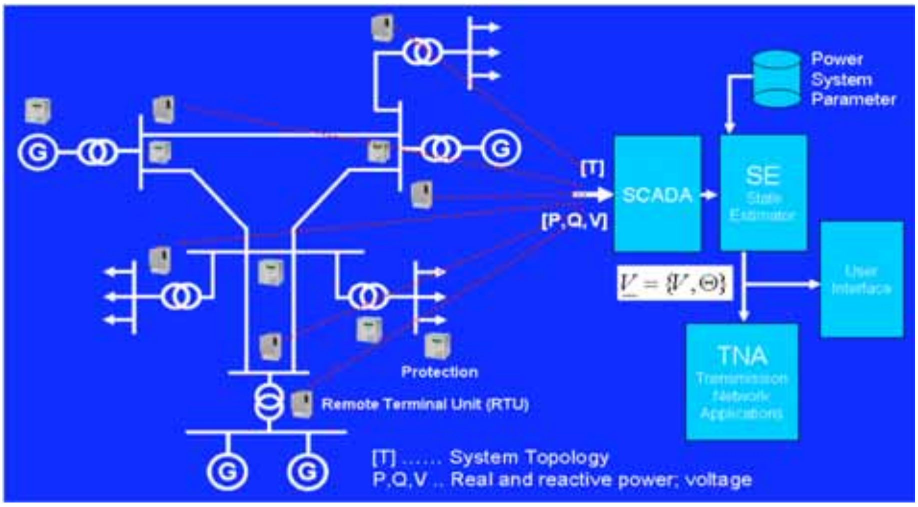


Fig. 2. Quasi Steady State System Measurement

The extremely high capacity loading of transmission networks means they are operated close to their stability limits; they tend more easily to oscillations during disruptions and, in future, will thus require improved observability for monitoring, protection and control. Today's existing PMUs (Phase Measurement Units), or devices with PMU functionality such as fault recorders, are characterized by four major points:

- time-stamped measurements with GPS synchronization
- highly accurate measurement of amount and gradient by current and voltage phasors
- highly accurate frequency measurement and df/dt measurement
- refresh cycles of 20 to 100ms

Using such equipment, oscillation can be detected and analyzed online and direct countermeasures derived to dampen it [9]. Furthermore, such well-correlated measurements are absolutely essential for dynamic power flow control (Fig. 3).

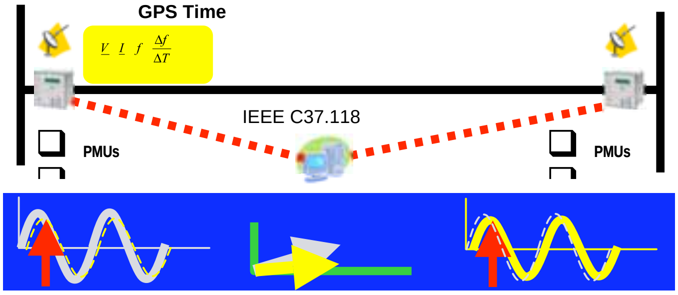


Fig. 3. Dynamic System Measurement with PMUs and Fault Recorders

4. NETWORK CONTROLLABILITY

According to the German Power Industry Act, every customer must be supplied with sufficient electrical power within the constraints of available technology. In the past, estimated consumption went hand in hand with the controllability of power generation. It was sufficient to intervene in the grid operation with switching actions and to control generation.
Today, two new aspects determine use of the transport network:

1. Electricity trading: The purchase and sale of electrical energy are determined by economic aspects only, regardless of the structure of the transporting network.

2. Use of renewable forms of energy: The obligation, imposed by the German Renewable Energy Act, to take up electrical power generated from renewable sources means that generation is increasingly subject to an overlying stochastic process.

On the one hand, this development must be met by a modification in the structure of the transport network; on the other hand, the power flow and dynamic processes resulting from the stochastic aspects in generation and consumption must be controlled. It is no longer sufficient to switch circuit-breakers to CLOSED or OPEN; what are now needed are regulable system elements such as phase angle regulators, static var compensators, HVDC back-to-back links – in other words: power electronics. As shown in Fig. 4, with the use of power electronics a number of aims can be achieved at the same time:

1. By reducing transmission losses and avoiding circulating flows, the transport network contributes to the reduction of CO_2 emissions.
2. The controllability (including in dynamic terms) of such system elements means they are in a position to considerably improve network stability whether they exercise local control or are integrated in national control strategies. Particular attention should be drawn to the impact of power electronics elements connected in series, as they act as firewalls in the network, blocking both short-circuit currents and blackouts.

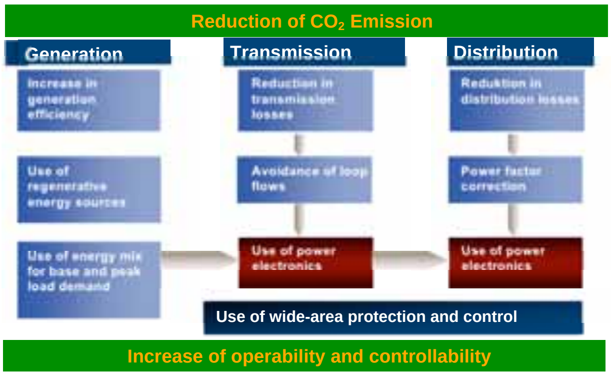


Fig. 4. Reaching 2 Goals with Power Electronics

Network studies can help to determine in advance the rated performance and the optimal installation locations of the power electronics elements.

Once such elements have helped to achieve a sufficient level of controllability in the transport network, and an appropriate level of observability has been attained by means of PMUs, a great many more stochastic generators, such as wind farms, can be integrated into the transport network.

5. NETWORK SECURITY WITH SIGUARD

5.1 Protection Security Assessment (PSA)

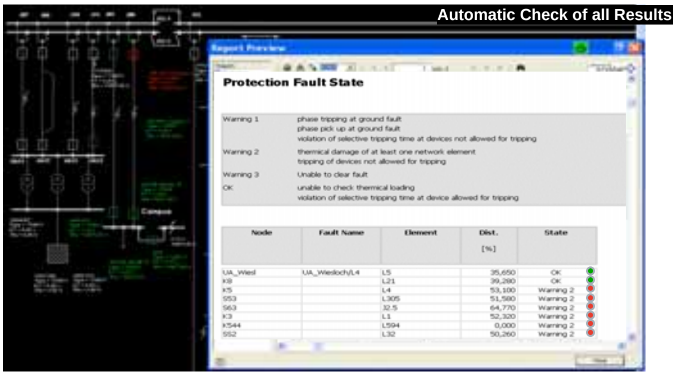
Analysis of network disruptions in various countries and continents has shown that there has been scarcely any blackout not involving protection devices with wrong or critical settings.

Recurring problems included:

- zone 3 openings of distance protection devices. This zone often also serves as overload protection instead of the thermal model as implemented in numerical relays
- uncoordinated or unselective short-circuit or overload protection, e.g. crossing borders between various grid operators

- synchrocheck settings too low
- reserve over current-time protection working parallel to distance or differential protection without added time delay
- primary networks extended, developed or modified without adjusting the protection concept or protection settings.

An important element in the prevention of blackouts is the online or offline Protection Security Assessment (PSA) [4, 5, 6, 7, 8]. Based on the current switching condition of the network, an automatic analysis of the selectivity of the network and generator system can be conducted. This requires of course the functions of the deployed relays, their characteristics and settings as well as communication between devices. With PSS^{TM}SINCAL as the basic functionality as shown in Fig. 5, any imaginable type of fault can be automatically placed at any location; starting and shutdown of the relays are simulated and then evaluated in terms of selectivity aspects. The results of the analysis can be alarm lists, which may serve as information for any protection study. However, an expert system can also be used which proposes improved, selective protection settings. These can be verified and documented within the scope of a further simulation loop, before actual parameterization in the relay.



Protection Fault State

Warning 1	phase tripping at ground fault phase pick up at ground fault violation of selective tripping time at devices not allowed for tripping
Warning 2	thermical damage of at least one network element tripping of devices not allowed for tripping
Warning 3	Unable to clear fault
OK	unable to check thermical loading violation of selective tripping time at device allowed for tripping

Node	Fault Name	Element	Dist. [%]	State	
UA_Wied	UA_Wiesloch/L4	L5	35,650	OK	●
K8		L21	39,280	OK	●
K5		L4	53,100	Warning 2	●
S53		L305	51,580	Warning 2	●
S63		32.5	64,770	Warning 2	●
K3		L1	52,320	Warning 2	●
K544		L594	0,000	Warning 2	●
S52		L32	50,260	Warning 2	●

Fig. 5. Protection Security Assessment with PSS^{TM}SINCAL

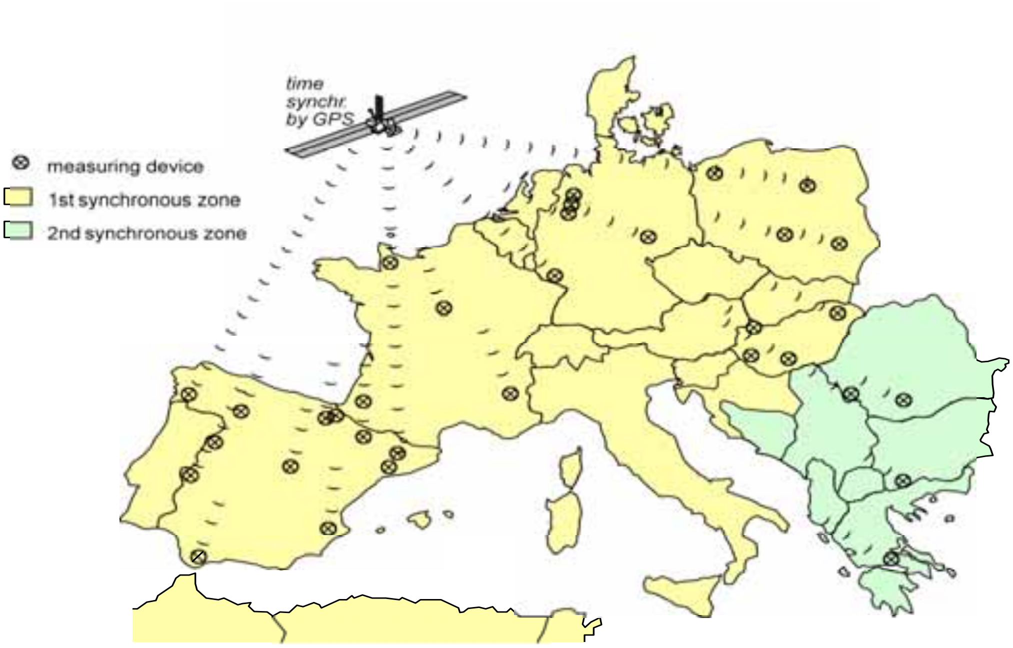
5.2 *Dynamic Security Assessment (DSA)*

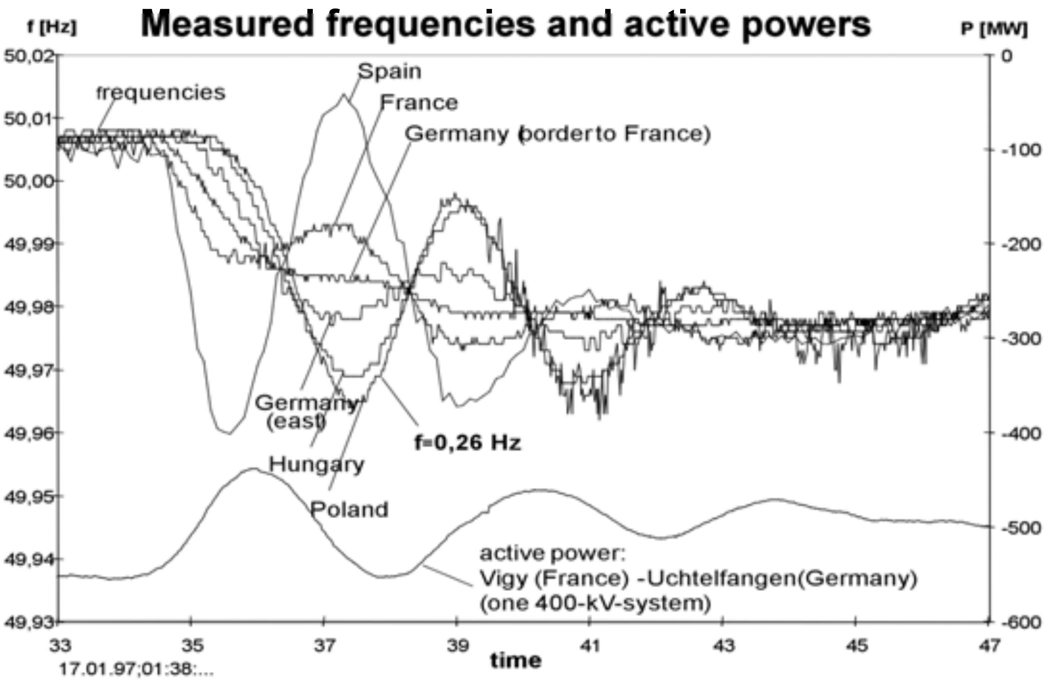
Network disruptions such as short-circuits, equipment failure, generator failure or sudden changes in the network resulting from switching actions trigger electromechanical compensation processes. A prior dynamic security assessment must be conducted to ascertain whether such processes pose not only static but also a dynamic threat to network stability [3, 4, 10, 11, 12]. In so doing, all passive equipment (such as wiring, cables, transformers,) as well as actively switched or controlled equipment (generators, capacitor banks, FACTS,), including their controllers, must be simulated.

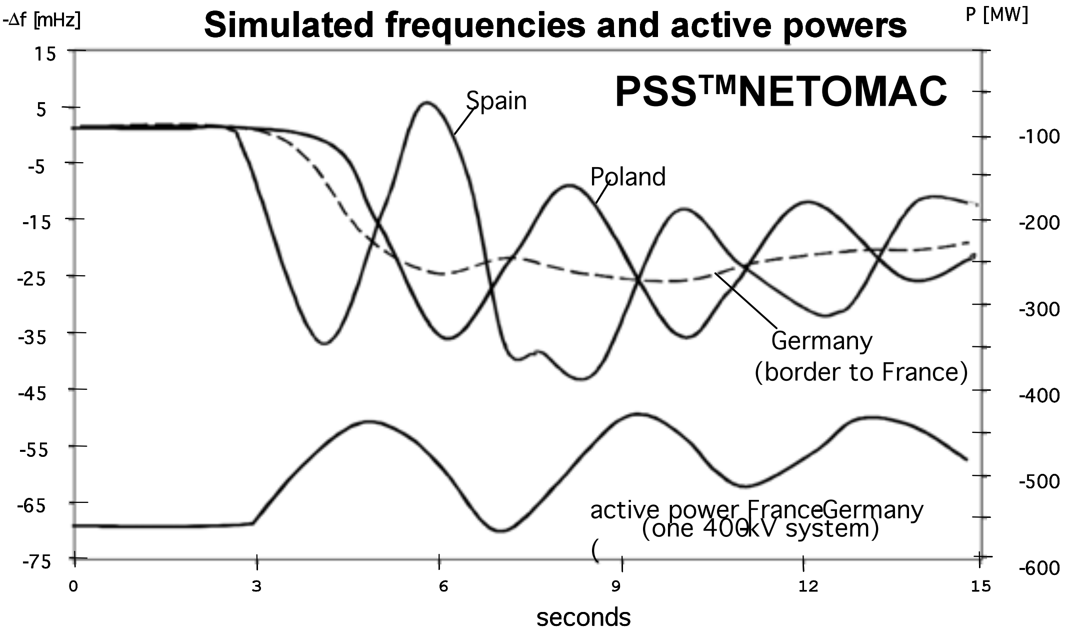
Fig. 6 shows how well this can be achieved using PSS^{TM}NETOMAC as the basic tool.

During an actual failure at a power plant in Spain, the local network frequencies were shown in various countries as well as compensation statistics between countries. These records served as a benchmark for the PSS^{TM}NETOMAC program, in which the UCTE network 2004 was simulated with 610 generators, 4400 nodes, 12000 branches and 1050 controllers. A comparison of the simulation results with the actual disruption clearly shows that the dynamic electromechanical network behavior following disruptions can be determined and evaluated in advance.

This network model can be simulated in a fraction of the real time on a standard laptop with an operation lasting 10-20ms, which is quite sufficient for electromechanical compensation operations. Many, possibly critical, network disruptions which must be examined online within the scope of the DSA can be processed in parallel on a PC cluster, meaning that the results are available for evaluation at the same time.







Source: E.ON - RWE Net - Siemens 11/2002

Fig. 6. Dynamic Security Assessment with PSS™NETOMAC
Trip of a 900 MW Power plant in Spain

6. SUMMARY

The challenges faced in power transmission and distribution are driven by a rising demand for electrical power, increasing urbanization, scarcity of resources and growing environmental awareness. This leads to increasing transport of large volumes of traded power over long distances with an associated upsurge in the load placed on equipment, taking it right to its thermal limits. More use of renewable energy (centralized by means of wind farms or decentralized in the form of solar installations) leads to an increase in the non-controllable share of overall generation. Transport and distribution networks must be adapted to changes occurring in generation.

There are a number of new ideas and solutions that can be applied in order to meet these challenges and to be able to ensure a continued reliable supply of power:

- An improvement in network observability can be brought about today using protection devices and fault recorders with PMU functionality, and decentralized or centralized analysis via standardized communication networks.
- Controllability of transmission networks can be considerably improved by the use of power electronics such as HV- or MV-FACTS.
- Wide-area networks are certainly the most efficient solution for trouble-free operation, but disruptions must be locally restricted. This can be accomplished using HVDC for long-distance transmission or as a B2B back-to-back link.
- Reliability of the overall network, provided by primary and secondary protection systems, can be significantly enhanced if the right conclusions are drawn from advance SIGUARD DSA and PSA analyses, and such conclusions are then made available to the operator in the form of recommended action.
- Finally, from a control point of view, we should set our sights on a Wide Area Monitoring Protection and Control System for such complex non-linear systems.

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8. BIOGRAPHIES

Rainer E. Krebs, born 1958 in Germany (member of VDE, CIGRE, IEC and DKE), received his Dipl.-Ing. Degree from the University of Erlangen in 1982. From 1983 to 1990 he worked as an assistant professor at the Institute for Electrical Power Supply at the same University. In 1990 he received his Dr.-Eng. degree in Electrical Engineering. 1990 he joined Siemens AG, Power Transmission and Distribution, System Planning Department. Since 1998 he is director of the System-Protection and System-Analysis Tools Department and since 2006 he is ‘Principal Expert for Power Technologies’. In parallel he started in 2003 as lecturer at the University of Magdeburg.

Edwin N. Lerch, born 1953 in Germany received his Dipl.-Ing. Degree from the University of Wuppertal/Germany in 1979, where he also completed his PhD (Dr.-Ing.) in electrical engineering in 1984. Since 1985 he has been a member of the systems planning department at Siemens in the industrial power system and machine group. He is currently working in the areas of power system stability, dynamics of multimachine systems, control, optimization and identification problems in electrical power systems. Since 1994 he is a director of the department group ‘Industrial Systems, Dynamic of Grid and Machine’. Since 2006 he is ‘Principal Expert for Power Technologies’.

Olaf U. Ruhle, born 1965 in Germany. He received his Dipl.-Ing. and Ph. D. degree in electrical engineering from the Technical University of Berlin in 1990 and 1994 respectively. Since 1993 he is a member of Power Transmission and Distribution Group and the system planning and consulting department at Siemens in Erlangen, Germany. He is working on power system stability, dynamics of multi-machine systems, control, optimization and identification problems in electrical power systems. He is responsible for the PSS^{TM}NETOMAC program system support, sales and training worldwide.

Paper 08GM1177
Received February 2 2008-02-02

5. Local DER Driven Grid Support by Coordinated Operation of Devices

Cor J. Warmer, Maarten P. F. Hommelberg, I. G. Kamphuis and J. Koen Kok, ECN, The Netherlands.

Abstract-- In the traditional operation of electricity networks the system operator has a number of ancillary services available for preservation of system balance. These services are called upon near real-time, after the planning phase.

Ancillary services consist of regulating power, reserve capacity and emergency capacity, each with their own characteristics. Regulating power is deployed via load frequency control. Reserve capacity is used to release regulating power and can be called upon to maintain a balance or to counterbalance or resolve transmission restrictions. Both are traded at the Dutch energy market under an auction model with a single buyer (TenneT). Emergency capacity is rewarded on the basis of accessibility/availability within 15 minutes.

In local electricity networks neither planning nor ancillary services exist. Planning is done by aggregation into large customer groups. For ancillary services one relies on the system operation as sketched above.

In local electricity networks with a large share of distributed generation the costs of keeping the electricity system reliable and stable will increase further and technical problems may arise. The European SmartGrids initiative responds to these challenges in their strategic research agenda. One of the issues addressed in this agenda is the changing role of the distribution grid in which users get a more active role. One opportunity is the introduction of ancillary-type services at the distribution level, utilizing different types of producing and consuming devices in the local network, in order to make the total system more dependable.

Distributed generation has a number of characteristics that are similar to characteristics of consumption. Part of it is intermittent / variable, although to a large extent predictable (PV, wind versus lighting, electronic devices). Another part is task-driven (micro-CHP versus electrical heating). Yet another part is controllable or shift able in time. And storage can behave both ways. The main key words here are flexibility and variability. This flexibility provides a virtual storage capacity within the electricity grid that can be utilized for balancing services at the local grid.

We will present how the PowerMatcher concept, developed by ECN, supports the setting up of local balancing markets in a flexible and logical way. The ICT is already available as an enabling technology. The concept has been demonstrated in several field tests.

Index Terms-- Multi-agent systems, Cooperative systems, Distributed control, Power distribution, Power system control.

1. NOMENCLATURE

CHP - Combined Heat and Power
CRISP - CRitical Infrastructures for Sustainable Power
DER - Distributed Energy Resources
DG - Distributed Generation
DNO - Distribution Network Operator
ECN - Energy research Center of the Netherlands
ICT - Information and Communication Technology
PRP - Program Responsible Party
PV - Photovoltaic
TSO - Transmission System Operator

VPP - Virtual Power Plant

2. OPERATION OF THE POWER GRID

Operation of the power delivery infrastructure is a delicate process aimed at obtaining a final balance at real-time between power supply and demand.

2.1 Phases in grid operation

Planning phase: Long-term contracts between producers and consumers determine a base load. To adapt to realizations differing from previous estimations and for Program Responsible Parties (PRP) who can decide on a short time range trading is done on a central market, the power exchange. In most countries a program is defined, in which contracted volumes are incorporated. In a program the amount of power generated as a function of time is fixed. Typically a program is defined on a day-ahead basis. As the time of delivery is nearing, slight updates and adjustments of the program are contracted by the program responsible parties in order to adapt to actual power demand. In some countries of Europe an intra-day market is operating for trading surpluses and deficits in capacity and demand.

Ancillary services: In the traditional operation of electricity networks the system operator has a number of ancillary services available for preservation of system balance. These services are called upon near real-time, after the planning phase and are market-based.

Ancillary services consist of regulating power (voltage control, reactive power), different types of reserve capacity and contingency/emergency capacity, each with their own characteristics. Regulating power is deployed via load frequency control. Reserve capacity is used to release regulating power and can be called upon to maintain a balance or to counterbalance or resolve transmission restrictions. Both are traded at the Dutch energy market under an auction model with a single buyer (TenneT). Emergency capacity is rewarded on the basis of accessibility/availability within 15 minutes. Depending on the sign of the momentary imbalance, parties supplying or demanding power less than contracted in the planning phase are penalized by the authority.

Local protection: Apart from the above-mentioned centralized control systems local protection and control is exerted by components such as circuit breakers and reclosers. Typically this type of control is based on local information only. Novel concepts based on intelligence in the distribution grid by deploying local agents have been developed in the CRISP project 0. This type of application is not considered in this paper.

2.2 Distributed energy resource

Several forces drive a change in the current worldwide energy supply. A main ongoing change is the growing penetration of distributed electricity generation. Volumes of electricity to be traded for which the ancillary market is accessible are beyond the scope of current distributed energy resources. There are two ways to open up the ancillary market for DER. The first one is to aggregate volumes to a level that allows participation on the global ancillary market. This aggregation in so-called virtual power plants is the scope of research in the Fenix project 0. But large-scale penetration of distributed generation may lead to more emphasis on local networks where ancillary services become a necessity. This will create opportunities for DER to deliver ancillary services to distribution networks. To allow DER to perform local tasks and at the same time be active in grid support new control strategies are being developed based on organization of DER using distributed control techniques.

The role of DG in local grid support has also been one of the conclusions from the DG-GRID

European project, in which it is stated "*DG through aggregators can participate in balancing and reserve markets. DG can provide voltage support and compensate energy losses as required by DNOs. In the future, with higher levels of network automation and DG controllability, DG would help to solve congestion management, and to improve quality islanding.*" 0. The European CRISP project 0 has shown what potential advanced ICT has if used to manage complex networks, evolving through the introduction of large scale DG. Note that in this paper we focus on DER rather than restrict ourselves to DG, including the demand side as well.

3. POWERMATCHER DISTRIBUTED COORDINATION

3.1 The PowerMatcher - a short introduction

The PowerMatcher is a control concept for coordination of supply and demand in electricity networks with a high share of distributed generation that implements market-based control theory. It is concerned with optimally using the flexibility of electricity producing and consuming devices to alter their operation in order to increase the over-all match between electricity production and consumption.

In the PowerMatcher concept each device is represented by a control agent, which tries to operate the process associated with the device in an economically optimal way. The electricity consumed or produced by the device is bought, respectively sold, by the device agent on an electronic exchange market 0, 0, 0. The electronic market is implemented in a distributed manner via a network structure in which so-called PowerMatchers, as depicted in Figure 1, coordinate demand and supply of a cluster of devices directly below it. The PowerMatcher in the root of the tree performs the price-forming process; those at intermediate levels aggregate the demand functions of the devices below them. A PowerMatcher cannot tell whether the instances below it are device agents or intermediate PowerMatchers, since the communication interfaces of these are equal. This ensures a standardized interface for all types of devices.

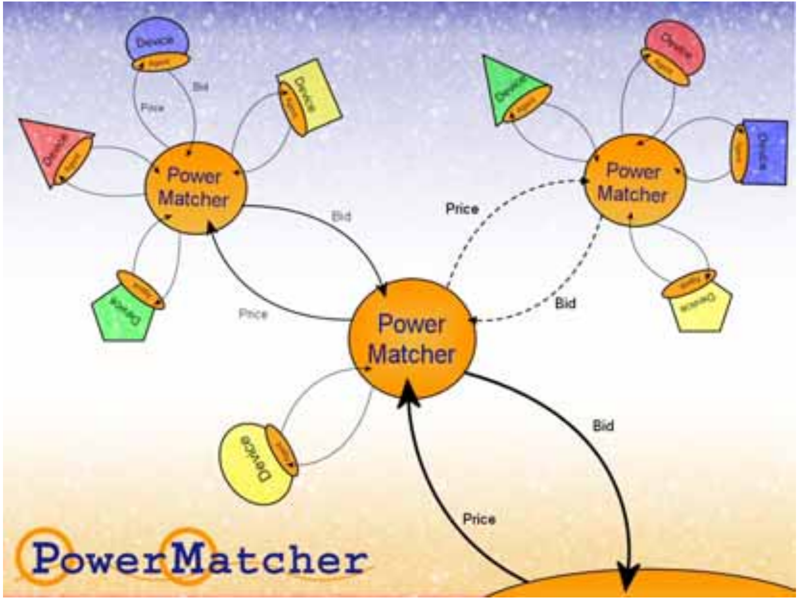

Figure 1 The PowerMatcher architecture; coming from a central tree based mechanism, growing towards a more organic, internet-like structure.

The root PowerMatcher has one or more associated market mechanism definitions, which define the characteristics of the markets, such as the time slot length, the time horizon, and a definition of the execution event (e.g. "every 5 minutes", "every day at twelve o' clock"). When an execution event occurs, the root PowerMatcher sends a request to all directly connected agents to deliver their bids. The device bids are aggregated at the intermediate matchers and passed on up-wards. The root PowerMatcher determines the equilibrium price, which is communicated back to the devices. From the market price and their own bid function each device agent can determine the power allocated to the device.

3.2 Flexibility of Demand and Supply

From the viewpoint of controllability, devices that produce or consume electricity fall into a number of main classes, each having a specific agent strategy implemented in the PowerMatcher agent library. An agent strategy is a mapping from the device state history to a demand function shape.

The first class consists of stochastic-operation devices, such as solar and wind energy systems, where the power exchanged with the grid behaves stochastically. As the power output is not controllable, the standard supply function shape is a flat line at a magnitude of the current production level.

The second class is shift able operation devices, which must run for a certain amount of time regardless of the exact moment and thus are shift able in time. An example of such a device is a ventilation system in a utility building that needs to run for 20 minutes each hour.

The third class comprises thermal buffer devices. Examples of these devices are heating or cooling processes, whose operation objective is to keep a certain temperature within lower and upper limits. Changing standard on/off-type control into price driven control allows for shifting operation to economically attractive moments, while operating limits can still be obeyed. Devices in this category can both be electricity consumers (electrical heating, electrical cooling/freezing) and producers (combined generation of heat and power).

As a fourth class grid-coupled electricity storage devices emerge, such as flywheels, super capacitators or redox-flow batteries, each with different time-scale of use. They are regarded as an enabling technology for increasing penetration of distributed generation, but currently only is economically feasible in niche applications. Also the expected revolution of the electric vehicle, especially in vehicle-to-grid scenarios will be a driver for the development of grid-coupled storage devices.

Freely controllable devices make up the fifth class. Example is an emergency generator.

A special class form user-activated devices that are expected to be operated on direct user command. From an agent point of view these devices - especially when aggregated into larger clusters - are comparable with stochastic operation devices.

Local agent’s self-interested behavior causes electricity consumption to shift toward moments of low electricity prices and causes production to shift toward moments of high prices. So, matching of demand and supply emerges on the global system level.

4. GRID SUPPORT BY COORDINATION OF DER

The changing role of the distribution grid and the availability of ubiquitous and low-cost ICT enable a number of potential ways in which distributed energy resources can participate in grid support. Note that we restrict ourselves in the following list to (soft real-time) coordination of devices, and do not take into account stability issues (hard real-time control). Also local protection falls outside the scope of this paper.

Participation in traditional ancillary markets: By aggregation of distributed energy resources into a so-called virtual power plant a (virtual) machine is created that contains the flexibility to deliver regulating services in case of a network imbalance.

Local balancing services: Future electricity networks will have a large degree of local generation to such a degree that local network balancing becomes a major issue. Especially if local networks are capable of running autonomously, such as in the MicroGrids concept, local balancing is has to be contained in the control strategy.

Reactive power compensation: As decentralized generation such as from wind or solar or from μ-CHP in general are devised to supply only real power, reactive power still has to be delivered by the higher grid levels. In a future situation, high-voltage grid parts may temporarily deliver a relatively low amount of real power to their middle-voltage grid parts whilst the reactive power need in these parts remains the same. To adapt to this situation in a flexible way, a significant part of the central generation capacity temporarily may have to be committed to delivering reactive power mainly. As delivering mainly reactive power is not an economically viable way of operating central generation capacity and high-voltage grids, a solution is sought by generating reactive power at the decentralized generators.

Network congestion: If in a distribution system the substation or line capacities are at stake the network operator has to fall down to load shedding techniques in order to alleviate the system. The optimal way to avoid distribution congestion is to avoid peak loads. Coordination if DER devices can become an important tool for network operators if their flexibility of operation is utilized such that demand is shifted to periods with lower demand and supply is shifted to periods with higher demand.

Connection capacity reduction: In critical circumstances network operators may put restrictions on household connection capacity. If not properly guarded this restriction may lead to local outage behind the meter. Local intelligence can prevent this by coordination – at a local level – of household appliances. If distributed generation or storage is available, the household may be able to stay up and running for some time with infringing only low priority task.

5. POWERMATCHER BASED FIELD TESTS AND SIMULATIONS

Although developed as a concept for balancing supply and demand in a cluster of devices, the current version of the PowerMatcher focuses on coordination of supply and demand flows and is capable of providing a variety of services. This is possible by inclusion of so-called business agents that focus on the different goals of these services. In some cases these services can be built around real markets and real prices; in other cases the prices are only meant as a paradigm and it is better to speak of 'value' instead of 'price'.

Balancing services: Balancing services for network operation closely resemble balancing services at a commercial level. The main difference is that commercial imbalance leads to penalties for the energy supplier, whereas balancing for network operators should lead to a real-time balance. Using the flexibility of distributed devices for balancing therefore are only the first steps in maintaining an instantaneous demand and supply balance in the network.

In 0 the results are described of a field test in the Netherlands aimed at commercial balancing. Wholesale trading parties have to make their production and consumption plan available to the transmission system operator (TSO). We refer to these parties as balancing responsible parties. Deviations from these plans are dealt with by the TSO by contracting capacity for primary, secondary and tertiary control. The cost for these services is imposed on the balance responsible parties that are responsible for the deviations. In order to reduce these costs an Imbalance Reduction System been developed, based on the PowerMatcher concept, to assist a PRP in reducing the imbalance of a cluster of devices including wind turbines (see Figure 2). Each 5 - 15 minutes the production and consumption plan of the cluster is compared with the real-time outcome and the operation of the controllable installations in the cluster (cold store, emergency generator, CHP for district heating and residential heat pumps) is adjusted to minimize the deviation between plan and operation. The operational goals of these devices serve as a constraint. The main focus of the field test is to reduce the wind power dominated imbalance in the cluster.

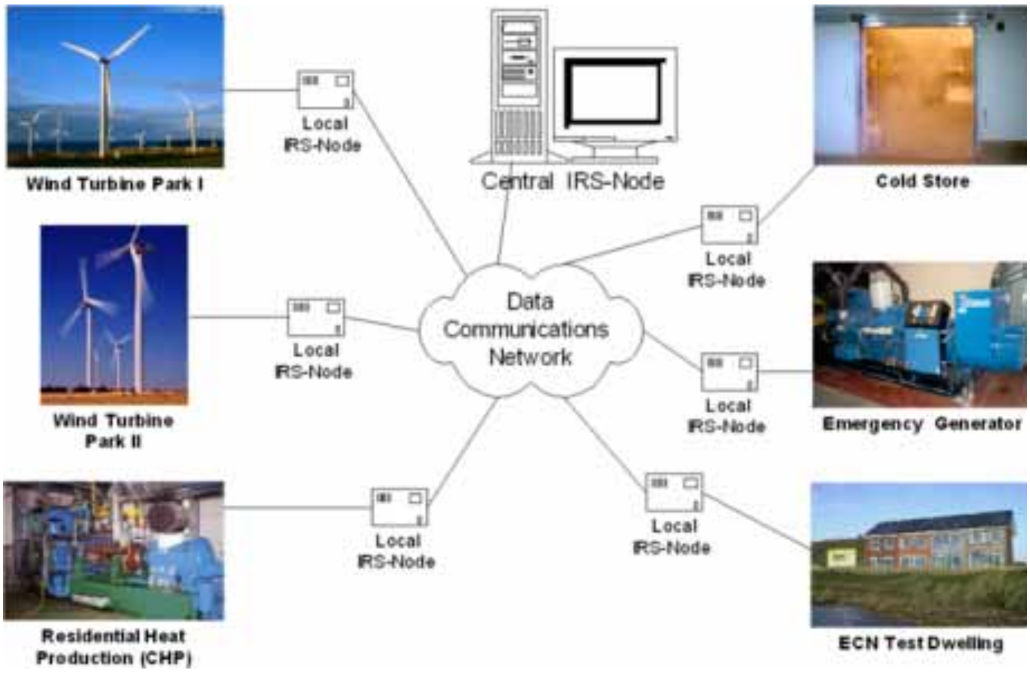

Figure 2 Field test configuration for the Imbalance Reduction System

The total imbalance reduction achieved over an 11-day period is 40%. This reduction has been mainly achieved by compensating for overproduction of wind power. Apparently, there is enough flexibility in the cluster to increase consumption and/or decrease production in these periods. A large part of the underproduction of the wind power has not been compensated. Close analysis of the individual agents' behavior suggests a reason for this. As the weather was quite cold during the measured period, the residential CHP's were scheduled at 100% operation. This 'must-run' situation did not allow for room to shift production towards the periods of wind underproduction. Yet the CHP's could be partially turned off for some periods without infringing the thermal comfort.

Peak reduction: The First Trial field test in the Netherlands *0* comprises of a cluster of μ-CHP units operated as a virtual power plant, demonstrating their ability to reduce the local peak demand of the common low-voltage grid segment the μ-CHP units are connected to. The field test uses 10 domestic Stirling based μ-CHP units, $1kW_{el}$ each, at consumer premises.

In this way the VPP supports the local distribution network operator (DNO) to defer reinforcements in the grid infrastructure (substations and cables). Although not all μ-CHP units included in the field test are connected to the same low-voltage cable, during the trial a connection to a common substation (i.e. low-voltage to mid-voltage transformer) is assumed. Note that the field test actually controlled the μ-CHP units at people's homes.

Figure 3 shows the operation for one day in May 2007. Five μ-CHP units were participating. There is no space heating demand, only demand for tap water heating. The figure shows four demand peaks at the substation, of which the third peak is the least compensated. The second peak takes care of the larger part of the heat demand for tap water. At the third peak, following immediately after the second peak, the heat demand is already largely satisfied. Such a sequence of peaks can no doubt be compensated well during the winter season because of a continuous space heating demand. Simulations have confirmed this expectation. Nevertheless in the situation described a peak reduction of nearly 30% was obtained.

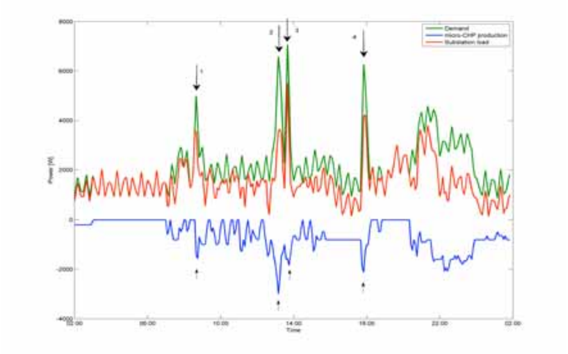

Figure 3 Time series of the substation demand pattern (green), the total μ-CHP production (blue) and the net substation load (red) for 5 μ-CHPs with PowerMatcher coordination.

Network congestion: A market outcome such as the PowerMatcher delivers is of no value if it does not yield a network feasible solution. The electricity transport network is subject to congestion by default due to capacity constraints on lines. In 0 a theoretical framework and an algorithmic method are described for finding transport network feasible solutions in market-based flow resource allocation. The algorithm can be built in the PowerMatcher algorithm, thus providing a powerful tool for congestion management in distribution networks.

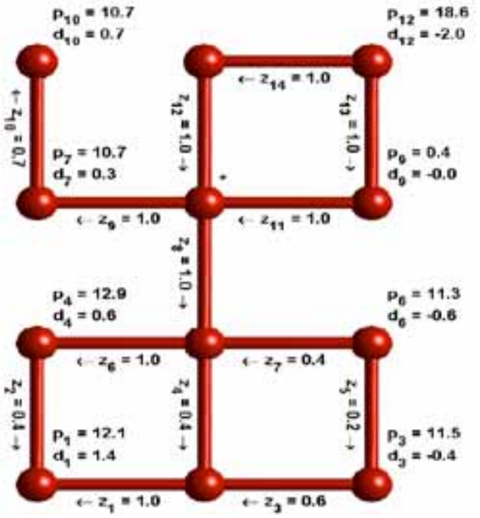

Figure 4 Example network feasible market result. The maximum line capacity is set to 1 for each line. Note that supply is indicated by negative demand.

Figure 4 shows the result of applying the above-mentioned algorithm in a network in which the maximum capacity of each line has been limited to 1. The figure shows the flows (z_i), the nodal prices (p_i) and the corresponding demand/supply (d_i).

Note that congestion in a competitive market can lead to price inflation by strategic bidding of generators. These effects have been mentioned by e.g. 0. Regulating measures have to be taken to tackle this risk. The effect of price inflation is less apparent in networks for which the

PowerMatcher is constructed. Not only are many of the generators task bound (e.g. temperature control for CHP units) and therefore less prone to strategic bidding. Also a substantial part of the consumers have the flexibility to alter their demand in case of high prices. Market power is more evenly divided and both sides can apply learning techniques to be better off.

Reactive power compensation: Several approaches have been proposed for local reactive power compensation. In one of these *0* the PowerMatcher approach is taken by letting decentralized generators equipped with power converters bid for reactive power compensation. Simulations of this approach show an effective reduction of the reactive power flow to zero at the sub station. At the moment it is under investigation whether active and reactive power can be traded in one market framework.

6. CONCLUSION

The paper describes the potential of the flexibility of distributed energy resources for a number of grid support services. The PowerMatcher concept for market-based coordination of supply and demand is demonstrated in a number of examples, both simulations and field tests. Main advantage of the PowerMatcher above more traditional price-reactive systems is the autonomy with respect to local processes, the scalability with respect to scaling up to large systems with tens of thousands and even millions of nodes. Business models need to be developed.

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8. BIOGRAPHIES

Cor Warmer was born in Utrecht on March 8 1955. He graduated as a mathematical statistician from the Universiteit van Amsterdam in 1981. He joined ECN in 1981 as a mathematics and statistics consultant in a scientific mainframe environment. He was later involved in a large number of projects focusing on data and object modeling. His current research includes process optimization of large energy consuming systems and optimization of power demand and supply flows in the distribution network using market based agent algorithms.

Maarten Hommelberg was born in Tilburg on October 9 1978. He graduated in the field of building services on the University of Technology in Eindhoven in 2005. The graduation subject was titled "Software agents for a building management system". His first and current employer is ECN. He is project leader in the Virtual Power Plant project and is currently working on optimizing power demand and supply flows in the distribution network using market based agent algorithms.

Koen Kok (1969, male) received Bachelor degrees in Electrical Engineering (1992) and Computer Engineering (1992). After a short working period at the University of Groningen, he started to study Computer Science at the same university and received his MSc in Computer Science in 1998. From 1998 to date, he is working as Researcher and Project Co-coordinator at ECN. He is working in the interdisciplinary field between electrical engineering, systems control and ICT. His current research focus is on intelligent distributed control mechanisms for electricity grids with a high penetration of distributed generation.

René Kamphuis was born in 1952. He graduated from Nijmegen University in 1976 in Chemistry. After that he got a Ph. D. from Groningen University in Chemical Physics. His employment experience at ECN started with a position at the computing center. From there he went to a number of software engineering positions. Since then he is involved in the Intelligent Energy Grids program at ECN. He has been involved in a number of projects concerning the application of agent technology for comfort management in buildings and dynamic distributed applications in the electricity network.

Received 11 February 2008
Paper 08GM0040

6. Distributed Generation Producers' Reserve Management

Zita A.Vale, Hugo Morais, Marrilio Cardoso, Carlos Ramos, and H. Khodr, ISEP/IPP, Porto, Portugal.

***Abstract* —** Sustainable development concerns are being addressed with increasing attention, in general, and in the scope of power industry, in particular. The use of distributed generation (DG), mainly based on renewable sources, has been seen as an interesting approach to this problem. However, the increasing of DG in power systems raises some complex technical and economic issues.

This paper presents ViProd, a simulation tool that allows modeling and simulating DG operation and participation in electricity markets. This paper mainly focuses on the operation of Virtual Power Producers (VPP) that is producers' aggregations, being these producers mainly of DG type.

The paper presents several reserve management strategies implemented in the scope of ViProd and the results of a case study, based on real data.

Index Terms -- Decision-making, Distributed Generation, Electricity Markets, Reserve Management, Sustainable Development, Virtual Power Producers

1. NOMENCLATURE

DG	Distributed Generation
Fp	Fp – Penalties factor
Fr	Fr – Reserve factor
HWP	HWP – HIRLAM/WAsP/Park (Prediktor)
ISO	ISO – Independent System Operator
J	j – Producer associated to VPP
MOS	MOS – Model Output statistics
Mp	Mp – Forecasted market price
Mpen	Mpen – Forecasted market penalties price
Perc	Perc – Percentage of intended reserve
P_f	Pf – Power forecasted
P_i^{max}	Pimax – Nominal Power of the biggest generation unit
Pp	Pp – Energy price by producer
P_{therm}	Ptherm – Contracted thermal power
P_{VPP}	PVPP – Power that VPP can negociate in the market
R_j	Rj – Contracted reserve with associated producers
RMS	Route Mean Square
Rp	Reserve Power
R_{VPP}	VPP Reserve
VPP	Virtual Power Producer
VPPpen	VPP maximum penalties in percentage

2. INTRODUCTION

The increasing concerns with sustainable development are especially important for the power industry, due to the highly pollution impact of this sector and also due to the forecasted increase of energy needs for the next decades.

Distributed Generation, mainly based on renewable sources, can significantly contribute to a less polluting power sector. This has giving place to energy policies which incentive the use of DG, which is the case of the European Union energy policy. Such policies have led to a significant increase of distributed generation, raising some complex issues, both of technical and economic nature.

Some of these problems can be addressed with the implementation of Virtual Power Producers (VPP), allowing taking advantage of common management of several power producers. The advantage of such an organization is relevant not only in technical terms but also in economic terms, making DG more competitive and prone to participate in today' competitive electricity markets [10].

This paper presents ViProd, a simulation tool that allows modeling and simulating DG operation and participation in electricity markets. This paper mainly focuses on the operation of VPPs that are producers' aggregations, being these producers mainly of DG type.

The paper addresses the problem of reserve management in the scope of VPPs. Several reserve management strategies implemented in ViProd are presented.

In the Section III the concept of VPP is explained and the importance of VPP implementation in practice is addressed. Section IV addresses VPP' reserve management strategies in the context of their participation in electricity markets. Section V presents ViProd and Section VI presents a case study, based on real data. Finally, Section VII presents the most relevant conclusions.

3. VIRTUAL POWER PRODUCERS (VPP)

The aggregation of DG plants gives place to a new concept: the Virtual Power Producer (VPP). VPPs are multi-technology and multi-site heterogeneous entities. VPPs can manage DG so that generators are optimally operated and that the power has good chances to be sold in the market. Morevoer, VPPs will be able to commit to a more robust generation profile, raising the value of non-dispatch able generation technologies.

Under this context, VPPs can ensure secure and environmentally friendly generation and optimal management of heat, cold and electricity. They can also provide the means to ensure optimal operation, maintenance of generation equipment and electricity market participation.

VPPs must identify the characteristics of each one of their associates and try to optimize the selling activity so that each associate delivers the biggest possible amount of energy. The ideal situation would be to sell all the energy that its associates are able to produce at each instant. The problem is that this is not possible due to the uncertainty of generation of the technologies that depend from natural resources as the wind, sun, waves or water flows.

Considering the problem of generation uncertainty, one of the functions of the VPP is to determine the amount of reserve (spinning and static) and the power to negotiate in the electricity market.

In a deregulated market, generation is scheduled through an open wholesale market where large amounts of electrical energy are traded daily. Today, market places are organized across one or several countries, each market with its own set of rules. VPPs should adopt organization and management methodologies so that they can make DG a really profitable activity able to participate in these markets.

4. VPPS RESERVE STRATEGIES IN ELECTRICITY MARKETS

The method used by electricity markets to penalize the violation of the established contracts is not uniform, which implies different forms of VPPs strategies, according to the market where they are operating.

In markets where penalty mechanisms exist, such as the French, the Italian, the Finnish, the

Swedish or the British [3-9], the VPPs have to conveniently manage the generation capacity of their associated producers to assure enough reserves, to compensate generation oscillations.

The energy reserves will have to be assured, in first place, by producers using technologies that allow them to control the net injected power, such as co-generation, fuel cells, or gas turbines [2-8]. These producers may establish contracts with the VPP, for supplying the imbalance settlement energy. Start-up costs must be considered to decide what units should be in spinning reserve.

Another possibility for the VPP to assure some level of reserve will be to have specific plants or storage systems for that. These plants can be managed by the VPP or by another entity. However, it will have higher costs, essentially due to the required initial investment.

It is also possible to establish bilateral contracts with large power plants. These contracts are established for large periods of time, for example 6 or 12 months, with a fixed power contract, or daily in the spot market, in function of the forecasted needs. If the energy is bought in the market the purchase price will be equal to the selling price, resulting in profits due to the inexistence of penalties. If the energy is acquired by bilateral contracts, it will have a fixed value and it can be used for reserve or as a part of the production after checking that it is not necessary to use all power for reserve.

The VPP can also adopt a hybrid solution, combing more than one option of reserve, in order to minimize the costs and to diversify options.

Whichever the strategy to adopt, the VPP must define, previously, who are the producers that will compensate these generation variations, taking the following into account:

- The change of producer cannot cause substantial network impact (VPP must consider the power flow, system capacity restrictions and technical operating limits). On principle, the nearest producer is the one that origins fewer modifications in the network. However, the VPP, in accordance with the ISO, can undertake a power flow analysis to evaluate the producer change impact.
- Another criterion is the characteristics of technologies.
    - In energy surplus situations, the generation in excess must be deducted from the thermal generation, increasing the spinning reserve. Later, the generation by technologies that will be able to store the primary resources (biomass, biogas, gas and fuel cells) can be reduced;
    - When shortage situations occur, the power that lacks is compensated using the plants in the following order: Small hydroelectric; Co-generation; Fuel Cell; Gas Turbines; Thermal.
- The power price is also important for VPP’s choice. If there are no constraints, the VPP buys reserve to the cheaper producer, always considering the established contracts with producers.

The reserve value that the VPP will have to guarantee depends basically from the penalties imposed by the Market and from the generation technologies that it can use.

A possible strategy is to have as reserve the amount of power that guarantees n-1 security. In this case, if the biggest generation unit gets out of service and if all the other producers are operating in accordance with the foreseen, the VPP will be able to continue to guarantee all the established contracts.

Let us consider a VPP with n associated producers. If this VPP contracts a fixed power value with a thermal producer, on an annual basis, to use for reserve proposes, we have:

$$PPR_{thermij} =+ {}^{max} \overset{n}{\underset{j=1}{\leftrightarrow}} \tag{1}$$

Where:

P_{therm} = *ContractedThermalPower*

P_i^{max} = *NominalPowerofthebiggest GenerationUnit*

j = *ProducerAssociatedtoVPP*

R_j = *ContractedReservewithAssociated Producerj*

The VPP can keep this reserve value constant, resulting in a higher security when the sold energy decreases.

Because of that, the VPP can reformulate its strategy, in function of the sold energy, changing the scheduled generation.

The VPP can negotiate the excess reserve with other market agents or with the system operator, in the scope of the required ancillary services.

When the forecasted generation for the bigger generation unit is lower than its nominal power, the required reserve is also lower. In this case, the VPP can sell the exceeding energy in the spot market. Generation and reserve values can change dynamically.

In this situation, we have:

$$PPPR_{VPPithermVPP} =+ \overset{n}{\underset{i=1}{\leftrightarrow}} {}^{f} \tag{2}$$

$$RP_{VPPi} = \left(\; {}^{f} \right)^{max} \tag{3}$$

Where:

P_{VPP} = *PowerthatVPPcannegociatein themarket*

R_{VPP} = *VPPReserve*

P_i^f = *Forecastedpowerforgeneration uniti*

In some situations, the n-1 security level cannot be assured. Even if the required security level can be assured, this can bring higher costs to the VPP. However, these solutions may be useful to avoid penalties such as: payments, warnings, suspension or exclusion.

Another solution is to guarantee as reserve a percentage of the foreseen generation in each moment. In this situation we have:

$$P_{VPP} = \frac{\Uparrow \overset{n}{\neq} \leftrightarrow PP_{itherm}^{f} + \;\Rrightarrow}{1 + Perc} \tag{4}$$

$$R_{VPP} = \frac{\Uparrow \overset{n}{\neq} \leftrightarrow PPPerc_{itherm}^{f} \;\Rrightarrow}{1 + Perc} \tag{5}$$

Where:

$Perc$ = *Percentageofintendedreserve*

The VPP can adopt a hybrid strategy to determine the reserve value; it must consider the following aspects:

- Resource forecast - if the forecast is made too early, bigger is the probability of error, what implies more reserve. There are two different short-term prediction models: the physical and the statistical approach. In some models, a combination of both is used, as both approaches can be needed for successful forecasts. In short, the physical models try to use physical considerations as long as possible to reach the best possible estimate of the local resources before using Model Output Statistics (MOS) to reduce the remaining error. Statistical models in their pure form try to find the relationships between a wealth of explanatory variables including NWP (HIRLAM/WAsP/Park, nowadays called Prediktor) results, and online measured power data, usually employing recursive techniques. Often, black box models like advanced Recursive Least Squares or Artificial Neural Networks are used. The most successful statistical models employ gray-box models, where some knowledge of the wind power properties is used to tune the models to the specific domain. [6]

- Sold energy forecast - The reserve has to be adjusted to the prediction of the energy to be sold in the market. This prediction is based on the VPP selling strategies and on historic data;
- Forecasted price - The importance of reserve depends on the power selling and buying price, the reserve cost, and the penalties cost. Several techniques are used for market price forecast: soft computing methods are applied to forecast electricity market prices. Our VPP model uses a price forecasting methodology based on Neural Networks, Data Mining and Particle Swarm Optimization [1];
- Generation units operating point - when considering co-generation, fuel cells or gas turbines, if they allow some overcharge or if they are working below their nominal charge, they can compensate some generation oscillation that could appear. In what concerns wind power generation, it is known that the delivered power of a wind turbine is almost constant when the velocity of the wind is between 15 and 25 m/s. If the wind forecast is at 20 m/s the wind turbine can stand a wind variation of ±25%. On the other hand, between 5 and 15 m/s, the smallest velocity variation can severally affect the production.
- Risk Management – The VPP can take more or less risk in his market bids. If a high generation quantity bid is submitted, the risk of penalties is higher than if the VPP assures some level of reserve. The VPP manages the risk considering the results of past market session's results and the primary resources. In this strategy the VPP uses the following method:

1 – Determination of the weather forecast and its range;
2 – Determination of the generation forecast for each generation technology (using the forecasted resource values) and the forecasted generation range (considering the forecasted resource range);
3 - Determination of the maximum market penalties for each time slice;
4 - Computation of the minimum reserve amount to limit the penalties, according to (6) and (7):

$$Fp = Mp + Mpen \times VPPpen \quad (6)$$

$$R_{VPP} = \frac{PP_f \times (1+\chi)}{Fp} \quad (7)$$

Where:

Fp = Penalties factor

Mp = Forecasted Market price

$Mpen$ = Forecasted Market penalties price

$VPPpen$ = VPP Maximum penalties in percentage

PP_f = Power forecast

$\chi +$ Forecasted error

5 - Determination of the producer who guarantees the reserve.

Each producer reserve factor is determined, according to expression (8):

$$Fr = Pp + Rp + Mpen\,Mp() \qquad 8$$

Where:

Fr = Reserve factor

Pp = Energy price by producer

Rp = Reserve price by producer

The producer with higher reserve factor is chosen to assure the reserve.

There are some markets where contract violations do not imply direct penalties, fixed taxes being paid by each seller agent to allow the system operator to handle the system reserve. This methodology does not prevent the market from inadequate behavior of seller agents what can impose taxes rise. On the other hand, this situation can promote speculations with the sellers negotiating, deliberately, energy without any type of guarantee of supply.

5. VIPROD – A VPP SIMULATION TOOL

A simulation tool, named ViProd, has been developed to simulate the operation of a VPP and its interaction with the market. This tool takes into account the characteristics of the technologies used by the power producers and can be used to provide decision support to VPPs [7].

ViProd is divided in two different parts: one that calculates the generation to the next day and other that simulates the generation.

Using this tool, producers can be associated to a VPP and each one of them can produce energy with different technologies and in distinct places. Figure 1 shows a producer with four different technologies.

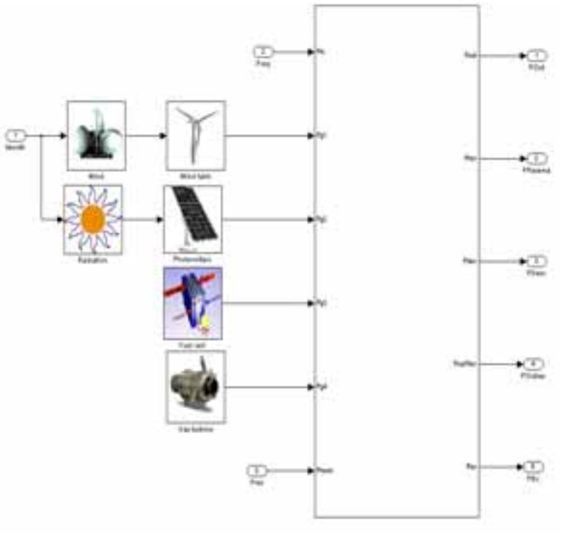
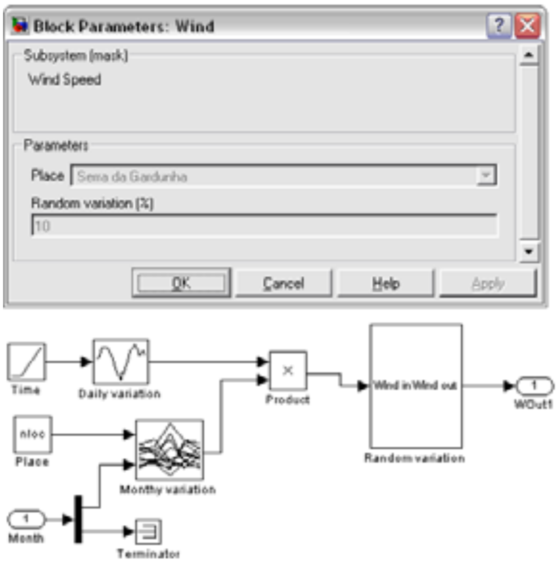


Fig. 1. Simulation of a producer with one wind farm, one photovoltaic plant, one fuel cell and one gas turbine

To estimate the power generated by different producers using technologies such us wind power, small hydroelectric and photovoltaic, real information concerning wind, water flows, temperature and radiation has been used. Figure 2 shows the wind simulation interface. In this example the user chose a wind farm in Serra da Gardunha and a variation of forecasted wind speed of 10%.


Block Parameters: Wind

Subsystem (mask)

Wind Speed

Parameters

Place: Serra da Gardunha

Random variation (%): 10

Fig. 2. Wind Simulation interface.

The bigger penetration of wind energy (and other technologies with similar characteristics) the less the generation stability causing oscillations around the values foreseen for the reserve and generation.

Since the forecast is done simultaneously for all the hours of the next day, the error associated with forecasted values increases as the day passes. Due to this reason, the differences between the forecasted generation and the effective one may be larger, therefore affecting the forecasting reliability. To cope with this problem, the simulator considers an increased error along the day (the variation of the random values in Figure 3 has been settled to ±10% by the user). The simulated values in each hour for primary resources (wind, sun, water flows, etc.) are given by the expression:

$$v_h = (v + \beta)^h \qquad (9)$$

Where:

v_h – value in the hour h

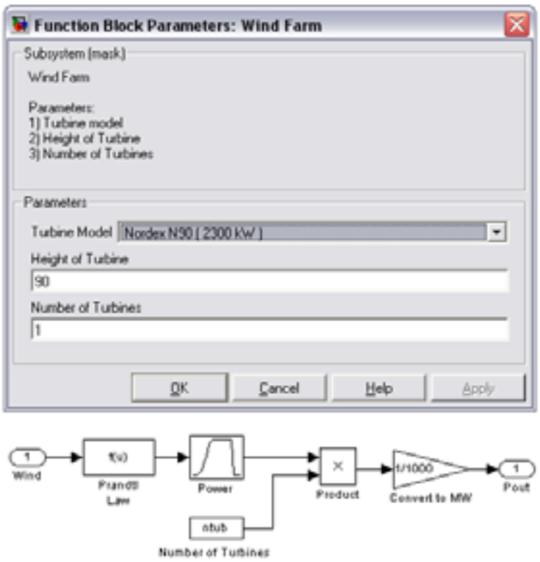
v – forecast value

β – random variation.;: $[\ 010010\ ]$

h – hour

We can define the local and the amplitude of the resource variation related to these phenomenon. A random variation allows the tool to be more realistic, making the forecasting errors dependent from the time to the forecasted situation. This characteristic helps to produce scenarios closer to the reality.

All the considered generation technologies were simulated. Figure 3 shows an aspect of the display concerning a wind farm simulation, considering the curves of power in function of the resources given by the manufacturers. In this example the user choose a wind farm with one wind generator Nordex N90 (2300 kW) with a tower height 90m



Function Block Parameters: Wind Farm

Subsystem (mask)

Wind Farm

Parameters:
1) Turbine model
2) Height of Turbine
3) Number of Turbines

Parameters

Turbine Model: Nordex N90 (2300 kW)

Height of Turbine: 90

Number of Turbines: 1

Fig. 3. Wind Simulation farm simulation interface.

Initially, each producer has to indicate, to the VPP, the foreseen generation to the next day, the energy prices, the power reserve and reserve prices. Based on this data, the VPP must compose the bids to be submitted to the market, according to the already referred criteria.

In case of the technologies that are dispatch able, the producers and the VPP make an agreement to consider some of the available power as reserve to assure the VPP reserve. The reserve value is calculated according to the penetration of non-dispatch able technologies.

The second part of the simulation tool simulates the management of all VPP generation. At the beginning, it makes a dispatch in function of the sold energy, producers' prices and their capacity of generation. Later, it makes the control of the generation of the producers and generates the reserves of each one, as excess or lack of generation exists.

The result is that we can check the generation by technology and the reserve that exists at each moment in the system.

6. CASE STUDY

With the developed simulation tool, several studies were done, using different levels of reserve. The goal was to test if the amount of reserve power was enough to allow the VPP supplying the sold energy, preventing penalty costs.

In this section we present a case study, simulating a VPP that aggregates three wind power producers. Each one of these producers has a co-generation unit with a nominal power of about 10% of the wind farm capacity. Table I presents the most important characteristics of these producers.

TABLE I
PRODUCERS

Producer	Technology	P (kW)	P_T (kW)
1	**Wind farm**	**30 000**	**33.030**
	Co-generation	**3 030**	
2	**Wind farm**	**20 000**	**22.100**
	Co-generation	**2 100**	
3	**Wind farm**	**13 000**	**14.250**
	Co-generation	**1 250**	

The co-generation will serve as support to the wind farms, to compensate the generation variations of this type of generating units.

In this case study, all the required reserve is assured by VPP own means.

In this case, the simulated scenarios are the following:

- Scenario 1 - Reserve assured by the producers, with all the co-generation production as reserve;
- Scenario 2 - Reserve assured by the producers, with 75% of the co-generation production as reserve;
- Scenario 3 - Reserve assured by the producers, with 50% of the co-generation production as reserve;
- Scenario 4 - Reserve assured by the producers, with 25% of the co-generation production as reserve;
- Scenario 5 - Without reserve.
-

Table II summarize the characteristics of these scenarios.

TABLE II
ENERGY BALANCING

Scenario	**E_S (MW.h)**	**E_D (MW.h)**	**E_U (MW.h)**	**E_E (MW.h)**
1	529.41	570.29	3.17	44.06
2	567.69	574.47	0.92	7.70
3	605.97	614.64	14.05	22.72
4	644.25	633.77	11.85	1.38
5	682.53	659.80	32.00	9.27

The simulation considered two different days, one of September and another of November, in two different markets (UK and France). All prices are in Euros, considering 1£ = 1.45€.

Figure 4 presents the VPP profits for each scenario.

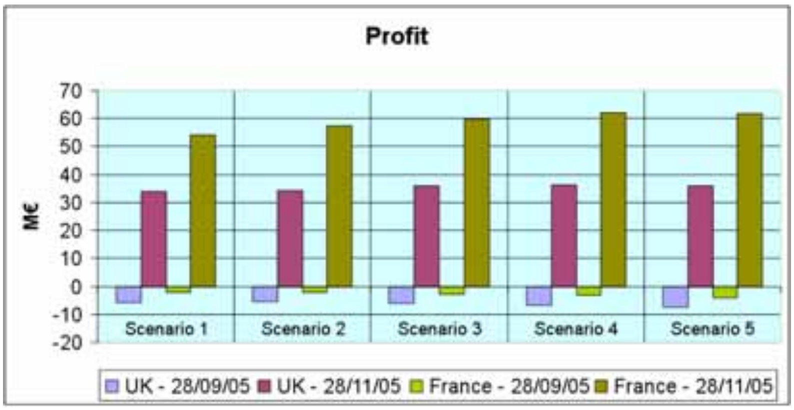


Fig. 4. VPP profits in considered scenarios

The simulation has considered the values provided by the entities responsible for the market management and/or for the balancing mechanisms that, in the case of UK and France, are, respectively, UKPX/Elexon and PowerNext/RTE [11-14].

The cost evaluation associated with the operation of the producers has been done with software available in the Retscreen web site [15]. With this software, it is possible to determine the costs of generation for the different technologies.

VPP costs are calculated using the values proposed by the producers; the cost of the reserve, and costs associated with VPP management and operation services**.**

Analyzing the values presented in Figure 4, it can be concluded that during a two months period, between September and November of 2005, the VPPs results of the VPP can vary a lot.

In both markets, we got results from about ten thousands Euros of losses in September to hundreds thousands Euros of profits in November. These variations reflect the instability of the oil markets, in this period of time.

It is important to point out that the undertaken calculations did not take into account any type of subsidies or benefits that usually are attributed to DG.

The results of the considered September day have been negative. For the considered November day, the results have been positive, and the scenario that presents greater profit is scenario 4. In this scenario the reserve is only 2.5% of the wind generation; however this reserve it is enough to reduce the penalties by half and to have some profits.

Comparing scenarios 3 and 5, we can see that, in France, scenario 5 is more advantageous; however, in UK, it is the inverse. On the other hand, in scenario 3, in France, the penalties are positive and in England the penalties are negative. While in the first one we have energy surplus, in the second we have energy shortage, modifying the penalty regime.

The results of this case study are according to the results of all the simulations we have undertaken, leading to common conclusions The most important conclusion is that VPPs' reserve strategies should take into account the context, namely in what concerns market model and characteristics and the considered situation. This is why the inclusion of VPP models in MASCEM, an electricity market simulator with dynamic strategies is producing interesting and valuable results [5].

7. CONCLUSIONS

The implementation in practice of the concept of Virtual Power Producers can mean a significant improvement in the role of DG in the scope of power systems and electricity markets. The success of this implementation requires adequate simulation and decision-support tools, able to provide VPPs with the required means to take advantage of their resources.

This paper has presented ViProd, a simulation tool able to provide VPP simulation. This simulator considers VPPs both from the point of view of technical operation and from the point of view of the participation of VPPs in the electricity market.

ViProd is able to simulate the details of each producer operation and also the operation of the VPP itself. It provides the means to manage internal resource and production forecasts, cost estimation and bid formation. Moreover, it also provides the means to manage VPP real-time operation.

Reserve management is a very relevant issue in the context of VPPs, as a good reserve management can be the difference between a profitable producers' aggregation and a low value non-dispatch able set of producers. This paper presents several reserve management strategies implemented in ViProd. A case study, using real data from UK and French markets is included.

The results of all simulation studies, which have been undertaken show that the choice of the adequate reserve management strategy, are crucial for VPP success in the context of competitive markets. To give VPPs adequate decision-making support in this field, the developed VPP models and simulation tools have been integrated in MASCEM. MASCEM is an electricity market simulator providing market agents with decision-support tools. These tools consider historic data; machine learning enables the agents to update their strategic knowledge [5]. Dynamic strategies are composed according to each market player model and to each situation.

The development of VPP models and simulation tools and their integration into MASCEM allowed to conclude the importance of the adequate choice of reserve management strategies, based on the provided decision-support tools, to maximize VPPs and DG producers' profits.

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9. BIOGRAPHIES

Zita A. Vale is a Coordinator Professor of Power Systems at the Engineering Institute – Polytechnic Institute of Porto (ISEP/IPP), Portugal.
She received her diploma in Electrical Engineering in 1986 and her PhD in 1993, both from University of Porto.
Her main research interests concern Artificial Intelligence (A.I.) applications to Power System operation and control, Electricity Markets and Distributed Generation. She is involved in several R&D projects concerning the application of A.I. and Decision-Support techniques to Engineering problems.

Hugo Morais received the B.Sc. degree in 2005 from the Polytechnic Institute of Porto, Porto, Portugal. He is also a PhD student with the University of Trás-os-Montes e Alto Douro, Vila Real, Portugal and his research interests include distributed generation and future power systems.

Marílio Cardosos received the B.Sc. degree in 2001 from the Polytechnic Institute of Porto, Porto, Portugal and he is currently an Assistant Professor of Electrical Power Systems with the same school. He is also a PhD student with the University of Trás-os-Montes e Alto Douro, Vila Real, Portugal and his research interests include distributed generation and future power systems.

Carlos Ramos received his graduation (1986) and his PhD (1993) in Electrical Engineering from the University of Porto. He is Coordinator Professor of Computer Engineering at the Polytechnic Institute of Porto/Institute of Engineering. His main R&D interests are Artificial Intelligence and Decision Support Systems

H. M. Khodr (M´99) received the Ph.D. and M.Sc./Engineer degrees in Electrical Engineering from the José Antonio Echeverría Higher Polytechnic Institute (ISPJAE) in 1997 and 1993 respectively.

Former Associate Professor of Electrical Engineering at Simón Bolívar University, Venezuela. He was a Researcher at INESC Porto, Portugal.

Presently, he is a Researcher at GECAD – Knowledge Engineering and Decision-Support Research Group of the Electrical Engineering Institute of Porto – Polytechnic Institute of Porto (ISEP/IPP). He has participated in a number of projects performed for the local industries. His current research activities are concentrated on planning, operation, and economics of electrical distribution and industrial power systems, power quality, grounding systems and optimization.

Received 29 February 2008
Paper 08GM0531

7. System Service in a System with a High DG Penetration - A Task for DG?

Antje Orths and Peter Børre Eriksen, Energinet.dk, Fredericia, Denmark

***Abstract*— a high share of wind power production characterizes the Danish system** as well as production from combined heat and power units, both called dispersed generation (DG).

The actual governmental plans for the implementation of additional 3,000 MW of wind power capacity until the year 2025 lead to a future situation where the installed wind power capacity reaches the level of annual peak load.

This new situation requires extended analyses, also with respect to system service. This paper describes the analytical approach and first results of the investigations.

Index Terms—dispersed generation, wind power, system service, CHP units, regulating power, energy market.

1. INTRODUCTION

During the last 30 years the Danish power system has developed from a system primarily based on centrally installed thermal condensing power plants to a system with a very high penetration of dispersed electricity production units, such as combined heat and power (CHP) units and wind turbines, 0.

TABLE I

KEY FIGURES OF THE DANISH POWER SYSTEM (01.06.2007)

	Western Denmark	Eastern Denmark
Min. Load [MW]	1,400	900
Max Load [MW]	3,700	2,700
Central Power Plants [MW]	3,400	3,800
Local CHP Units [MW]	1,700	650
Wind Turbines [MW]	2,400	750
Penetration Level Wind [%]	65 … 171	28 … 83
Penetration Level CHP [%]	46 … 121	24 … 72
Exchange Capacity		
Export UCTE [MW]	1,500	,550
Import UCTE [MW]	,950	,550
Export Nordel [MW]	1,440	1,700
Import Nordel [MW]	1,460	1,300
Share of consumption		
Wind Turbines [%]	24	11
CHP units [%]	28	18

Thus, today in Western Denmark dispersed units cover an energy share of about 24 % (wind) and 28 % (CHP) of the annual consumption electricity consumption (exclusive exports), see table 1. The penetration level, being defined as the relation of installed production capacity to maximum respective minimum load today has for wind power a value of 65 %…171 % and for CHP units a value of 46 %… 121 % in the Western Danish system, while the values for the Eastern Danish system are smaller. Both Danish systems are not electrically connected today, but an HVDC connection is planned.

In 2005 CHP production made up to 55 % and wind power about 18 % of the total electricity production, and since the Danish government published their energy strategy, a significant further increase is expected until the year 2025, see Fig. 1.

This amount and expected increase of dispersed production related to either heat demand or available wind power is a challenge with respect system operation, i.e. balancing production and demand, voltage stability and reactive power flows, but also during system planning. In this regard, the adequacy of power, transmission capacity and of energy plays an important role concerning reliability and security of supply aspects.

Operational security is defined as system characteristics with respect to withstand disturbances or interfering actions. Wind turbines increase the demand for provision of system services as e.g. reserve and control power, but they simultaneously also have an ability to reduce this demand and they are able to deliver the respective contribution themselves. These characteristics should optimally be used in order to minimize the socio-economic costs.

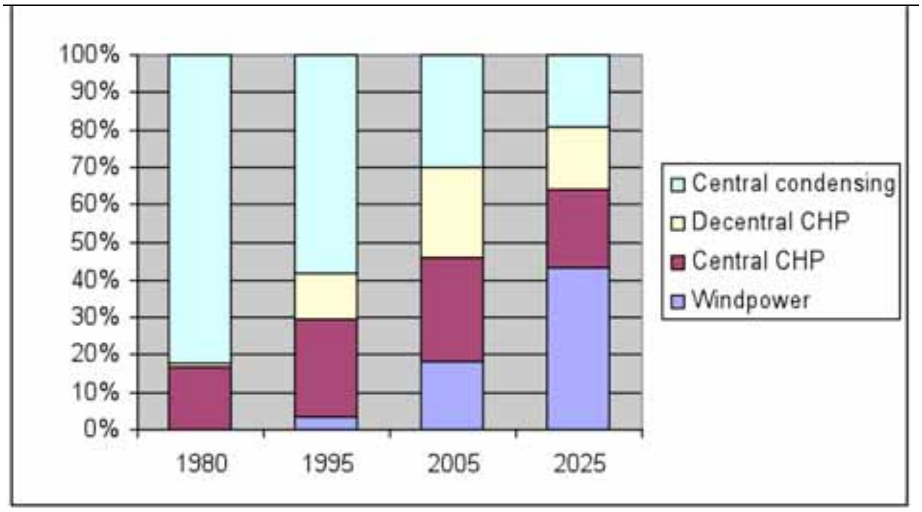

Fig. 1. Electricity Production and share of Wind Power, CHP and Condensing Technology in Denmark.

Security of supply is defined as the probability of electricity availability for the consumers. It is affected by sufficiency (energy resources, production capacity and transport capacity) on the one hand, and operational security on the other hand.

Wind energy being a fluctuating energy resource shows a direct dependency of production capacity and wind energy feeding. Additionally, the forecast quality can due to physical reasons not be 100 % on wind farm level.

During the system planning process, security of supply has to be ensured and estimated for the future power system. This is among other things done by calculating reliability indices like expected unserved energy ("EUE"), electric power not served ("EPNS") and loss of load probability (LOLP). Concerning the latter an estimation of wind power availability and CHP availability is essential.

Probabilistic methods are used in connection with system adequacy calculation for future systems with a high amount of stochastic production.

2. BALANCE A SYSTEM WITH HIGH AMOUNT OF DG

Denmark is situated between several borders, Fig. 2. In the North there are the hydro-based systems of Norway and Sweden, whereas Denmark and the Continent are mainly thermal systems. Additionally the country is situated in two synchronous zones at the same time (east and west), and last but not least there is a virtual border concerning market systems south of Denmark. This situation places chances and challenges on the Danish TSO.

In Denmark already today the wind power production sometimes exceeds the electricity demand (Fig. 3). Furthermore, the production situation is quite dynamic and might change from a surplus situation (wind power production > electricity demand) to a deficit situation (wind power covers << demand) within only few hours. An example is given in Fig. 3, showing the first two weeks in January 2005.

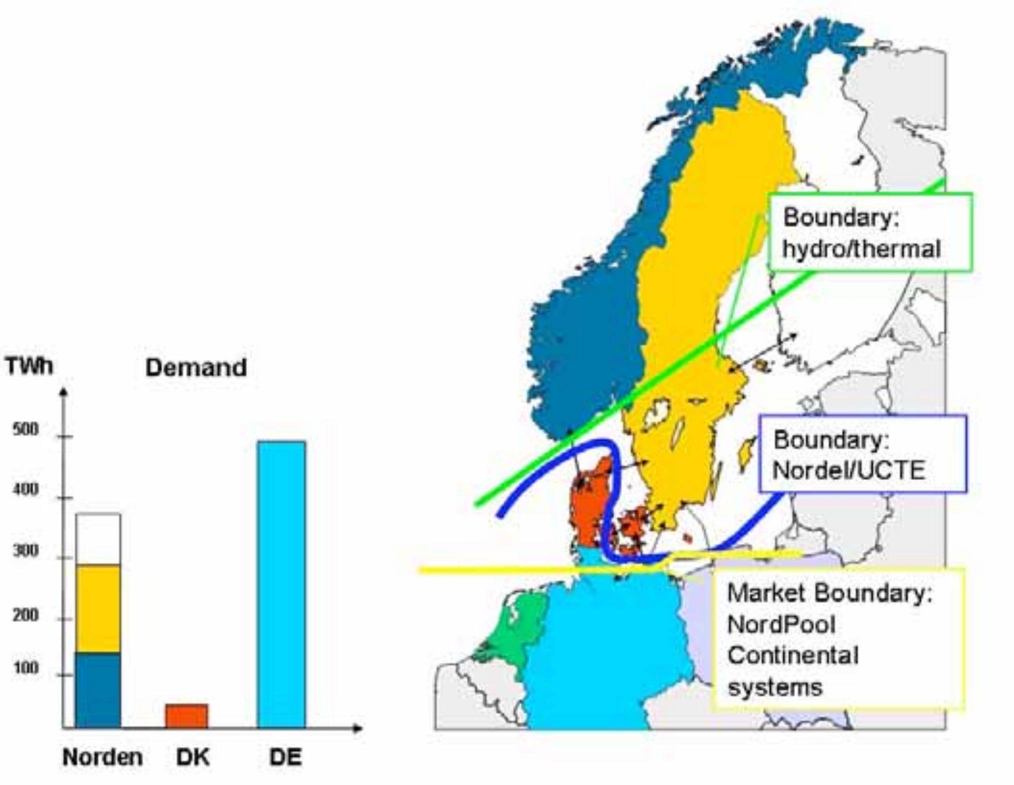

Fig. 2. Denmark between several boundaries

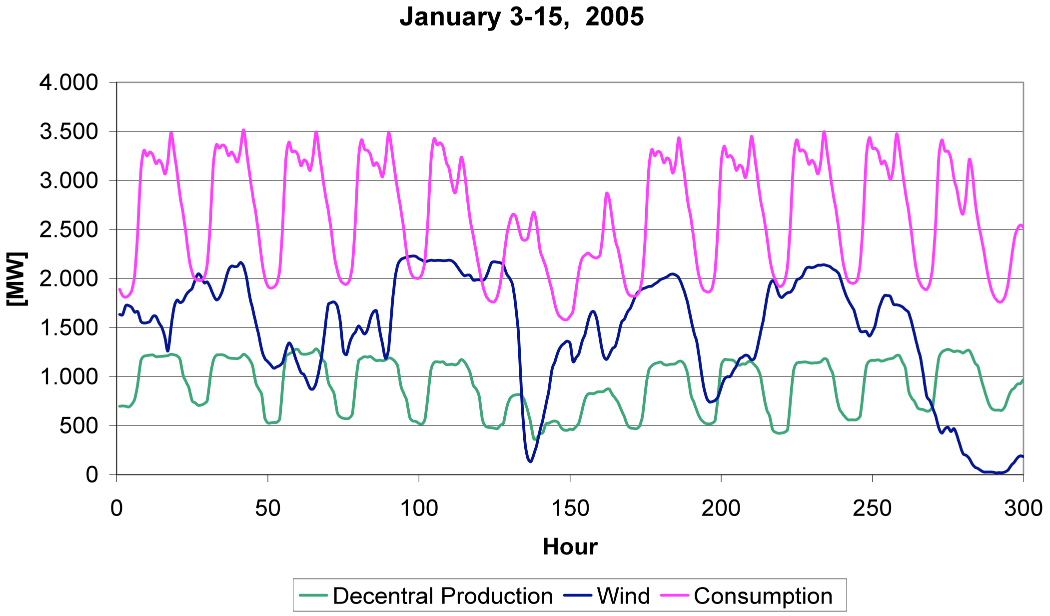

Fig. 3. Consumption, CHP- and Wind Power Production (www.energinet.dk)

On January 8th a storm front was passing the country, changing the wind contribution from a surplus to being shut down within only 4 hours. During the same period the electricity demand increased by 47%. In this case the lost power could be balanced by an increased import from Norway 0.

Up to today these situations could be solved by a combination of production planning including wind power production forecasts and by an exchange of power with neighboring countries, having either a high amount of hydropower (Norway/Sweden) or thermal condensing power plants (Germany). Load and production uncertainties have not only in extreme situations, but continuously to be balanced. This can generally either be done utilizing domestic reserves or using external reserves via the interconnections.

Fig. 4 shows the percentage of up- and down regulation sorted by sources for a period of 24 months.

Thus, for the Danish TSO the interconnections to neighboring systems are of vital interest. In both Danish systems there is interconnection capacity to export 40 % of the production capacity, and to import 70 % of the consumption. The AC connections help to keep the frequency whereas the HVDC connections to hydro-based systems are valuable with respect to balancing issues.

However, the availability of foreign reserves is not constant, as is illustrated in Fig. 5, showing the available and actual positive and negative regulation reserve. In both directions the available reserve is partly offered by domestic sources and partly by foreign resources, which are available at the regulation power market, resp. the hour-ahead market of NordPool. To be independent of the availability of interconnection capacity, domestic flexibility should be increased as far as possible.

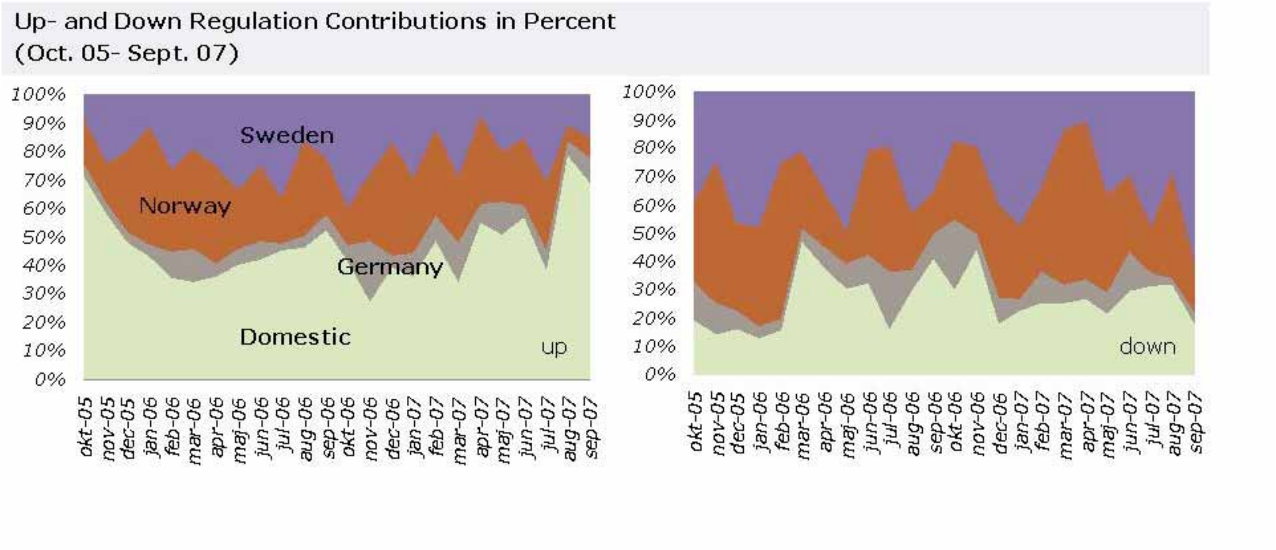

Fig. 4 Contribution to Up- and Down Regulation Oct. 05 - Sept. 07

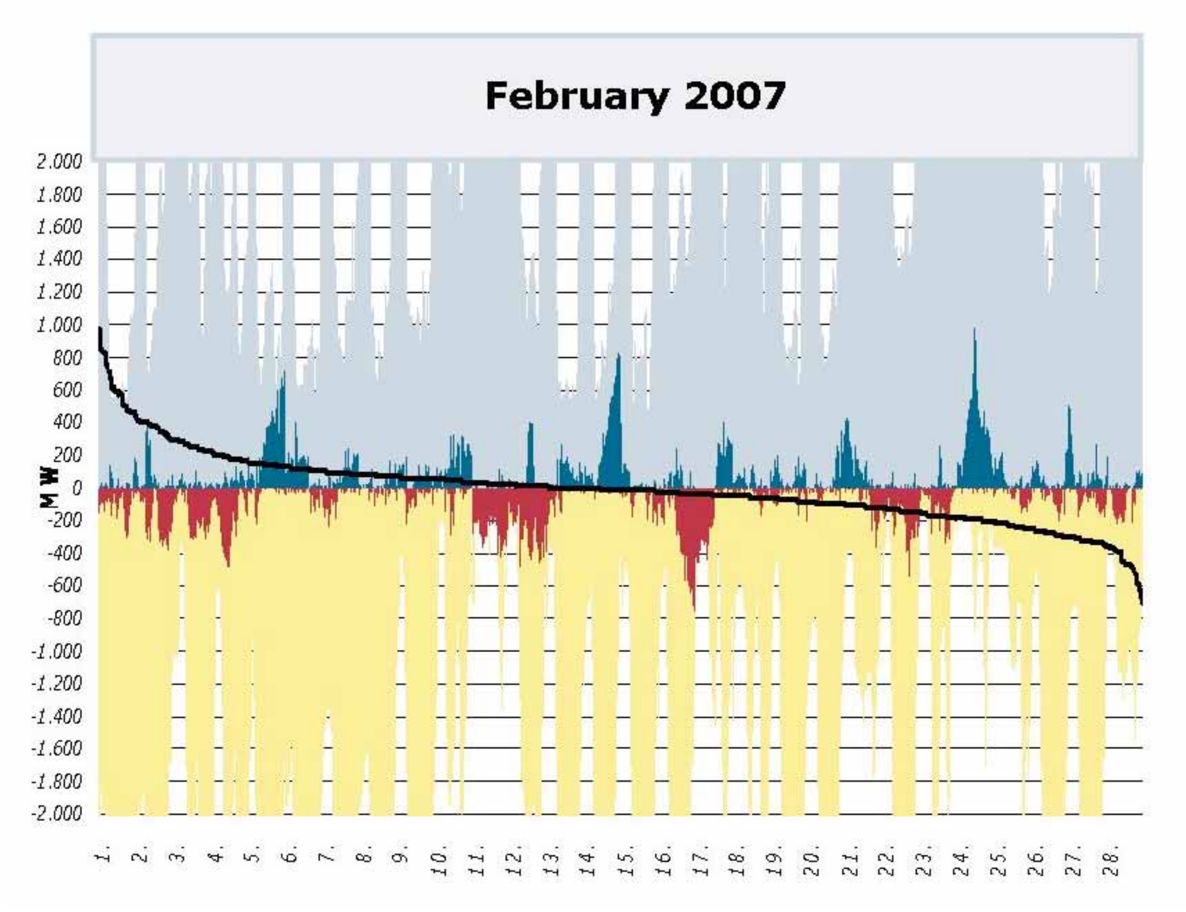

Fig. 5. Available and Actual Regulation Power

This is also important knowing that in the neighboring systems a significant increase of fluctuating resources is expected, especially in Germany, where 20 GW offshore wind power production is expected to be built in direct vicinity to the Danish grid. The correlation between wind in Norway, Sweden and Denmark is smaller than the one between Denmark and Germany. Thus, it will definitely not be possible, that these neighbors rely both on the respective other one to balance the own wind power, but it is necessary to find a common solution to the related challenges.

Beside the TSO's balancing requirement the producers already today make use of regulation capabilities of wind farms [2]. They down-regulate the output according to certain limits or delta regulation to save money by avoiding switching off a conventional unit. The ability to follow certain limits is a requirement for the park controller, and is fixed in the grid connection rules of the TSO [3]. This regulation ability should in future be utilized in an even higher extent.

3. DENMARK IN 2025

According to the governmental strategy from January 2007 Denmark has the objective of significantly increasing the wind power production from offshore wind power parks during the next decades. This shall lead to a system with an electricity consumption covered by 50 % wind energy. The wind power penetration will then be between 100 % and 260 %. This increase in stochastic production will further increase the challenge of balancing the power production and consumption, see Fig. 6, and also create challenges with respect to voltage stability, behavior at grid faults and reactive power issues. After the Government published its strategy a commission, including the Danish TSO, published a list of possible locations for another 4,600 MW offshore wind power, Fig. 7 [4].

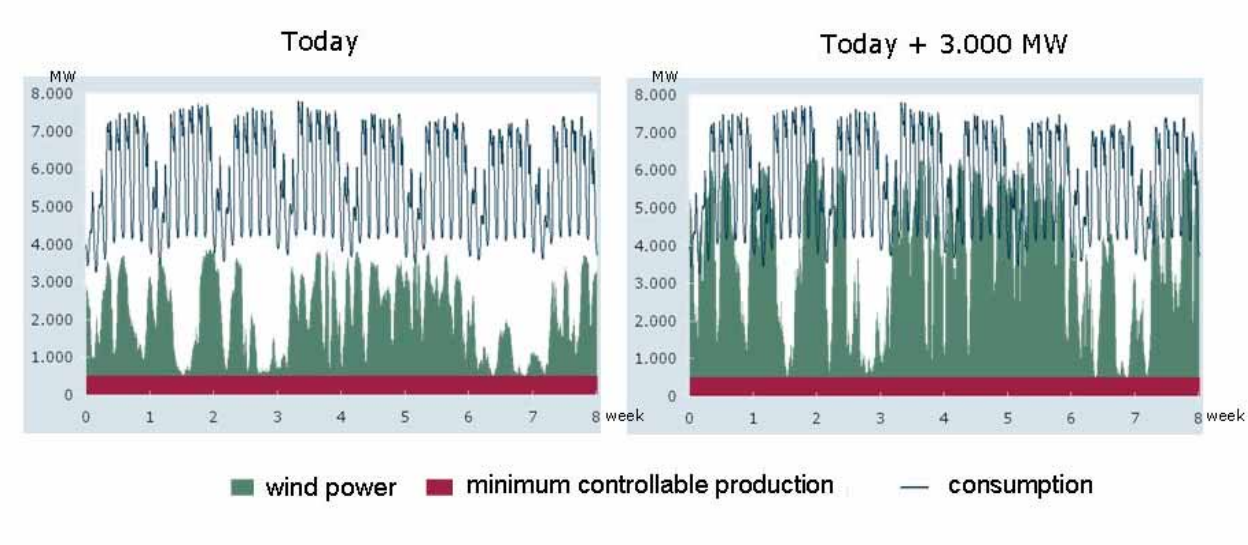

Fig. 6. Wind Power Production Today and Expectations for 2025

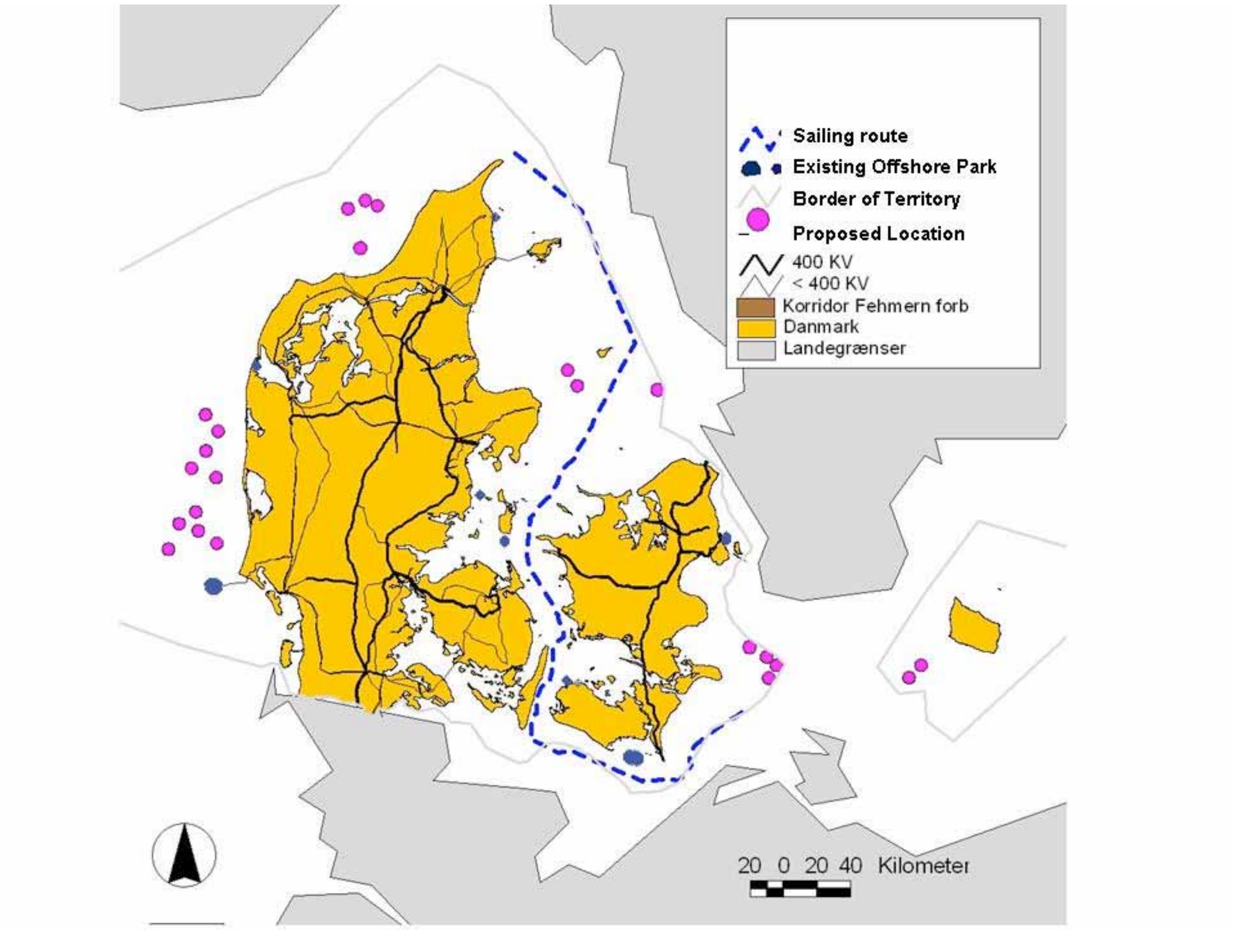

Fig. 7. Possible Locations for Offshore Parks, Source: [4]

This plan provides not only a certain planning security to the TSO, but also enables him to produce and evaluate variant comparisons, where e.g. to electrically connect the offshore parks to gain an optimal security of supply, avoiding network congestions on the one hand and reducing correlated wind production being connected at the same point of common coupling on the other hand.

Concerning the prediction of correlated wind production at one geographical location only a limited impact of improvements of wind energy production forecast tools on system security is expected, because the forecast quality is naturally limited with respect to the extension of an area, especially the output of a single park or an area like e.g. the Danish west coast, where the expected correlation is evident.

While the on-land wind turbines are subject to a smoothening effect due to their geographical distribution, the only chance to smooth out the offshore production, which additionally is characterized by significant higher fluctuations, Fig. 8, is to connect parks from a similar area to different grid connection points. Additionally, certain ramp-rate limits help to minimize the effect of big fluctuations.

Implementing Large-Scale wind power and other dispersed units is not only a question of balancing, but contains aspects from regional to system wide level and requires investigations with a time resolution from ms to years, dependent on the type of investigation. This has been shown in [5] [6], where several international studies have been compared.

On Danish regional level currently technical measures are implemented in the distribution grid, which aim at a basic restructuring of the system architecture. The idea is to prepare grid "cells" which, in case of a failure, are able

- to disconnect itself from the high voltage grid and transfer to island operation balancing production and load at every instant
- after a total system collapse, to black-start to a state of island operation.

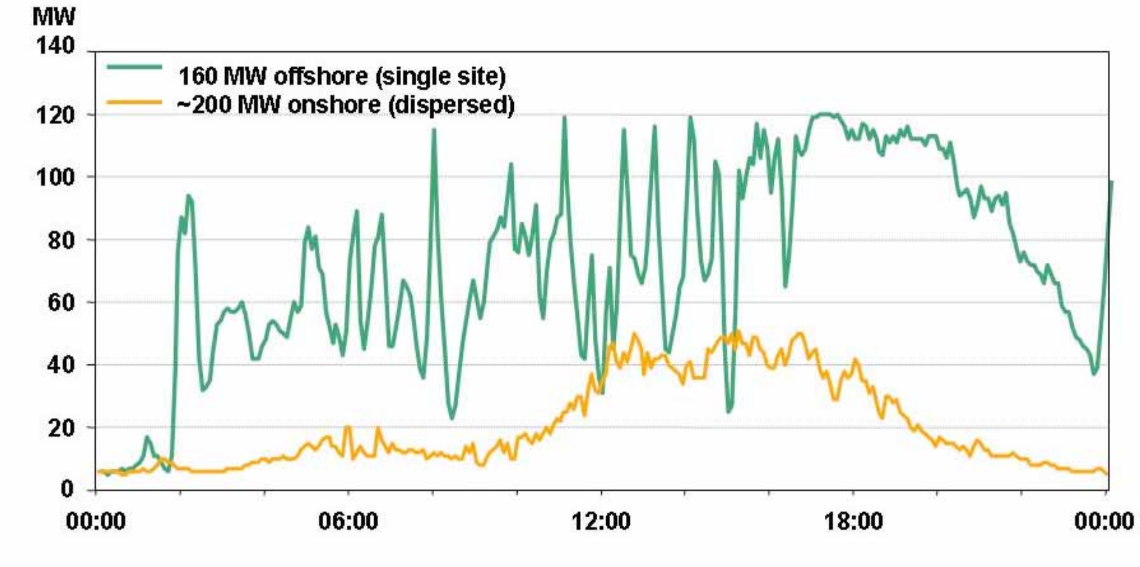

Fig. 8. Production of Single Offshore Site (160 MW) and Dispersed Onshore Sites (200 MW)

This project is called cell controller pilot project (CCPP), defining also a demonstration area of a real distribution network, where the new concept implementing new communication systems and new controllers into the production units of a region (cell) is being tested [7], [8].

On system wide level together with the Transmission System Operators of the Nordic neighbors Norway, Sweden and Finland different investigations are executed, as e.g. investigations on necessary transmission capacities, as well as adequacy investigations on power and energy.

4. WIND POWER AVAILABLITY

As has been mentioned above, system operators increasingly use probabilistic tools to estimate system reliability and to determine reliability indices, such as LOLP.

During deterministic calculations, wind power is typically set to zero, in order to represent the worst-case scenario when wind power might not be available during a critical load situation.

Using probabilistic tools the wind power can be included in the calculation of the probability of unserved energy.

The availability for offshore and land based wind power have different characteristics and are shown in Fig. 9. These characteristics can be simplified by a step-characteristic to fit into the probabilistic tool. For the probabilistic calculation of security of supply the correlation between wind power production and power demand is needed. This correlation is typically below 0.20, see Fig. 10.

Introducing a better price signaling to the electricity consumers in the future, promoting a price elastic demand, might increase this correlation. Thus, it is also possible to get system service from the demand side.

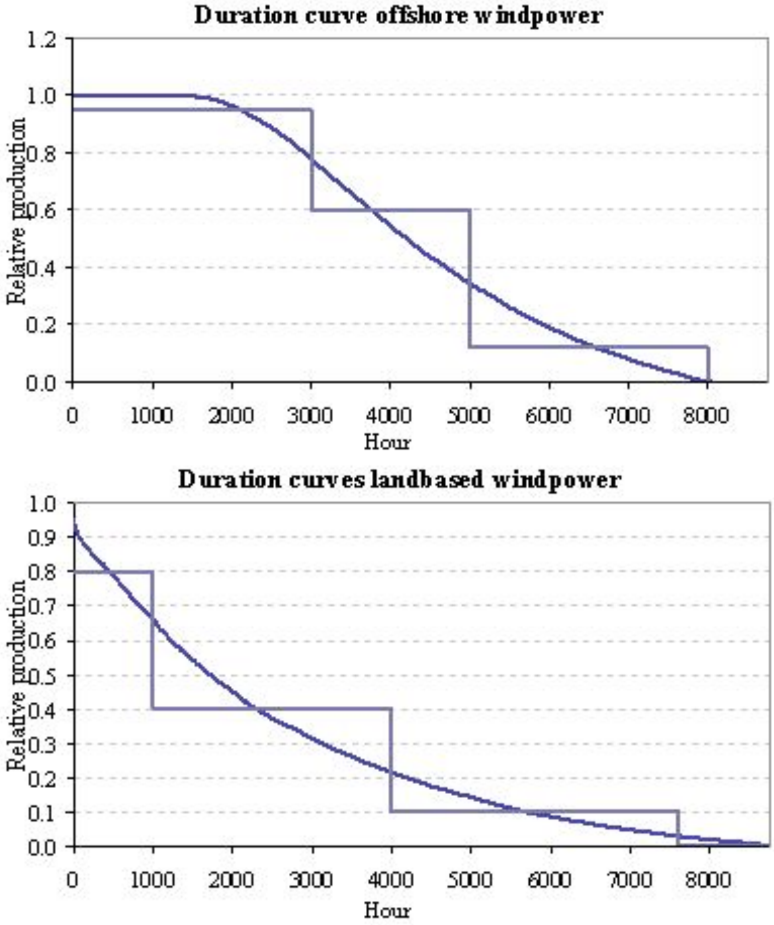

Fig. 9. Duration Curves for Offshore and Onshore Wind Power (Energinet.dk)

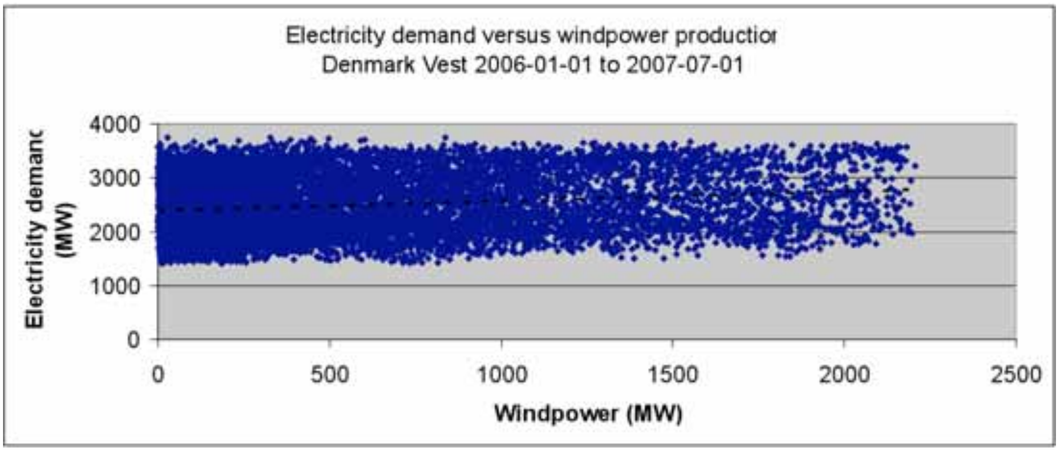

Fig. 10. Correlation between Electricity Demand and Wind Power Production in Western Denmark

Currently in Denmark the implementation of the instrument of price elastic demand is discussed, Fig. 11. Thereby the elasticity coefficient of the demand curve is varied on the one hand, but afterwards this might also interact with the production curve due to changes in im- and export, which might move the production curve horizontally. These phenomena are object of current investigations. Another reason for horizontally moving of the production curve is the amount of wind energy being fed in. At times of high wind there is a larger capacity for a low price, which even can be zero, than during times of low wind, indicated by the green curves. Using at the same time elastic demand, the prices will generally be stabilized as indicated by the arrows, showing that the difference between high and low prices would decrease.

5. CHP POWER AVAILABILITY

In Denmark more than 50 % of the thermal electricity production is based on combined heat and power production. Thus, the contribution from CHP-electricity to power adequacy has to be considered during probabilistic analyses. In the period 1980-2005 the dispersed production was optimized to a tariff payment with three price-levels (peak-, high- and low load). From 2005 the major part of all CHP-production is compensated according to spot-market prices. This has increased the participation of dispersed CHP in system adequacy, and a correlation of more than 0.8 is typically found between electricity demand and CHP-production, Fig. 12.

The dispersed CHP-production in Denmark had originally been designed to produce according to heat-demand. Separate electricity production is expensive for these units, and typically no cooling device is available at the plant. But on the other hand a relatively high heat storage capacity is available due to heat storage systems at the plant itself and additionally in the district-heating network.

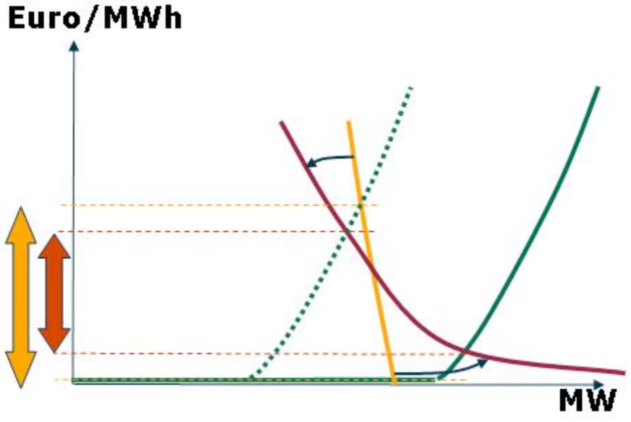

Fig. 11. Principle of Demand Response

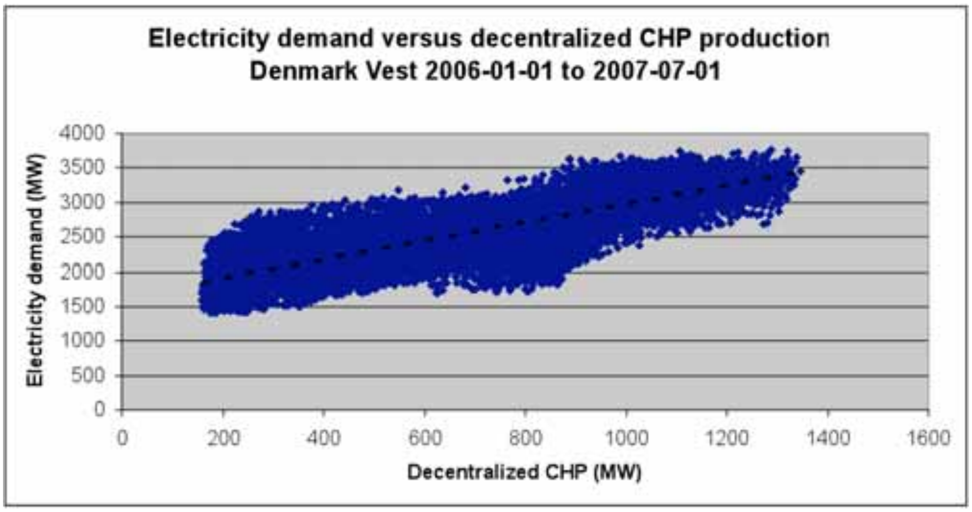

Fig. 12. Correlation between Electricity Demand and CHP Production in Denmark West

In case of power shortage in the system, the CHP-units will typically be available for production.

With respect to the future Danish system with 50 % energy being covered by wind energy it might even be profitable for CHP units to deliver system services and power backup even at times with no heat demand, due to more volatile market prices. The flexibility of the CHP units has then to be as high as possible, which especially in summer times due to lack of cooling systems, is a new challenge for the producers.

The first success making use of the idea of CHP units working on market terms can be seen at the spot market since 2005, where a decoupling of high wind energy forecasts and low electricity prices can be observed, Fig. 13.

Situations with exporting wind energy for a very low - even zero - price have been reduced. This helps also to relieve the transmission system, because the probability for congestions due to simultaneous electricity production by wind and CHP units decreases.

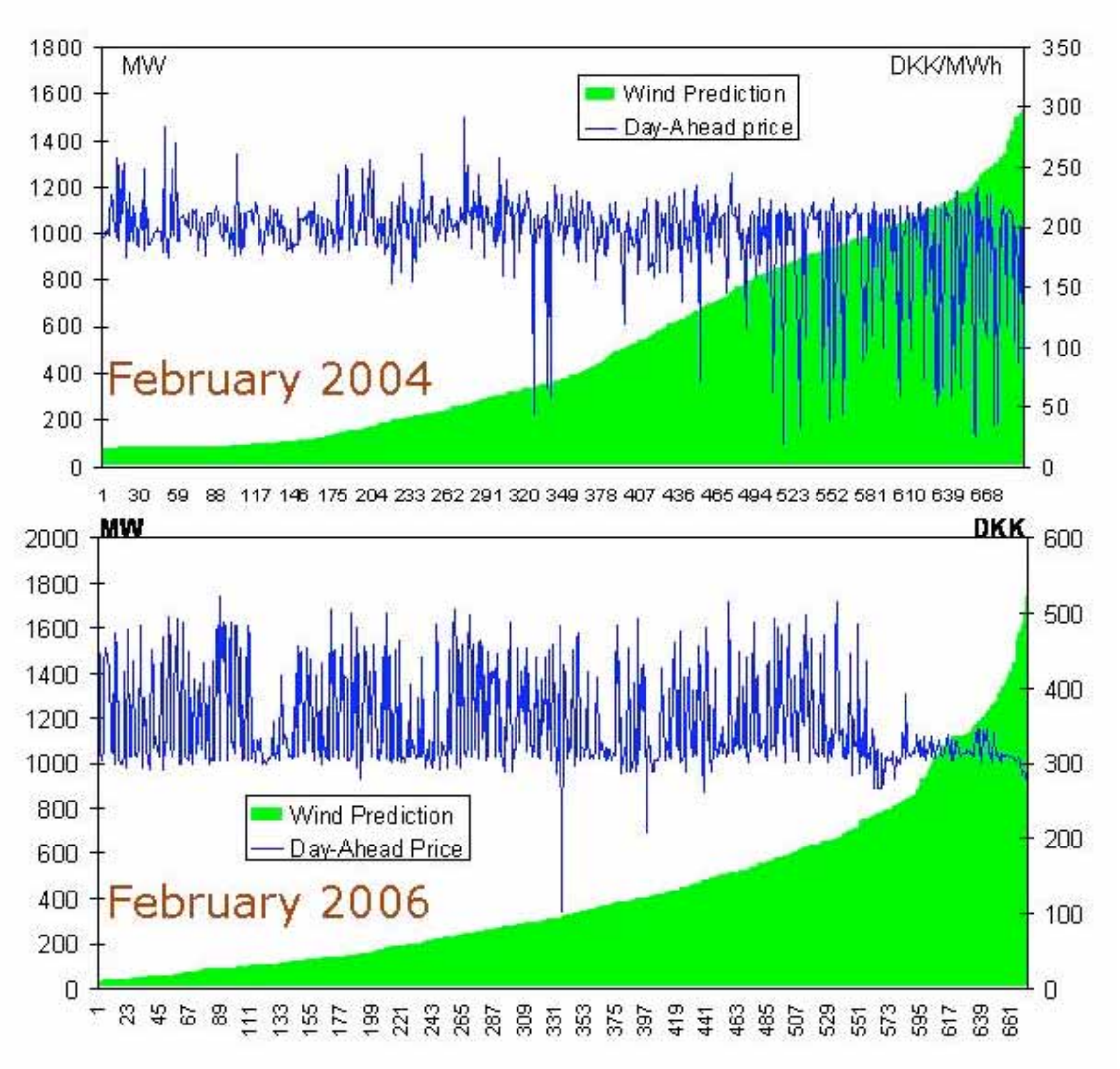

Fig. 13. Dependency of Wind Power Prediction and Spot Process at Nordpool

6. METHODOLOGY FOR THE EVALUATION OF FUTURE SCENARIOS

The Danish TSO tries already during the planning phase to systematically model and evaluate future scenarios. This is necessary to ensure the provision of sustainable solutions with respect to the grid. These solutions have to be socio-economically optimized.

Fig. 15 gives an overview over the methodology that aims at providing an optimal grid structure. First, the data and assumptions on production, consumption, fuel prices, production characteristics of different units, electricity prices in neighboring areas and exchange capacities between all Nordic countries and to the continent are fed into a simulation tool (SIVAEL).

This tool optimizes the hourly schedule of the Danish heat and electricity system, minimizing the total operation cost. The output is the power balances for every hour of a year, the costs, environmental data, exchange data etc. These power balances are fed into a load flow calculation tool, which delivers the respective results and enables the TSO finally to make some statistical evaluations on appearance of congestions or to execute variant calculations e.g. with respect to the effect of offshore connection point variants.

The tool SIVAEL, which was developed by the Danish TSO, minimizes the total operation costs using the following equation:

$$\min K = \sum_t \Big(\sum_i (PO(p(i,t),q(i,t)) + SO(i,t,p(i),q(i)) + \sum_u PO(p\ (u,t)) +$$
$$\sum_w PO(p(w,t)) + \sum_s PO(p(s,t)) + \sum_v PO(q(v,t)) - \sum_x V(p(x,t)) \Big)$$

PO: Produktion Costs
SO: Start Costs
V: value
t: index for hour (time)
i: index for produktion device

u: index for foreign country (udland)
w: index for wind
s: index for el- storage
v: index for heat pump
x: index for flexibel el consumption

Usually, the solutions are also tested on their robustness using special scenarios, which open up a solution space between extreme settings of the environment, Fig. 15.

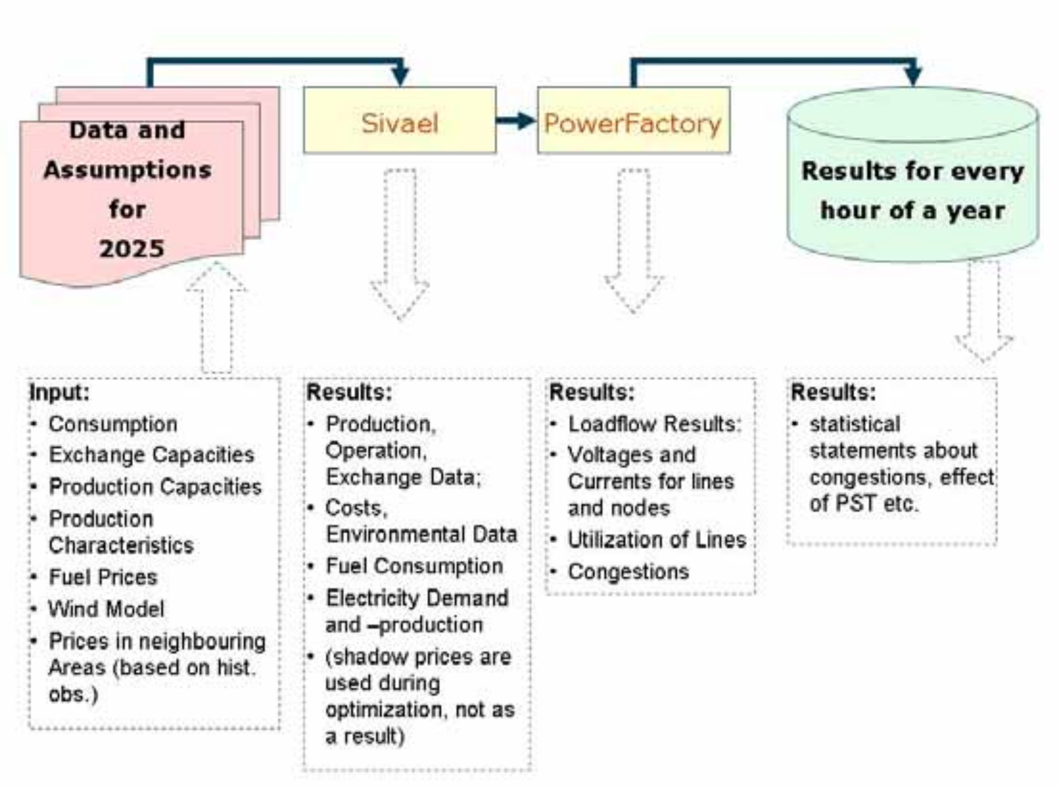

Fig. 14. Methodology for System Evaluation

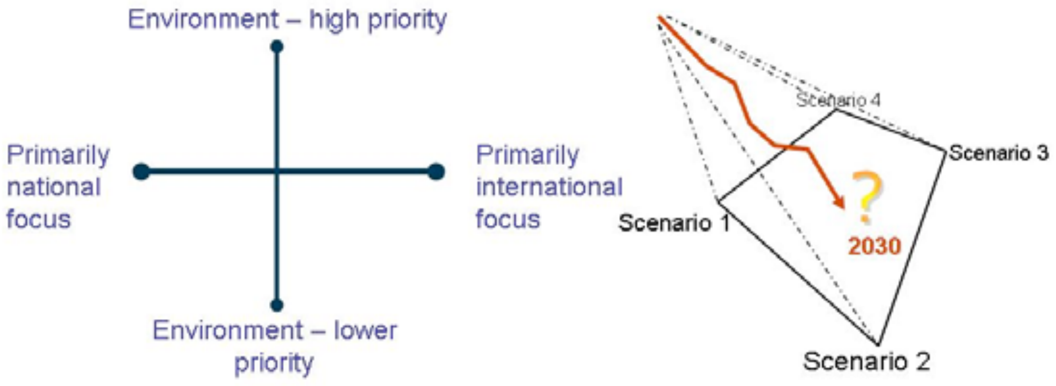

Fig. 15 Robustness Test on Extreme Scenarios

The reality will find itself somewhere between these extreme scenarios. If the proposed solutions are sustainable for the extremes, then they also should be sustainable for the solution space in between, Fig.15.

7. RESULTS AND MEASURES

The scenario which describes the governmental energy strategy for the year 2025 deals with a slightly increase of demand from 35 TWh (2005) to 38 TWh (2025) – even with strengthened savings. Concerning production facilities it was simulated a power park plant with 6,400 MW thermal power stations and 6,500 MW wind power capacity. Two alternatives have been calculated; varying generally the exchange capacities in the year 2015, table 2. Alternative 0 shows the variant with today's capacities, resp. the ones which are decided. Alternative 1 assumes increased interconnections both, in the North and South of Jutland, as well as an increased Great Belt connection, see table 2.

The methodology as mentioned above has been used, and the congestion-related result is shown in Fig. 16. It is obvious, that an increased transit through Jutland will lead to overloading of lines, if no countermeasure is taken.

Countermeasures could be implemented on several sides of the power system.

At the market side:

- Market coupling (e.g. NordPool-EEX etc.) to increase the possibilities of sharing reserves,
- Improvement of Intraday trading possibilities,
- International exchange of ancillary services.

At the electricity production side:

- Utilization of an electricity management system for wind turbines, which regulates the generation,
- Geographical dispersion of offshore wind farms,
- Mobilizing of regulating resources and new types of plants,
- Further improvement of local scale production units working on market terms.

TABLE 2
EXCHANGE CAPACITIES FOR TWO ALTERNATIVES FOR 2025 SCENARIOS

	Alternative 0	**Alternative 1**
DKWest - DK East	600 MW	1,200 MW
DKW - DE	Imports: 950 MW Exports: 1,500 MW	2,500 MW
DKW - NOR	1,000 MW	1,600 MW

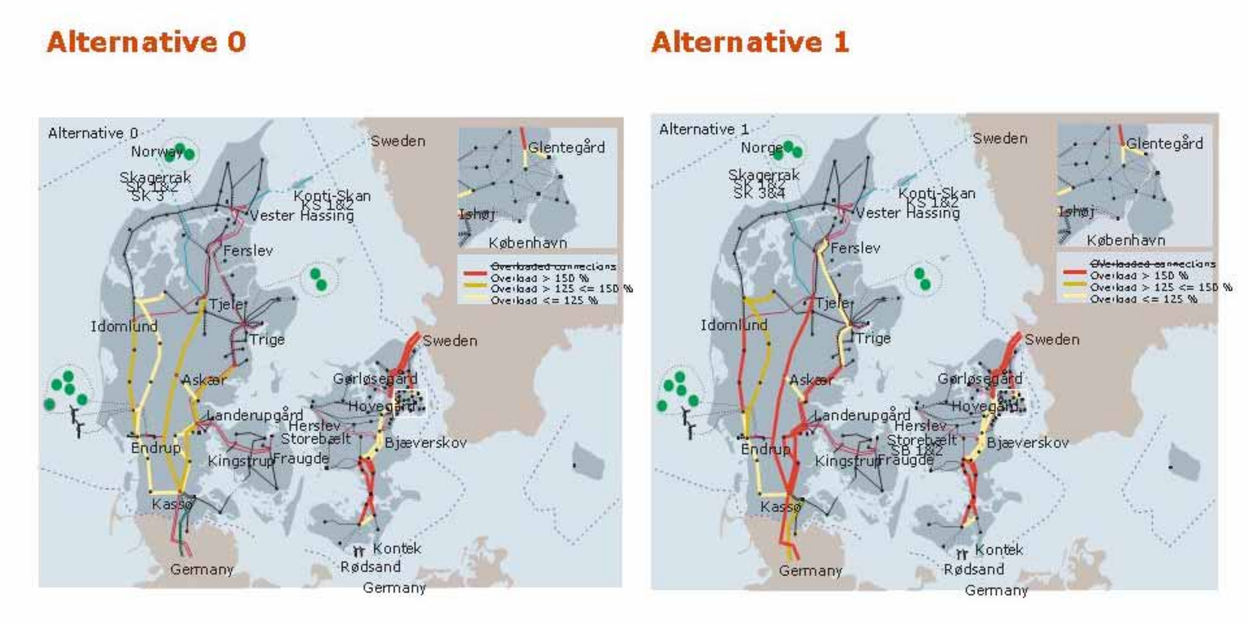

Fig. 16. Congestions at both Alternatives

At the electricity transmission side:

- Reallocation of the grid connection point for offshore wind farms,
- Increased grid transmission capacity, e.g. including the utilization of high temperature conductors,
- Reinforcement and expansion of the domestic grid and interconnections.

At the demand side:

- Further development of price dependent demand,
- Utilize and strengthen the coupling of the power system to heating systems: electric boilers and heat pumps,
- Develop and exploit coupling of the power system to the transport sector (electric vehicles as price dependent demand),
- Introduction of energy storage: hydrogen, Compressed Air Energy Storage (CAES), batteries.

The Danish TSO investigates the measures mentioned above and partners in research a development to enable the "plus 3000 MW" scenario 2025.

Fig. 17 shows the results related to energy balance. Here it is also obvious, that for alternative 1 the Danish system faces a higher northbound transit, while the production of primary plants is slightly decreasing [9].

Thus, the emissions of these two alternatives are very similar for Denmark, but seen in a bigger - European - frame, it will make a difference if large-scale wind power is implemented in the power system. Already today new solutions have to be prepared with respect to system operation. And these solutions should be good coordinated with respect to sustainability and variability for future developments, nationally as well as internationally.

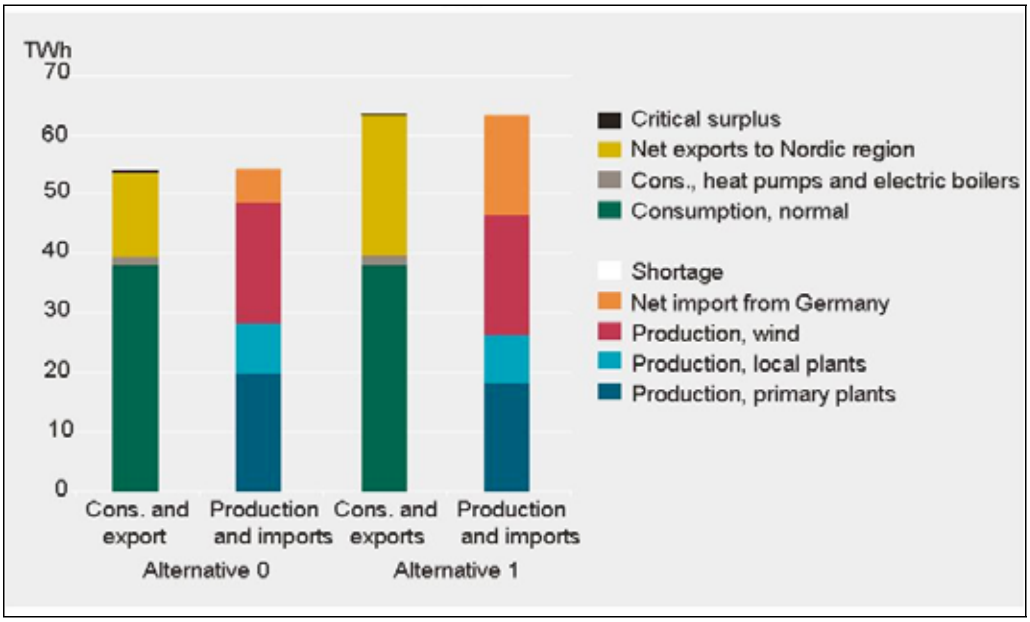

Fig. 17. Energy Balances for both Alternatives

8. SUMMARY

The recent investigations of the Danish TSO have shown that a further large-scale integration of wind power calls for exploiting both, domestic flexibility and international power markets. Both means are prerequisites for maintaining security of supply and maximize the economic value of wind power, and they are strongly connected to the provision of system service. This is not a question of one single measure, but the combination of a bigger package is essential.

Measures of large-scale wind power involves:

- measures on the market side
- measures on the production side
- measures on the transmission side
- measures on the demand side

Utilizing and further development of couplings of the wind power dominated electricity system to district heating systems, the transport sector (e.g. via electric vehicles) and energy storage systems are vital for future successful large- scale wind integration.

The combination of these measures will continuously be investigated in more detail.

9. ACKNOWLEDGMENT

The authors gratefully acknowledge the contributions of our colleagues Anders Bavnhøj Hansen, Jonas Christoffer Villumsen and Jens Pedersen for their work on the original version of this document.

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BIOGRAPHIES

Antje G. Orths (M’2001) joined the Planning Department (Analysis and Methods) of Energinet.dk, the Danish TSO for Electricity and Gas in 2005. Before, she was researcher at the OvG-University Magdeburg, Germany, where she finished her PhD in electrical engineering. She was head of the group Critical Infrastructures at the Fraunhofer Institute "IFF" in Magdeburg. Her special fields of interests embrace electric power networks and systems including the implementation of wind energy, modeling of dispersed energy resources, distribution network planning and optimization problems. She is member of the IEEE-PES, VDE-ETG and CRIS.

Peter Børre Eriksen 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. 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 Research and Development Department from 2000 until 2005. His main interests include the modeling and analysis of power and natural gas systems. Peter Børre Eriksen is author of numerous technical papers on system modeling.

Paper 08GM0038
Received 1 February 2008

8. Network Security Management Tool for Distribution Systems

Zbigniew A. Styczynski and Chris O. Heyde, Otto-von-Guericke-University, Magdeburg, Germany, and Bernd Michael Buchholz and Olaf Ruhle, Siemens, Germany.

Abstract—In this paper a network security management tool, which is integrated in a power system simulator, has been introduced. The network security management (NSM) is used by network operators to avoid insecure network states due to high penetration of DGs. Especially in situations of low load and strong wind the operation parameters e.g. current or voltage can exceed the allowable values [5]. The NSM tool introduced in this paper is performing new NSM algorithms within the power flow calculations. On the one hand, it can be used as an online application to support the network operator in his decisions using measurements and short time forecasts. On the other hand, by using the tool for long time simulations it can be used to optimize the NSM algorithms, to optimally plan network reinforcement and to predict the intensity of the NSM system on the profitability of the DG operators.

Index Terms—Power System, Network Security, Network Security Management, Generation Response, Power System Simulation, Remedial Measures

1. INTRODUCTION

The integration of decentralized generators (DGs) has nowadays a very high priority in many countries in Europe and America [7]. In some regions, e.g. of Germany, the generation level of DG has exceeded the local demand by far. Especially in regions with very good wind conditions this is often the case. In situations with low load and strong wind or in other than normal network situations the high penetration of DGs may lead to violations of the operation parameters and hence to security problems [5]. Therefore, the network operators have installed a network security management system (NSM) to reduce the power output from the DGs in order to ensure the secure operation of the network [5], [7].

The reduction of the possible power output results in less economical benefits at least in the case of wind and PV generators because the primary energy that is not used is lost. This practice is against the current renewable energy law, and must be fixed in the contracts and can lead to penalties. On the other hand the network reinforcement is cost intensive and time consuming which is why the NSM is a temporal compromise in order to integrate as much as possible DGs into the network. For reasons mentioned above the NSM must be well coordinated and its impact to the DG operators must be determined.

In recent investigations the impact of the NSM to the DGs was determined e.g. with the use of Monte-Carlo simulations [2]. A DC load flow method was applied to recognize the bottlenecks that were usually assumed to be located at the border of the considered network to the connected transmission network. In this way the long-term impact of the NSM can be determined but the effect of different NSM algorithms like additional load response for example or bottlenecks located within the network cannot be analyzed.

Therefore, an NSM tool, which is integrated into a power system simulator, was developed that is able to:

- Observe all operation parameters concerned,
- Assess the actual power injections of all DGs in the network,
- Consider load and generation forecasts,

- Choose remedial measured in case of parameter violations (NSM algorithm).

In section two of this paper some of the presently working NSM systems in Germany are described. Section three gives an overview of the methodology of the long term application for the investigation of the intensity of the NSM to the DGs and of the short term application for supporting the network operator in finding the best solution in cases of network insecurity. A study case will be described in section four and first results will be discussed in section five.

2. NSM SYSTEMS IN GERMANY GENERAL PROCEDURE

As aforementioned the NSM system reacts to an unwanted system state that can influence the power system security, caused by high power injections from DGs, with the limitation of their output power. Therefore, previously defined operation parameters are observed. In case of a violation of these parameters, the NSM instructs power limitations to the dispersed generators. The communication is done via wired networks if available, or by a unidirectional radio signal. The network operator usually knows the possible bottlenecks in his network and pools the generators that are most likely responsible for the bottleneck situation. In such a pool every generator gets the same signal from the network operator.

As a rule, the power limitations are differentiated in three steps:

- step 1 – limitation to 60% of the installed power,
- step 2 – limitation to 30% of the installed power,
- step 3 – limitation to 0% of the installed power.

In order to avoid permanent switching, the network operators usually wait a certain time (normally 15 to 30 minutes) before they decide whether to cancel the limitation or not. In most cases network operators also use weather forecasts or measurements from the influencing factors like wind speed or outside temperature for this decisions. Some network operators also use the installation date to form subgroups within the pools of generators in order to burden the DGs that were installed the latest more than the ones that were installed earlier in times when no bottleneck existed. This is called the “first-in-last-out principle” [1],[5]. Other network operators’ treat all generators in one pool the same that is called the “solidarity principle”.

3. METHODOLOGY

There are two targets aimed by using the NSM tool. Firstly, to determine the impact the NSM has on the DGs in the near and far future by performing long-term simulations. And secondly, to use it as an online application in order to find the best solution in case of insecure network states and to suggest it to the network operator. For both cases the methodology is slightly different.

3.1 Long Term Simulations

To determine the impact of the NSM on the DGs, long-term simulations have to be performed. The results of these long-term simulations are the network security level indices $E(n_{NSM})$ and $E(d_{NSM})$. Because insecure network situations are very rare in power systems, a very long time (several hundred years) has to be simulated to reach statistical convergence of the indices. For this reason the authors have developed stochastic models to simulate [2], [3] the behavior in time of loads, wind generators and PV generators and to generate synthetic time series for any number of years. These normalized time series are then scaled up for each node in the network. They serve as input for the power network simulation.

The NSM tool then is observing the operation parameters and, in case of a violation, it reacts using the algorithm defined before. This algorithm should include both the way of recognition of and the way of reaction to a network violation. In this paper the exceeding of certain boundary values simulates the recognition of parameter violations. The reaction of the NSM is, until now, simulated by the "solidarity principle" as described above.

The aforementioned network security level indices are defined by the expectancy values of the yearly number of NSM cases $E(n_{NSM})$ and their average duration $E(d_{NSM})$. For the number of NSM cases only the activation of one consisting limitation counts. This means, after the DGs are limited once and this limitation lasts without interruption for a certain period of time, it counts only as one NSM case. The calculation of the indices is done as shown in (1)-(4).

$$E(n_{NSM}) = \frac{1}{m} \cdot \sum_{y=1}^{m} \sum_{t=0}^{a/\Delta t} k_n(t) \qquad (1)$$

with

$$k_n(t) = \begin{cases} 1 & \text{if NSM state changes from not - active to active} \\ 0 & \text{else} \end{cases} \qquad (2)$$

and

$$E(d_{NSM}) = \frac{\sum_{y=1}^{m} \sum_{t=0}^{a/\Delta t} k_d(t) \cdot \Delta t}{\sum_{y=1}^{m} n_{NSM}^{m}} \qquad (3)$$

with

$$k_d(t) = \begin{cases} 1 & \text{if NSM is active} \\ 0 & \text{else} \end{cases} \qquad (4)$$

In these formulas $k_n(t)$ indicates only the changes from no limitations to any limitations, whereas $k_d(t)$ indicates all time steps where limitations are active. Δt presents the chosen time step (here 15 minutes) and a stands for one year. In order to reach high confidence of the results, m years are simulated.

Generally these indices can reflect three cases:

- both indices values are high – undesired security level,
- both indices values are low – acceptable security level,
- one value is high and one is low – undesired security level.
-

Therefore, to get quantitative information about the security level, both indices can be multiplied. This provides the expected absolute duration the NSM is activated during one year.

3.2 Short Term Simulations

In short term simulations the main target is to find an optimal reaction of the NSM system to the current network situation. The input for the power system simulator is the current network state and the prediction for the near future (15 min to 24 hours) of the load and generation behavior. The NSM tool observes the operation parameters calculated with the current and predicted situation. In case of a violation, the NSM tool proofs a list of possible remedial measures to successfully remove the parameter violation. If the measure is successful, it can be proposed to the network operator. The list of remedial measures can contain the limiting of the power injections of DGs as well as demand response plans or network topology changes [6].

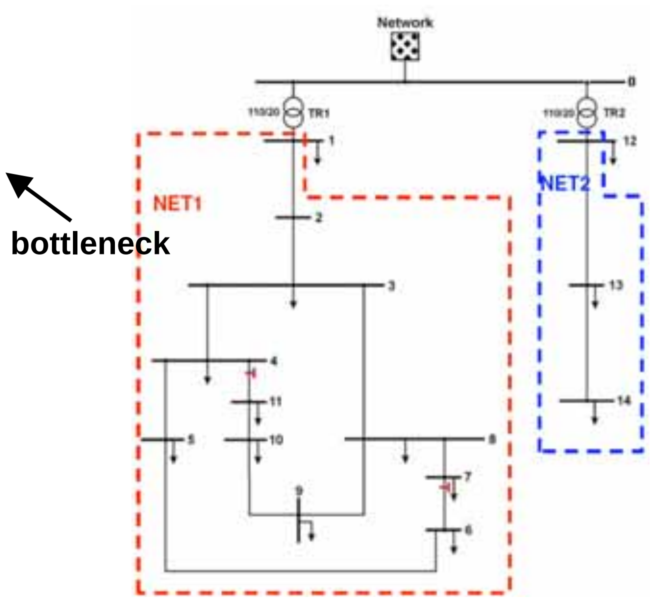
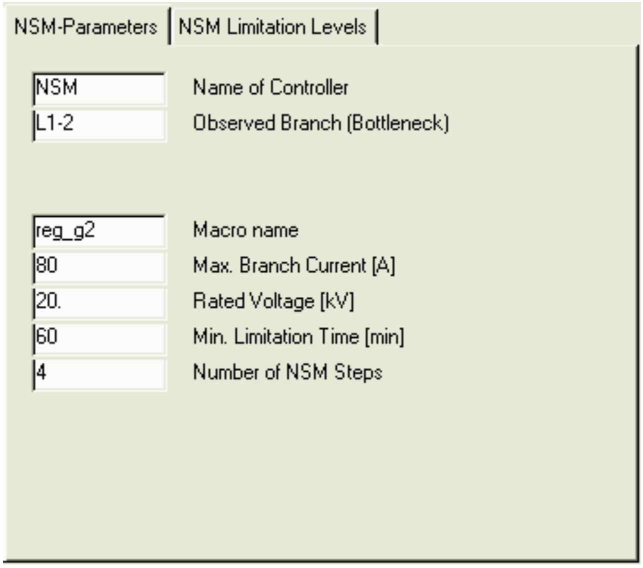


Fig. 1. Topology of the CIGRE benchmark network.



NSM	Name of Controller
L1-2	Observed Branch (Bottleneck)
reg_g2	Macro name
80	Max. Branch Current [A]
20.	Rated Voltage [kV]
60	Min. Limitation Time [min]
4	Number of NSM Steps

Fig. 2. Parameter mask of the NSM - Tool in NETDRAW.

4. STUDY CASE

For the study case the CIGRE distribution benchmark was chosen (see Fig. 1) [4]. This network is a 20kV distribution network. In this paper the long-term simulations with the NSM tool are going to be represented. The input time series are generated with the stochastic processes as described in [3]. The installed DG power was set to a level where parameter violations become possible. In numbers: the generation power was set in three steps from 250% to 300% of the maximum demand in this network. The bottleneck is, as indicated, the line between node 1 and node 2. The maximum thermal current $I_{1\text{-}2\ max}$ on this line is 80 Ampere.

The NSM tool now has to be configured as shown in Fig. 2. Any number of bottlenecks can be considered. In the following the simulation has to be started and the NSM tool will react in cases of exceeding the thermal current of line 1-2. After each simulated year the network security level indices are given and after these indices converge statistically the expectancy values can be calculated.

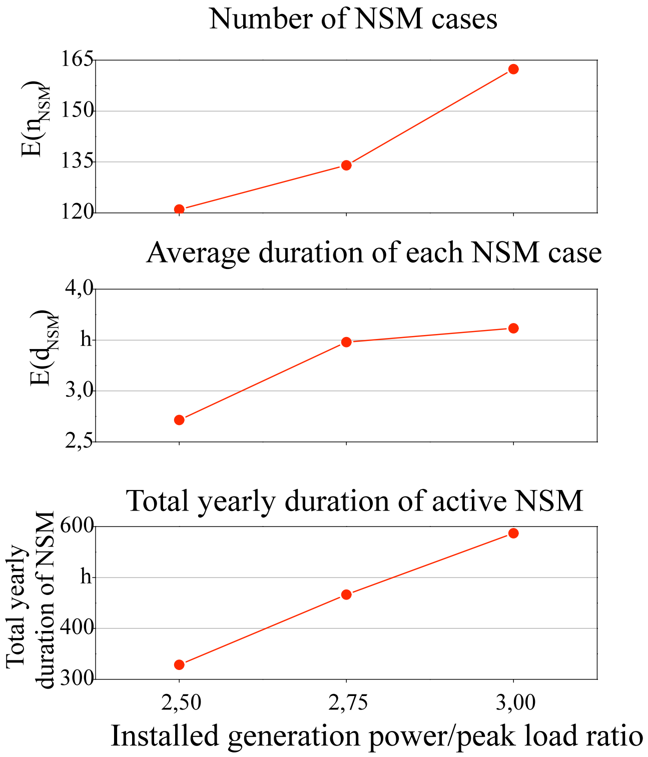


Fig. 3. Results of long term simulations with three scenarios, 250%, 275% and 300% DG power in relation to the maximum load.

5. RESULTS OF THE LONG TERM SIMULATIONS

In Fig. 3 the results are presented. The diagram a) shows the expectancy value of the yearly frequency of NSM cases and diagram b) shows the average duration of those NSM cases. The multiplication of both values represents the total amount of time the NSM had to be activated during one year (diagram c)), it represents the impact of the NSM system on the DGs in quantity. As expected the NSM intensity increases when the installed power of DG generators is increasing.

The results can be used for decisions concerning either investment in the network (network extensions), or for profitability questions in DG installation planning. In this case, at 300% installed DG power the total yearly NSM duration lies at about 600 hours (Fig. 3 c)). For a CHP with 6000 full load hours and the opportunity to store the primary energy, this would be 10%. A wind generator that has 1500 to 2000 full load hours and no opportunity to store the wind energy, 600 hours refer to 30 – 40%.

In Fig. 4 the resulting time curves from applying the NSM tool to the study case with DG power of 300% of the maximum power demand are presented. As one can see, NSM cases are occurring, when the load demand (diagram c)) is very low and, at the same time, the available DG power (diagram d)) is between 70 and 80% of its maximum.

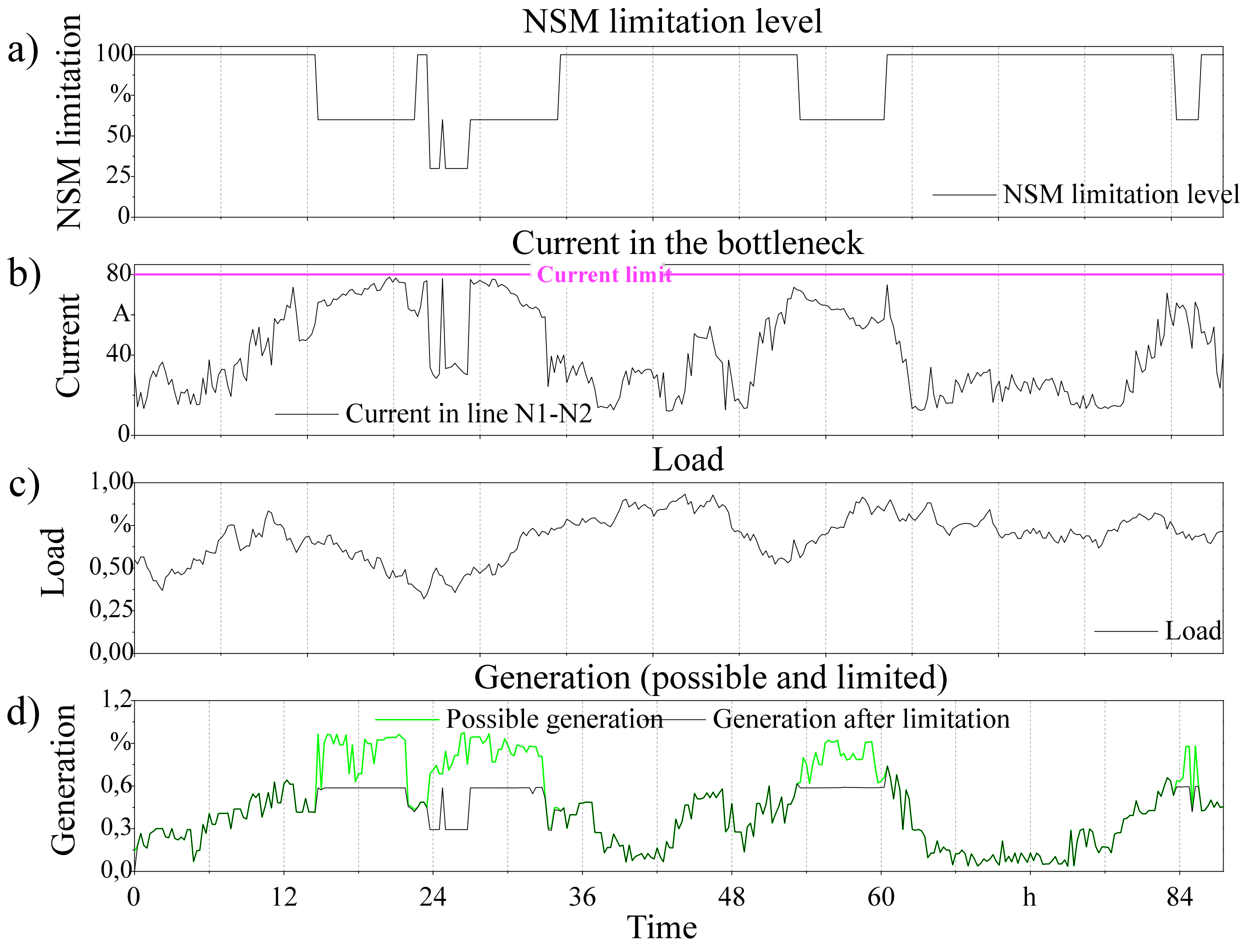


Fig. 4. Results from the NSM – Tool over 3.5 days.

The NSM tool limits the generation power successfully, so the current limit is not exceeded (diagram b)). If desired, also the “green energy” that is “lost” can be calculated by subtracting the surfaces under the “Possible generation” curve and the “Generation after limitation” curve in plot d) of Fig. 4.

6. DISCUSSION

The integration of an NSM algorithm into a power system simulator has been found very reasonable. It makes it possible to observe all operation parameters that are located anywhere in the network. Through the execution of the algorithms during the load flow, the real behavior of existing and new algorithms and NSM procedures can be analyzed. The long term simulations using synthetic input data makes it possible to obtain the long time performance of new algorithms and to determine the influence of the NSM on the DGs. The short-term application of the NSM tool gives the network operator the opportunity to test several remedial measures before making the decision which one to use. In the future the NSM tool should be included in other online network security applications, because applying the NSM to a network in emergency state can change the situation significantly.

7. ACKNOWLEDGEMENT

The presented methods and tools in this paper were developed partially with a financial support of the Local Government of Saxonia Anhalt, Germany and local power utilities EnviaN and E.ON Avacon. The authors would like to express their special thanks to Dr. Hans Roman and

Mr. Lutz Schulze for the many discussions and support for this work.

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Chris O. Heyde studied electrical engineering at the Otto-von-Guericke University Magdeburg, Germany. He graduated in 2005 at the same University with the degree Dipl.-Ing.. He joined the Chair of Electric Power Networks and Renewable Energy Sources at the Otto-von-Guericke University Magdeburg, Germany as a research engineer in 2005. His primary field of interest is network security.

Zbigniew Antoni Styczynski (SM ‘01) served from 1973 until 1991 at the Technical University of Wroclaw. From 1991 until 1999 he worked at the Technical University of Stuttgart, Germany. In 1999 he became the Professor and the Chair of Electric Power Networks and Renewable Energy Sources 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 Saxonia Anhalt, Germany. He is author of more than 150 scientific papers, senior member of IEEE PES, member of CIGRE SC C6, VDE ETG und IBN and fellow of the Conrad Adenauer Foundation.

Bernd Michael Buchholz graduated in electrical engineering and received his Ph.D from MEI, Moscow. From 2000 until 2006 he was the 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 the parts 4 and 7 of IEC 61850. He is author of many papers and member of many organizations e.g. the German member of the SC C6 of CIGRE “Dispersed generation in distribution systems”, member of the Advisory Board of Technology Platform Smart Grid of the European Commission.

Olaf Ruhle graduated in electrical engineering at the Technical University of Berlin, Germany, and received his Ph.D there in 1994. In 1993 he joined the Power Transmission and Distribution Group of the Siemens AG, Erlangen, Germany where he is currently a senior researcher and head of the PSS™NETOMAC group. His special field of interests include power system stability, dynamics of multi-machine systems, control, optimization and identification problems in electric power systems.

Received 19 February 2008
Paper 08GM0762

9. Distribution Grid Security Management with High DG Penetration Rate: Situation in France and some other Trends

Christophe Kieny, N. Hadjsaid, B. Raison, Y. Besanger, R. Caire, and D. Roye (INPG and EDF, France)
T. Tran Quoc (IDEA, France)
O. Devaux and G. Malalarange (EDF R&D, France).

Abstract**--** The major change in the last decade concerning distribution network is related to the penetration of distributed generation (DG). The current practice in France concerning the connection of DG was to fit the network to the worse case of use of DG to avoid any problem. This approach will reach his limits and many developments will be necessary to optimize the network operation, taking the presence of DG into account. In this document, we introduce some research topics going on in our team as voltage control, management of load and generation, stability analysis of networks with DG, optimization of use of fault indicator, choice of optimal configuration and automatic post fault restoration, distribution system availability assessment. We also stress on the problem of interdependency between power and ICT infrastructures.

Index Terms: Critical infrastructure, Power distribution reliability, Voltage control, losses, Load management, Fault location, Power system stability.

1. INTRODUCTION: DIFFERENCE AND CONVERGENCE BETWEEN TRANSMISSION AND DISTRIBUTION NETWORKS

Distribution grids are facing tremendous challenges due to several factors among them the most important is the increasing penetration of Distributed Generation especially those based on renewable energies. These challenges have to put a special emphasis on the evolution of distribution grids with respect to the security of the whole electrical power system. Indeed, the transmission grid will no longer be “decoupled” from distribution grid. In addition, given the current practices regarding the generation disconnecting protections and the increasing number of DG interconnected at the distribution level, it is important to reconsider the concept of “security assessment” of the distribution grid without necessarily being independent from the transmission grid.

It is to be noted that the security concept is considered differently when considering transmission network or distribution network. Below is reminded the main characteristics of the both systems:

Transmission network are meshed. In case of a line trip (following for example a short-circuit and fault clearing) all substations remains fed. Customers connected to these networks may see voltage sag of short duration but no disconnection.

For the network operator, he has to balance between two problems: if the network is too strongly meshed, the short circuit currents may be too strong and he will face equipment problem on his network (lines, switchgear, ..). He then may have to open some lines or split some electrical nodes (in substations) to reduce short circuit currents. One of the major parameter he has to manage is the critical short circuit clearing time. This duration is related to network topology and rotating machines control system. It is directly linked to the stability of the system. It is well known that the stability problem is crucial for a transmission network and the operator has to take any needed action in order to avoid the problem or minimize its consequences. The stability of transmission network is often the process that leads to a blackout. For transmission systems, managing security means avoiding blackouts.

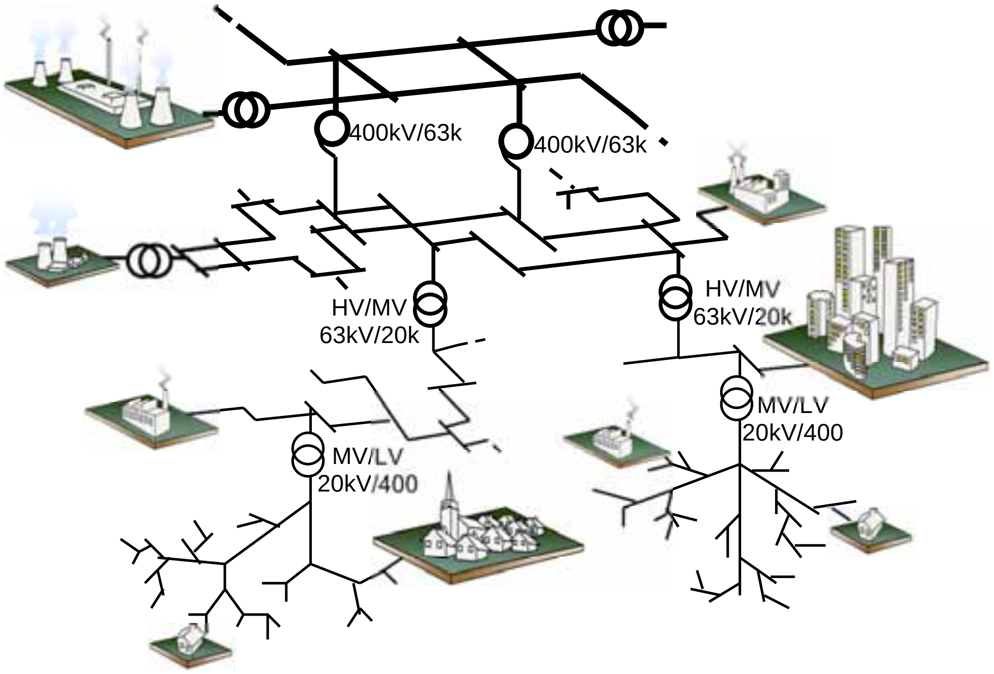

Fig 1: Transmission and distribution network

Distribution networks are built with another principle concerning its security. It is considered that in case of short circuit, as the number of customers concerned is limited, the interruption of the supply service during a short period (say some minutes) can generally be accepted. The average interruption time for customers is less than 50 minutes in France. This load curtailment has no dangerous effect on stability of the transmission network. The distribution networks are operated radially, the energy comes mainly from the substation (transformer) connected to the upper voltage level. If a short circuit occurs in the distribution network following by a feeder disconnection (trip), the operator has to localize the fault and to reconfigure the network so that most of the customers will be re-energized. Often, the main objective to be fulfilled is the increase of availability. The criterion is the minute losses or SAIDI. In order to allow some reconfigurations, the network topology is structurally meshed but radially operated with switches that remain normally open.

This architecture was chosen when DG was very rare and so did not present significant problems. Recently, due to environmental issue, and progress of production technology, more and more small size generations are being interconnected to the distribution network. This type of generation is often renewable, dependant on whether conditions, and finally random and highly variable. Nowadays, for some countries and networks, distribution networks with significant local generation have already been observed even above the local consumption. Electrochnical problems related to DG interconnection to distribution networks are now well known.

When a distribution network is operated with DGs, we may have the classical philosophy of fit and forget. All the problems have to be coped with when we interconnect DGs. In order to guarantee a good security level, operators consider the worst case and adapt the network to the DG interconnection (or forbid interconnecting DGs in case of any problem). In the future, distribution system may be operated more dynamically, i.e. verify that constraints and security criteria are fulfilled in real time, and choose the configuration and the production means allowed to operate the whole system in real time. Differences between operation of distribution and transmission network will reduce.

2. CURRENT PRACTICES OF EDF DISTRIBUTION CONCERNING AUTOMATION AND INTERCONNECTION OF DGS

In order to guarantee a good quality of service supply and optimal costs the French distribution grid is operated radially but has spear-feeding ways to reconfigure the network in case of faults. Typically, each feeder is built to have the ability to feed another feeder in emergency scheme. When a fault occurs on a feeder, using remote controlled switches, it is possible to separate the feeder into three to four sections, and isolate the fault. Generally, each section can be re-fed by another line or cable. Inside of each section, it is possible to separate the network in smaller subsections using manual switches. In order to localize the fault, remote detected fault passage indicators are used. A control center accesses to all this information and operators control all the remote controlled switches.

With this strategy, the average minutes losses for a French LV customer is about 70 minutes with large differences between rural and urban areas.

When there is a DG interconnection request into the network, a specific study is undertaken by the network operator. The potential technical problems that are assessed are the following:

Current constraints, voltage constraints, protection, etc.

When some constraints occur in the distribution network due to the DG interconnection, a solution is studied and the cost of this solution (restricted to the part of the network of the same voltage level as the interconnection point) has to be taken in charge by the DG owner. When we look at the case of wind farm, whose rated power is typically between 5 to 20 MW, they are often interconnected to the substation with a separated MV cable. This practice, decided by the French government, guaranties a good quality of service for all the customers and very few over costs for the distribution network operator due to DG interconnection. The growing presence of DG on the Medium Voltage grid has been treated up to now by fitting the Medium voltage grid and the DG units to guarantee a satisfactory operation of the system at all times. The Distribution System Operator (DSO) would operate the grid with very limited knowledge if not no knowledge at all of the real time state of DG units. We are expecting this approach to reach limits in the future. To facilitate the interconnection of DGs, and to solve some remaining problems, we undertake some research activities [1].

3. EW TOPICS AND CHALLENGES IN DISTRIBUTION NETWORKS

In the future distribution networks, two major evolutions are expected to occur. The first one is related to the management of generation and load to provide services to the network operator. We will go from a fit and forget approach to the concept of active network.

The other major evolution will consist in going to more flexible networks. The progress of information and communication technology (ICT) allows having more remote controlled devices.

3.1 Voltage management and control

Voltage issues often limit large-scale integration of DG in distribution networks. The voltage profile along the feeder, which was simple as the voltage was just decreasing along the feeder, is now more complicated due to power injections. These voltage violations are the consequences of a high penetration rate of distributed generation. However it is possible to change the reactive power production / consumption set point for each DG and, therefore, avoid some voltage constraints hence allowing the maximum DG penetration rate to be increased. In order to implement this solution, the distribution system operator (DSO) needs to control reactive power production of some DG interconnected to its network [2]. Additional grid automation can provide a finer optimization of grid losses. Grid configurations are usually optimized using peak demand situations. When interconnecting DG, the VAR flows are not optimized: a coordinated VAR control of generation and substation would ensure that the generated and consumed VARs are optimized. The value of a coordinated VAR control will increase as the presence of DG increases. These systems will involve monitoring and control of capacitor banks and/or voltage regulators on distribution circuits including on-line tap changers.

Voltage control problem could be seen as a mathematical optimization problem [3]. Several solving methods exist but their implementation on real time systems seems tricky, as computation times could be too extensive. Different strategies will be tested. A first approach transposed from transmission network practices is based on an optimal power flow calculation that is done during the day-ahead process, and results in specified values for voltages in some pilot points. In real time, the control system uses these pilot point voltages as set point to a coordinated reactive power control for DGs. [4]

3.2 Management of generation and load

The presence of DG units on the MV system adds uncertainties on the total active and reactive power flows seen on the primary side of HV/MV transformers when there is no way to observe. Variations in DG active and reactive power output can move the system from its optimal point that is calculated every year in order to prepare the next year contractual values with the TSO. When active and reactive flows exceed contractual levels, EDF Distribution has to pay penalties to the TSO. In order to control the flows between the TSO and our primary substations, it will be necessary to forecast, then monitor closely and control the DG active and reactive power injections. Today, these are the limits of the fit and forget approach on the transmission and sub-transmission systems. The recent experience shows that the fit and forget approach is not always chosen for HV systems: in windy regions with scarce loads the power injection can reach peaks that leads to congestions on the HV system in certain conditions; these limitations reduce DG output.

This is the first example where the network operator has to control the production of DG to solve his own business. In the future we can also consider the case where congestions on the distribution network will need management of generation or load to be solved. Increasing expectations of customers, regulatory bodies, local governments, assets aging and new occurrence of peak loads in summer time are foreseen to increase the constraints on the distribution grid. On the other hand, the development of DG can release some constraints but can also increase the constraints (voltage constraints, power flow constraints when major loads are not close enough to a generation site, etc.). In the long term, new loads such as heat pumps, or rechargeable hybrid vehicles may increase the peak load. This may lead to new ways for the distribution system to deal with peak demand (to send broadcasted or individualized signals to customers about peak time or low load time periods, to implement different interconnection contracts depending on the load curve, etc).

Let us consider the case where one of two parallel feeding transformers is out of order. Due to some other cable unavailable in the network, it is not possible for the operator to find an adequate configuration, fulfilling all the constraints. In this case, which is rather rare, the best approach would be to manage local production or load to reduce the peak flows of approximately 10%. This flow management is necessary during 6 hours in the day.

Using only thermal load management (space heating), which represents 30% of total load at peak hour, and limiting the curtailment to one hour for each customer, we could conclude that simple approach is not sufficient to solve the overload of the feeder we were looking at. We need a more sophisticated strategy, for instance by taking into account the real inertia of each building, or by managing other loads.

The other aspect to be solved so that this kind of service could be offered to the distribution operator is the financial problem. An approach is developed in the European project FENIX in which we are involved. It consists of a transposition of the redispatching principle used by transmission system operators. This will need a major change of the DSO role: it will be for instance involved in the redispatching operation made by TSO [5, 6].

3.3 Stability analysis for distribution network with distributed generation

Although considerable attention has been dedicated to DG generation technologies based on non-synchronous machines, e.g. fuel cells and photovoltaic, the great part of generation on the medium voltage network are synchronous generators, particularly for Combined Heat Power applications. However, the fault clearing time of distribution network is normally very long whereas the inertia constant of DG is typically low. Therefore, following a large disturbance (short-circuits, line outage voltage dips…), they are disconnected from the network by the decoupling protection. When the penetration of DG is still low, the influence of this disconnection may be neglected. However, when the DG penetration rate increases, this disconnection may lead to significant load shedding. As seen from the transmission network the behavior of the interconnected distribution network during the disturbance is very important. The stability of the whole network depends on all the components. Therefore in order to study the stability of the whole network it is necessary to model all these components, especially those having an impact on the overall dynamic behavior of the electrical system.

As the distribution network is a large system, representing all the elements is a complicated task. The first principle used to solve this is to develop methods to simplified equivalent models of the network. This approach drastically reduces the computation time while keeping a good accuracy.

In a study going on in our team, the transient stability of synchronous generators, which are connected to distribution systems, is investigated. The conventional method to assess the transient stability of power system is based on time domain simulation of system dynamic equations. The determination of index of transient stability limits, and hence the Critical Clearing Time (CCT), is performed by around ten or hundreds of repetitive simulations. This method provides the most accurate and reliable results and it has unlimited modeling capabilities. However, the method is very slow because of numerical integration of dynamic equations and it does not provide sufficient information about the index of stability of the system.

Thus, to quickly assess the ability of the DG to withstand severe disturbance while ensuring the continuity of service and then apply the preventive action to safeguard them, two hybrid methods are studied: the Individual Transient Energy Function and the SIME methods [7]. The direct outcomes of these methods are: substantial gain in the computing time over time-domain methods on one hand and assessment of margin and identification of the system critical machines on the other hand.

3.4 Optimal Number and Positions of Fault Passage Indicators

Distribution networks perform the connection to final customers and have to fulfill services and ensure a good power quality. The service continuity is one of the most important concerns to the utility company but a fault is often unavoidable and results in power interruption. Faults detection and localization is therefore of first importance in the network management by the DSO.

In order to localize the fault before isolating it and reconfiguring the network, the classical means may give false results and need to be adapted.

Fault Indicators (FI) are main devices used for faults detection and spread along the feeder. As a permanent fault occurs, they make it possible to localize the faulty part of the network and to isolate it from the sane parts (fast fault localization). FI may deliver the following information:

- Local visual signs,
- Remote information to SCADA.

With this information, the DSO and the maintenance crew can isolate the faulty part of the feeder, supply the customers and repair the conductor. For the moment, the FI placement is performed by the maintenance crew or the DSO when the feeder is created or modified. One can ask whether a help tool could be useful to propose a relevant FI placement.

Besides distribution networks are nowadays facing new challenges with the probable massive introduction of dispersed generation. One of them is to continuously ensure the safety and the security of the network in spite of many versatile actors. The efficiency of FI placement is therefore influenced. We have performed a study that deals with the optimization of FI placement and analyzed the DG effect upon the efficiency of this placement [8].

An optimization tool of FI placement was developed. The method makes it possible to select the optimal placement by knowing the characteristics of the network (load, type of conductor, switches, fault probability, etc.).

Among the different existing optimization methods, the genetic algorithms have been selected to perform the placement process. Guidelines are proposed to tune this optimization process for the considered application.

The DG insertion influence (islanded functioning or not, cost of non-supplied energy) on the efficiency of FI placement in this network has also been analyzed.

3.5 Towards a More Automated Post-Fault Restoration

When a fault occurs on an MV feeder, the control engineer downloads data from fault passage indicators, locates the remotely controlled switches that need to be open to isolate the fault and then performs the fault isolation. Usually power can be restored on the healthy segments in the upstream part of the feeder. Downstream from the fault, restoration is usually possible in N-1 conditions. These actions are usually taken within three minutes, thus keeping the number of long interruptions low. When power to a whole bus bar or a whole substation is lost, or during storms, restoration is a far more complex operation. The presence of DG makes the evaluation of the restoration more challenging as well if the control engineer wishes to use the DG capacity when backup feeders do not have sufficient capacity. The number of solutions that need to be evaluated can be far greater.

Innovation in Distribution Automation (DA) uploading of fault passage indicators, automatic localization and isolation of faults, automatic restoration of healthy feeder segments, and integration of DG capacity in restoration schemes can bring significant value in these situations, especially as the number of substations per control center increases. By providing a significant help to the control engineer in improving his reaction to faults, the control engineer can handle a larger number of substations. This is particularly valuable at night or during storms.

The value will eventually be for both customers and DG owners who will benefit from higher grid reliability. We expect these improvements to reduce the customer minutes lost by 2 to 5 min depending on the region of France.

The challenges for these innovations are mainly in the quality of topological and load data, in the quality of the communication with DER units, and the robustness of the optimal solutions proposed when DER units are included in the restoration schemes.

3.6 Choice of the configuration and impact on security levels

The Distribution Networks (DN) is designed as looped or meshed structures and is operated radially. Normally opened switches (generally remotely controlled) are chosen considering fault management, network losses and voltage control purposes. Their positions are changed especially when the grid is reconfigured after a permanent fault or for maintenance actions.

Nowadays, because of the increasing amount of DG, these practices should be modified for a better network operation. A more flexible topology may be useful in order to reduce the network losses and to optimize the voltage profile.

This aspect should be considered, taking into account the emergence of ICT technologies in DN. For instance, remote measurements make a better possible DN state estimation and an increasing amount of remotely controlled devices should allow a more flexible operation to be achieved.

In this context, optimal DN topology computation tools have to be developed [9]. They should consider the losses reduction and/or the voltage profile optimization into the cost function. Topology constraints (staying radially operated) and security constraints (accepted voltage and currents values) should be considered. This is a non-linear constrained combinatorial optimization problem. Heuristic optimization methods, which are frequently employed, may only converge to a local minimum. Moreover, DG presence increases the risk of converging to a local optimum.

A stochastic optimization method (genetic algorithm) is developed for the optimal solution computation. Graph theory and matroïd properties are used to ensure a good topology modeling constraint and efficient genetic algorithm process [10, 11, 12].

The optimal topology has determined that to minimize losses could not be optimal for reliability concerns. The integration of a reliability index computation in the optimization process can be a very consuming time task. A first approach based on electric moments computation (active load multiplied by conductor length) can be used in order to consider the reliability aspects in the optimization process.

Table 1 presents the results of the optimization for one hour of the day, near peek hour. For each considered criterion, the results are reduced compared to those of the initial configuration.

Table 1: optimization at peek hours

	Initial Configuration	Optimal configuration for Power Losses	Optimal configuration for Reliability
Network Losses [% Total Active Load]	3.31 %	2.87 %	3.22 %
Non Served Energy [MWh]	1.7	1.73	1.53

3.7 Distribution system availability assessment

The major changes in distribution systems brought by the introduction of DG, make their operation as well as their operational reliability more complex to be assessed and need to be modified. A re-evaluation of system reliability is therefore needed. The two often-used approaches for power system reliability evaluation are the analytical and simulation methods. Analytical techniques represent the system by a mathematical model, often simplified, and evaluate the reliability indices from this model using direct mathematical solutions. Simulation techniques estimate the reliability indices by simulating the actual process and random behavior of the system and are generally more flexible when complex operating conditions and system considerations (bus load uncertainty, weather effects, etc.) have to be taken into account. The type of simulation involving the sampling of values of stochastic variables from their probability distribution using random numbers is denoted as Monte Carlo simulation. There are two basic techniques used in Monte Carlo simulation: sequential and non-sequential. The sequential simulation permits chronological issues to be considered and the reliability indices distribution calculation. The Monte Carlo simulation needs many trials to obtain a reasonable accuracy in the result of the estimate and each trial requires significant computational effort.

The distinctive way to handle this issue is the simulation of the dynamic behavior of the system, meaning that, along the time axis, not just one event is modeled but a sequence of events. During simulation, different system states can be reached, involving even the blackout and the restoration of the system. The reliability indices are computed for each system state and for each load bus. [13]

4. INTERDEPENDENCY WITH INFORMATION AND COMMUNICATION TECHNOLOGIES (ICT) INFRASTRUCTURE

The increasing use of information technologies within the electrical supply networks (production, transmission and distribution) reveals the concepts of vulnerability and interdependency. The three essential infrastructures, namely, electrical, information and communication networks are so closely dependent that it is essential to have an "integrated" vision of the safety of the whole system by taking properly into account their interactions.

The reliability of the critical infrastructures is the aptitude to deliver a justified confident system and to avoid most frequent failures or more serious than acceptable: it results from the causes analysis (failures, faults, errors, etc.) in a cycle of prevention, tolerance, elimination of the expected faults in order to offer the necessary services and reliability: availability, harmlessness, confidentiality, integrity, maintainability. Many blackouts are due to accidental causes such as natural events, errors of use, loss of essential services and internal malfunction. Malicious acts such as data hacking or virus introduction then come in addition to these traditional “safety” incidences. However, accidents in large technological systems are not always due to simple cause and effect, but sometimes due to chains of disruptions, which can mean masses of damaged lines at the same time, cascading effects or emergency systems that are supposed to prevent failures being out when they are needed.

Considering security in distribution networks including this type of failures shows that a lot of efforts have to be done to model and analyze these interdependencies. This is a major concern for a distributor. [14]

5. CONCLUSION

Distributed resources will introduce tremendous changes on generation business as well as on electrical energy distribution and management. It will require redesigning planning strategies and tools, design methodologies, operations and control of electrical networks. Indeed, these networks were not designed and built in this perspective (interconnecting large amount of distributed resources) and the integration of such resources into the grid may have significant consequences on system performance and security and hence on the philosophy of the management systems and robustness.

In addition, with significant DG penetration rate into distribution grid, the interaction between distribution and transmission grid will be stronger. They will be more interdependent particularly with regards to security management. Depending on the situation, the security may be improved or jeopardized.

In this context and beyond the distributed resources aspect, the whole distribution network should be redesigned with innovative equipment, more automation, new control and supervision functions, specific network architectures, intelligent protection systems where information and communication technologies can achieve low cost goals regarding these new functions. Hence, the whole electrical system and its philosophy of planning, design and management is in profound mutation. In this paper we presented some examples of new features or methods adapted to future distribution grid management.

6. ACKNOWLDGMENT:

The authors would like to acknowledge Schneider Electric, partner of most of these different projects.

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BIOGRAPHIES

Christophe KIENY (M' 91) was born in 1956. He graduated from Ecole Polytechnique (X77) and received the engineer degree from the Ecole Supérieure d'Electricité in 1982. He has been with Electricite de France- R&D department - since that date. He is now, deputy director of IDEA, a join research team between Schneider Electric, EDF R&D and Grenoble INP, specialized in distribution network.

Nouredine HADJSAID received his Ph.D. degree in Electrical Engineering and "Habilitation à Diriger des Recherches" degree from the Institut National Polytechnique de Grenoble (INPG) in 1992 and 1998, respectively. From 1988 to 1993, he served as a research and teaching assistant at the Ecole Nationale Supérieure d'Ingénieurs Electriciens de Grenoble (ENSIEG) and at the Grenoble Electrical Engineering lab (G2Elab). He is a professor at INPG.

Daniel Roye is professor at National Polytechnic Institute of Grenoble (INPG)

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

Bertrand Raison (M'03) was born in 1972. He received the M.S. and Ph.D. degrees in electrical engineering from INPG, Grenoble, France, in 1996 and 2000, respectively. He is now an Assistant Professor at at the National Superior Electrical Engineering School of Grenoble. His general research interests are fault detection and localization in electrical systems.

Raphael Caire (M'04) is an Assistant Professor at INPGrenoble-ENSIEG-
LEG. His research is centred on the impacts of dispersed generation on distribution system, and critical infrastructures.
Tuan TRAN-QUOC (M' 93, SM' 99) received his Ph.D. degree in Electrical Engineering and "Habilitation à Diriger des Recherches" degree from the Institut National Polytechnique de Grenoble (INPG) in 1993 and 2000, respectively. His research interests are in the fields of power system analysis, operations and electromagnetic transients.

Olivier DEVAUX was born in 1969 in France. He received his degree of Electrical Engineer from the Ecole Supérieure d'Electricité in 1992. He joined the EDF's R & D Division in 1993. His research interest is Distribution network automation.

Gilles Malarange is research engineer at EDF's R & D Division. His research interest includes connection of dispersed generation to distribution networks.