Power Systems

Ulf Häger
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Monitoring, Control and Protection of Interconnected Power Systems

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Monitoring, Control and Protection of Interconnected Power Systems

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Foreword

Electric energy systems have undergone two major paradigm changes during the last 20 years:

- Liberalization of the electricity market by unbundling generation and energy market on one hand and transmission/distribution systems on the other hand.
- Transition from the existing fossil fuel and nuclear generation to an increasing share with respect to renewable energy sources.

To effectively support the aims of these changes, the transmission systems have to be regulated because they are a natural monopoly. Planning and operation of modern transmission systems become more and more complex for the following reasons:

- The location of generation sites depends on the availability of renewable energies and not on the location of the major customers.
- The nature of renewable energy sources creates a substantial volatility in the transmission network.
- Dispatchable power sources are replaced by stochastic generation patterns which need complex and sophisticated prediction tools.
- The acceptance for new transmission lines by the public is a major barrier for the adequate expansion of the transmission system.
- The key for the successful transformation from fossil fuels/nuclear generation to renewable energies is a powerful transmission system tailored to its needs.

The continuous growth of interconnected transmission systems is an immense challenge because it leads to the most complex technical system ever built by engineers. Although the frontiers for the size of future interconnected systems are continuously expanding there is a conjecture concerning the optimal size of a transmission system. This conjecture cannot be confirmed without looking into the details of monitoring, control and protection of interconnected power systems keeping the above mentioned paradigm changes in mind.

The expansion of the existing interconnected electric power transmission systems offers significant advantages with respect to operational security, integration of renewable energy, as well as energy trading. On the other hand, the complexity of operational problems significantly increases and hence large R&D

efforts are urgently required in order to make full use of recent technological innovations with respect to new power system components like wide area monitoring, control, and protection equipment, as well as advanced network controllers such as flexible AC transmission systems (FACTS) and HVDC systems. Furthermore, power system disturbances may result in major blackouts if monitoring, operation, and control of interconnected power systems is not based on efficient and innovative information technologies. The objectives of the FP7 project Intelligent Coordination of Operation and Emergency Control of EU and Russian Power Grids (ICOEUR) sponsored by the EU commission are directly linked to the aspects of a secure and economic operation of large interconnected power transmission systems, the integration of renewable energy power generation, and the efficient system handling under emergency conditions.

To achieve these objectives, a close and trustful cooperation between many experts with a wide range of expertise is an important prerequisite for creating a large impact on the future development of interconnected power systems. Leading experts in all the relevant fields successfully completed the ICOEUR project. It is most welcome that the important results and insights obtained in this successful project are documented in this book. It supports the dissemination efforts of the ICOEUR research consortium in order to adopt the accomplished results concerning innovative monitoring, simulation and control concepts, experience with tools and equipment, and the implementation of the results.

This book offers a systematic approach in looking for the optimal size of a large interconnected system from a technical point of view. A suitable basis for tackling the related problems is a well-defined basis consisting of system models and systematic description of relevant dynamic phenomena. This leads to a holistic simulation approach indispensable for the thorough understanding of the future energy system. Monitoring aspects based on state estimation and wide area monitoring deal with the reliable and complete assessment of the current operational state of the power system. Without detailed knowledge of the actual system state, a secure and economic operation is unthinkable. Since the first efforts in the 1960s of the last century much technological process significantly contributes to new effective solutions for the secure assessment of the current system state.

In view of the aforementioned increasing volatility due to renewable generation, the dynamic control of interconnected power systems is of increasing importance. These control aspects are based on new operational equipment such as FACTS and HVDC as well as modern information technologies such as multiagent control systems. Dynamic control intrinsically is related to system stability and the associated protection techniques. The reliable assessment of a stable operating point with respect to voltage and frequency is a great challenge for modern information systems. Interesting contributions have been achieved based on neural network approaches and artificial intelligence techniques. Although being powerful, all these methods have limits and suitable methods are required for stabilizing the power system under emergency conditions. Under-frequency load shedding is a suitable method to guarantee a stable system state even under extreme conditions. All these methodological approaches lead to an important answer to the aforementioned conjecture related to possible limits of future interconnected transmission systems. The close interaction between energy and information technologies is under all circumstances an important prerequisite for successfully tackling the future challenges.

This book is a comprehensive description of all aspects related to modern power transmission systems. As it is the result of a fruitful cooperation under the FP7 program of the European Commission in collaboration with the Russian Federal Agency for Science and Innovation, it is an impressive contribution across national boundaries based on a successful cooperation between scientists and engineers. May this book be an important reference for all those responsible for the future electric energy transmission systems.

Germany 2013 Edmund Handschin

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This book has arisen out of the results of the joint research project Intelligent Coordination of Operation and Emergency Control of EU and Russian Power Grids (ICOEUR) with partners from Europe and Russia. We express our deepest thank to the European Commission (under the 7th Framework Program) and the Russian Federal Agency of Science and Innovation for supporting this work.

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The challenging task of writing and editing this book was made possible by the excellent cooperation of the team of authors together with a number of colleagues and friends. Our sincere thanks to all contributors, proofreaders, the publisher and our families for making this book project happen.

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Part I
Introduction

Chapter 1
Requirements for Monitoring, Control and Operation

Christian Rehtanz, Nikolai Voropai and Ulf Häger

1.1 Introduction

The interstate integration of power grids provides multiple advantages concerning operational security as well as energy trading. Due to these facts the Central European Power System (ENTSO-E-CE, formerly UCTE) expands continually since its establishment and the ties to other interconnected systems like NORDEL grow stronger and further new ties with neighboring countries are either being constructed or planned. The recent interconnection of Turkey underlines this trend.

Similar developments are valid in the IPS/UPS system of Russia and its neighboring countries. Particular consideration has to be given to different scenarios of joint operation of the ENTSO-E- and IPS/UPS-systems.

With large scale deployment of renewable generation throughout Europe, in particular large scale wind farms and future solar power plants, interstate interconnections are of growing importance to secure energy supply. They optimize the utilization of energy sources within larger areas, promote electricity trading between different regions, and meet the requirements of economic development. IPS/UPS can achieve similar benefits (so called system effects), by initiating joint operation with ENTSO-E using interstate interconnections.

The major benefits that motivate TSOs to build up interconnections to neighboring transmission systems are:

- Optimization of the use of installed capacities
- Reliability improvements reducing the economic cost of power outages

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- Improved control of system frequency to minimize major disturbances
- Sharing reserve capacities and reducing the level of reserves required
- Providing mutual support for the interconnected systems in case of emergency
- Improved energy market conditions in better integrated large scale systems
- Facilitating large scale integration of renewable energies due to higher flexibility of the interstate network operations.

Due to the fact that both systems of Europe and Russia alone and especially with interconnections are second to none in the world in terms of the scale and distance of the interconnection and number of countries involved, strong R&D and innovations are urgently required along with the recent development of technologies. Presently, there are numerous enlargement projects of ENTSO-E and IPS/UPS under consideration and investigation:

- interconnection of Turkey was recently established,
- interconnection to northern Africa (Tunisia, Libya, Morocco, etc.),
- interconnection to P.R. China,
- and, most significantly, the interconnection of the two largest systems
- ENTSO-E and IPS/UPS.

It has to be mentioned that there are actually several system bottlenecks identified within the networks of EU and Russia. These congestions have to be considered as well and need to be relieved with the right technologies strengthening the interconnected power systems.

The realization of an interconnection of bulk power systems, which differ in their technical characteristics, is not trivial and its technical and economical efficiency depends on the chosen technology as well as its impact on system operational security. Currently there are multiple transmission technologies with miscellaneous technical properties available: i.e. cost efficient and well proven HVAC technologies, with the disadvantage of direct disturbance extension between interconnected systems or more sophisticated HVDC transmission systems with better controllability but high investments. In order to improve system stability, to control load flow, to facilitate electricity trading and to optimize the utilization of energy resources in interconnected power systems Flexible AC transmission Systems (FACTS) and HVDC as well as other innovative compensation or control devices can be used. Due to that complexity as a first step the technically and economically optimal realization of future large scale interconnected power systems have to be investigated regarding interconnection technologies. The beneficial integration of appropriately selected technologies is a precondition for the future development of large scale interconnected power systems.

However, bulk power grids may encounter major blackouts, often with catastrophic consequences for system and consumers. Some of such severe blackouts occurred for instance in Europe and Russia in 2003, 2005 and 2006, respectively. Among the main factors leading to occurrence and development of such emergencies, researchers call complication in operating conditions of the power grids and their control in a market environment as well as insufficient coordination of control at an interstate level. The latter particularly manifested itself during the 2006 European blackout. Therefore the possible future extension of power system interconnections requires elaborating methods for monitoring, control and operation of large scale systems and especially for the support of their interconnections. Besides, the possible future interconnection between the Pan-European and Russian electricity transmission systems would be greatly simplified if common/compatible software tools, hard ware equipment and operational procedures are adopted by all TSOs involved. The joint development of these tools and equipment will promote their adoption. The presentation of recent developments and their prototypically demonstration is the major goal of this book. The operability of the results is demonstrated based on extensive network simulations using realistic network data.

1.2 Large-Scale Interconnected Power Systems

All investigations in this book are related to real power system requirements. As examples the interconnected power systems of Europe (ENTSO-E) and Russia (IPS/UPS) are considered.

1.2.1 General Characteristics of IPS/UPS

The Interconnected Power Systems/Unified Power Systems (IPS/UPS) is a power union presently comprising synchronously operated power systems of 14 countries: Azerbaijan, Belarus, Kazakhstan, Kyrgyzstan, Moldova, Mongolia, Russia, Tajikistan, Ukraine, and Uzbekistan belonging to the Commonwealth of Independent States (CIS) and Estonia, Georgia, Latvia, Lithuania as unbelonging th the CIS. The system is actually based on the former USSR Unified Power Systems originated in the mid 1950s of the last century and being continuously developed over the last 50 years.

Synchronous operation of the power systems of these countries is coordinated by the Electric Power Council of the CIS (EPC CIS). Within the framework of the EPC CIS the Commission on Operational-Technological Coordination of parallel operation of the power systems of the CIS and Baltic countries (COTC) establishes recommendatory principles of technical interaction and develops corresponding documents.

The cooperation of the Baltic power systems with the power systems of the CIS countries is performed within the framework of the BRELL-Committee established on the base of multilateral international agreement between TSO’s of Belarus, Russia, Estonia, Latvia and Lithuania signed in 2002.

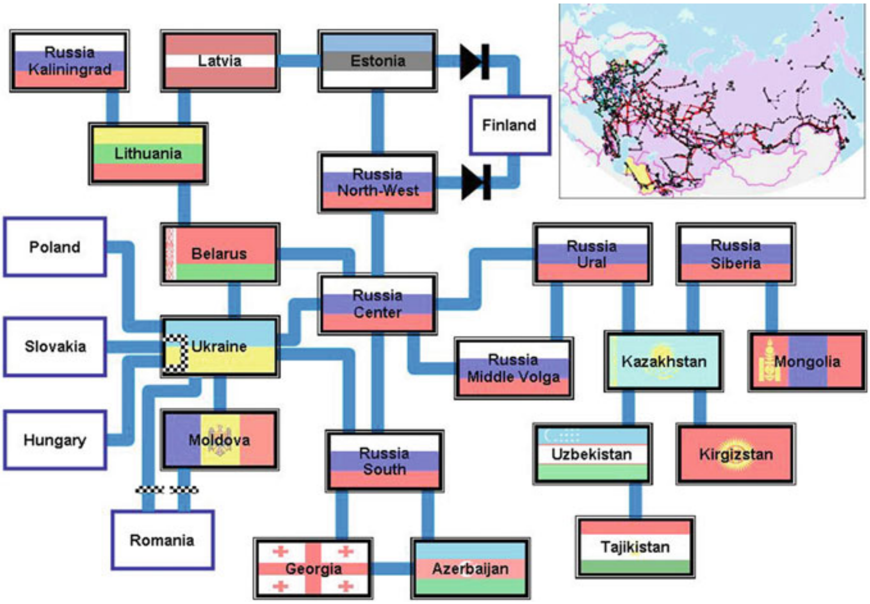

Fig. 1.1 Structure of interconnected power system (IPS/UPS) of Russia and its neighboring countries

At the moment, with 335 GW of installed capacity IPS/UPS annually supplies about 1,200 TWh to more than 280 million consumers. This is the world's most geographically extended power system, spanning over 8 time zones. Such vast territory impedes certain specific features of the power system:

- Comprises of internally almost balanced regional power systems interconnected in most of the cases by congested links;
- Extensive use of long-distance extra high voltage transmission lines (up to 1,150 kV);
- Use of automatic emergency control systems (in certain cases the N-1 criterion is only satisfied with the automatic emergency control system);
- All power systems composing IPS/UPS are structurally allocated to 14 power regions (see Fig. 1.1):
  - 6 IPS in Russia (North-West, Centre, Middle Volga, South, Ural, and Siberia),
  - Baltic States (Estonia, Latvia, and Lithuania);
  - Ukraine and Moldova;
  - Central Asia (Kirghizstan, Tajikistan, and Uzbekistan);
  - 5 individual powers systems of other countries (Azerbaijan, Belarus, Georgia, Kazakhstan, Mongolia).

In addition to Fig. 1.1, IPS/UPS has weak cross-border AC interconnections with Norway, Turkey, Iran, Afghanistan and China.

Each power system regulates the active power balance with or without frequency deviation correction, with or without automatic systems. The UPS of Russia controls frequency in the whole synchronous zone.

North-Western IPS of Russia has a DC-link with Finland. Another DC-link between Estonia and Finland (ESTLINK) was commissioned in December 2006. AC radial operation of near generation is operated with Finland, too.

Two scales of nominal voltages are used in the IPS/UPS: 750-330-220-110 kV and 1150-500-220-110 kV (now 1,150 kV equipment operates at 500 kV). The backbone network of 220–1150 kV performs power transmission; while the lower voltage lines form distribution grids.

In fact many electric ties in IPS turn out to be underloaded for a long time and their transfer capabilities are even below the limits determined by the standard margins.

The European part of Russia's UPS including Ural, has a rather developed closed structure of the main network. It encompasses relatively weak extended transmission lines between and within IPSs, which cause problems of irregular power fluctuations and angle stability (small signal and transient). The Asian Part of the UPS of Russia is characterized by lengthier transmission lines that are mostly extended in latitudinal direction. In West-Siberia they are mostly extended structure of the main network and have a chain-like structure in East Siberia and Trans-Baikalia. The problems of irregular power fluctuations in transmission lines and small signal and transient stability with respect to angle are also pressing here. Until recently voltage stability problems arose mainly at local nodes that contained large amount of asynchronous loads and appeared in the centers of oscillations during emergencies.

In the last decades development of large cities and megapolises has changed the main network structure. This resulted in formation of rather large highly meshed zones with relatively short transmission lines between substations. For such zones the problem of system voltage stability is getting urgent. This problem was shown by the blackout in Moscow and adjacent area in May 2005.

The following technical regulations are now in force in the synchronous area of IPS/UPS but, however, not fully confirmed by other countries than Russia:

- IPS/UPS Intergovernmental standard 1516.3-96 "Electrical equipment for a.c. voltages from 1 to 750 kV. Requirements for dielectric strength of insulation" [1];
- Methodical Guidelines for Power System Stability of RF Ministry of Energy [2];
- Guidelines of technical maintenance of Power Plants and Grids of Russian Federation [3];
- IPS/UPS Intergovernmental standard 14209-97 "Loading guide for oil-immersed power transformers" [4].

Fig. 1.2 Geographical representation of synchronous areas in Europe (ENTSO-E and IPS/UPS) (Map: © Lutum+Tappert)

1.2.2 ENTSO-E CE

The "European Network of Transmission System Operators for Electricity" (ENTSO-E) is the association of transmission system operators in Europe. The sub-region for Continental Europe the former UCTE is named ENTSO-E-CE in the following. The organization aims to provide a reliable market base by coordinating the operation of power system interconnections over the entire European mainland.

The transmission networks of the ENTSO-E-CE members supply electricity to about 450 million people with an annual consumption of approximately 2,500 TWh. The ENTSO-E-CE system covers 23 European countries with some 220,000 km of 400-kV- and 220-kV-lines, thus being by far the largest interconnected system in Europe. The annual peak load in 2006 was about 390 GW. Figure 1.2 gives a geographical overview about the synchronous areas of ENTSO-E-CE, IPS/UPS and other synchronous areas in Europe [5].

Over the 2nd half of the 20th century the ENTSO-E-CE interconnected system was designed in order to implement principles of solidarity and economy. The ENTSO-E-CE system developed progressively into the highly meshed network that provides routes for electricity from the generation in-feed to the consumption and allows getting missing power from a neighboring control area through the available reserves of partners. Building on the essential principle of solidarity, the reliability, adequacy and quality of supply were continuously improved.

Today, TSOs are in charge of managing the security of the operation of their own networks in a subsidiary way based on the ENTSO-E Operation Handbook. Individual TSOs are responsible for procedures of reliable operation in their control area from the planning period as in view of the real-time conditions, with contingency and emergency conditions. The coordination between TSOs contributes to enhancing the shared solidarity to cope with operational risks inherent to interconnected systems, to prevent disturbances, to provide assistance in the event of failures with a view to reducing their impact and to provide re-setting strategies and coordinated actions after a collapse.

However, the ENTSO-E interconnected system is being operated more and more at its limits. Markets trigger an increase of cross-border power flows between countries since markets by definition aim at optimizing produced power depending on short term price differences. This leads to important variations of generation patterns within the ENTSO-E-systems displacing substantial amounts of electricity from one area to another, from 1 h to another, or even shorter.

One current example of changing generation patterns is due to the rapid development of wind generation characterized by short term predictability: within a few hours, the production of wind farms can change from minimum to maximum and conversely. This can only be mastered with an adequate transmission infrastructure and a more and more complex management of the interconnected networks. In reality, many ENTSO-E-CE TSOs face increasing difficulties to build new network infrastructures (lines, substations, etc.). This puts more pressure than ever before on all TSOs to be able to rely on each other via closer coordination mechanisms as those stated among ENTSO-E-standards.

This is why ENTSO-E and formerly UCTE supported by the European Commission and all relevant stakeholders developed from 2002 their own "Security Package" as a set of complementary tools:

- The ENTSO-E Operation Handbook (OH) as a compendium of technical standards to be applied in the ENTSO-E interconnected system; OH constitutes the technical/operational reference for seamless and secure operation of the power system;
- The Multilateral Agreement (MLA) as a cornerstone of the legal framework for the security of the ENTSO-E interconnected systems, since MLA introduces a binding contractual relation between all ENTSO-E TSOs referring to OH.
- The Compliance Monitoring and Enforcement Process (CMEP) as a recurrent ex-ante process verifying the implementation of the OH standards by all TSOs as well as any measures individual TSOs have committed to towards the entire TSO community in cases of temporary non-compliance.

Even if due to national legislation and regulatory frameworks as well as due to internal procedures each TSO has to follow additional rules, the ENTSO-E Security Package remains the basic reference for security of the interconnected system. It substantially increases transparency of the fundamentals of the TSO rules and therefore the necessary mutual confidence of TSOs among themselves as well as their credibility towards stakeholders.

1.2.3 Interface Tie Lines Between ENTSO-E and IPS/UPS

Several interfaces between ENTSO-E and the IPS/UPS are still existing because of the historical development of the system boundaries. Table 1.1 (following mainly [6]) gives an overview about the interface lines between ENTSO-E CE and IPS/UPS.

Table 1.1 Existing transmission lines between ENTSO-E and IPS/UPS

ENTSO-E CE Substation	Country	IPS/UPS Substation	Country	Voltage (kV)
Rzeszow	Poland	Khmelnitska NPP	Ukraine	750
Vel'ke Kapusany	Slovakia	Mukachevo	Ukraine	400
Sajoszeged	Hungary	Mukachevo	Ukraine	400
Albertirsa	Hungary	Zakhidnoukrainska	Ukraine	750
Kisvarda	Hungary	Mukachevo	Ukraine	220
Tiszalok	Hungary	Mukachevo	Ukraine	220
Rosiori	Romania	Mukachevo	Ukraine	400
Isaccea	Romania	Pivdennoukrainska NPP	Ukraine	750
Isaccea	Romania	Vulkaneshty	Moldova	400
Elk	Poland	Alytus	Lithuania	400
Bialystok	Poland	Ross	Belarus	220
Zamosc	Poland	Dobrotvirska	Ukraine	220
Dobrudja	Bulgaria	Vulkanesti	Moldova	400

These transmission lines were operated as an integrated part of IPS/UPS and power system "Mir" until 1995 when Poland, Hungary, Slovakia and Czech Republic became synchronously interconnected to UCTE. For a synchronous coupling of ENTSO-E CE and IPS/UPS some of these lines need to be refurbished and partly reconstructed.

Due to their independent development the major differences in system structure and certain operation philosophy variations exist between ENTSO-E and IPS/UPS. While both systems follow the (n−1)-criteria, in IPS/UPS a wider range of means is used to overcome the consequences of disturbances (i.e. power imbalances, grid elements tripping or overloads, violations of voltage limits, etc.): protection, re-dispatching and automation actions comprising load and generation shedding.

1.3 Requirements and Innovation for Future Interconnected Power Systems

The considered interconnections would result in the largest power system in the world, which provide a large energy market platform and integration platform for renewable energy to all participants. An efficient and secure operation of the largest electrical interconnections assumes:

- optimal choice of network interconnection and extension technologies,
- effective control and monitoring systems and strategies,
- well defined protection functions that ensure secure operation of all partner networks in critical cases.

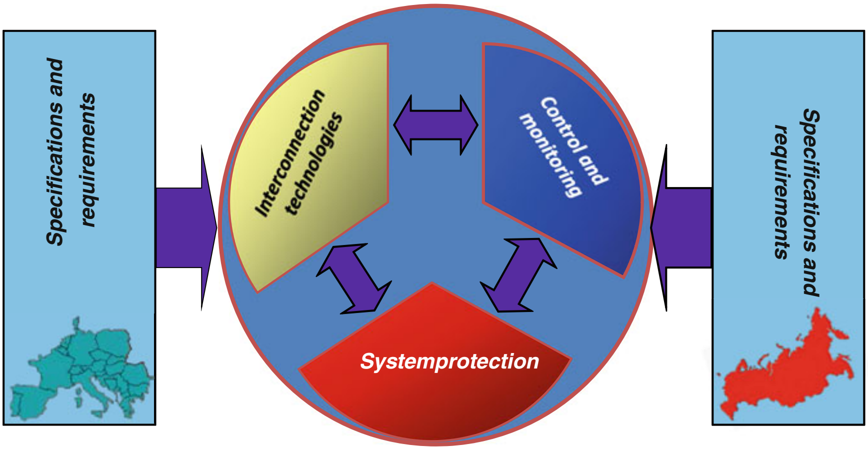

Fig. 1.3 Requirements for development of large-scale interconnected power systems

These are the core requirements for a large-scale interconnection of EU and Russian networks. Figure 1.3 summarizes these requirements.

Optimal technical interconnections within and between EU and Russian electricity transmission networks allow secure and stable operation of the common as well as of isolated power systems. Such interconnections provide "highways" for energy exchange between the energy market areas. Secure operation has to be ensured by innovative control and monitoring systems, which include innovative monitoring and control tools, intelligent control devices and ingenious protection functionality. Such an innovative concept realizes the secure interconnection of both networks while retaining autonomies of all the participants with consideration of their individual technical and regulatory requirements.

In conclusion the presented results shall support the following urgent, high-impact functional needs, which can be regarded as improvements of the current state of the art:

- Delivery of clear concepts of optimal interconnection of large-scale power systems as of EU and Russia
- Concepts for future oriented and sustainable grid expansion and grid enhancement
- Methods to increase observability of large scale power system interconnections
- Better sensing, monitoring, understanding and predictability of the power system state
- Novel control methods of large scale interconnected transmission systems
- Innovative concepts for cooperation of TSOs in interconnected power systems with regard to stability control issues.

For each of these power system functional needs, different technologies require a more in-depth review, in order to have a portfolio of different solutions to address wide issues. These technologies are:

- Wide area monitoring of power system state using Phasor Measurement Units (PMU)
- Real time simulators of ultra-large power system interconnections
- PMU-based control applications of large scale interconnected networks
- Coordinated planning, operation and control of flexible power flow control devices.

Based on the requirements specified above the following innovations can be identified for the development of future interconnected power systems.

1.3.1 Concept of Optimal Interconnection of Large-Scale Power Systems

There are several examples for successfully implemented interconnections between previously independent power systems. ENTSO-E CE consists actually of 34 TSOs from 22 European countries.

These TSOs are connected via AC technology and are operated with the same frequency at 50 Hz. A similar example is the NORDEL interconnection, which was established in 1963 and comprises the power systems of Denmark, Finland, Norway and Sweden via AC links. AC technology is well approved and requires low investments. But AC transmission leads to high losses over long distances and requires therefore expensive compensations. Disturbances in AC interconnected systems are visible in the common network and affect therefore all partners.

Alternative to HVAC technology HVDC is often used to create an interconnection between power systems. Due to its technical nature HVDC allows higher operating voltages and provides higher capacity in combination with low line losses. The experience has shown that HVDC links can stabilize power systems, and in contrast to AC links they can maintain interconnected system operation during large disturbances, as happened during blackouts in USA and Canada in 14th August 2003. The HVDC links are also well approved and often used for the interconnection of large power systems. Examples for HVDC interconnections are links between ENTSO-E CE and ENTOS-E Nordic (former NORDEL) or ENTSO-E CE and ENTSO-E UK.

Compositions of both technologies are possible and are used i.e. in North American electricity transmission networks.

A closer look to currently existing interconnections shows a high similarity of linked power systems concerning the used transport technology and network structure. Almost all ENTSO-E networks use solely AC technology and only sparely HVDC transmission system. The used transmission lines have short distances and the resulting grids are highly meshed.

In contrast to this, an interconnection of EU and Russian networks is an interconnection of power systems with significant differences. The IPS/UPS network includes high rates of HVAC links, due to the fact that large distances have to be covered between generation and load centers. Therefore the interconnection design for such power systems has to consider the specific features of both networks.

Another motivation for new innovations is the fact that the AC technology has already reached its limits. Due to this, previously minor issues for the European interconnected grids are now raised in their importance, i.e. voltage stability problems that previously presumed to be a problem of weak, sparse meshed or large distance grids are considered as raising problem in the ENTSO-E CE network. In particular, the creation of very large synchronously interconnected electrical systems is a potential source of stability problems, e.g. with regard to inter-area oscillations.

Such phenomena, if not adequately controlled and damped, can cause unexpected and cascading tripping of critical cross-sections of the system, thereafter determining unmeshed system operation conditions and outages, also in absence of significant system disturbances. This can be solved only by enhancement of existing power networks and making them more effective with regard to interconnected operation, by means of proper controls.

Further challenges to the interconnected power grids result from new large changing power flow scenarios due to liberalized electricity markets and a growing share of renewable generation.

Due to this previously adequate designed networks and interconnections are actually operated towards their limits. Therefore measures for wide area grid and interconnection enhancement are required.

1.3.2 State Estimation of Large-Scale Interconnected Systems

State estimation is normally applied for internal TSO control areas and considers only steady state network behavior. New sources of generation, like large-scale wind power penetration, and smart transmission devices, like HVDC and FACTS, are either not considered at all or not modeled adequately. The current generation of state estimators assumes steady state behavior within their calculation intervals of some tens of seconds. During alert or emergency situations, when the system state changes fast, the accuracy of state estimators deteriorates drastically. In addition, inaccurate information about the state of the neighboring systems may create a false sense of security and hence affect the effectiveness of security controls taken in case of large disturbances.