Challenges, Experiences and Possible Solutions in Transmission System Operation with Large Wind Integration

Zongyu Liu[1], Lou van der Sluis[1], Wilhelm Winter[2], Helmut Paeschke[2], Raik Becker[3], Christoph Weber[3], Jonas Eickmann[4], Christian Schroeders[4], Frauke Oldewurtel[5], Line Roald[5], Thilo Krause[5], Michael Rogge[6], Peter Gilsdorf[6], Patrick Wajant[7]

[1]Delft University of Technology (the Netherlands), [2]TenneT TSO GmbH (Germany), [3]University of Duisburg-Essen (Germany), [4]RWTH Aachen (Germany), [5]ETH Zurich (Switzerland), [6]Amprion GmbH (Germany), [7]TransnetBW GmbH (Germany)

Zongyu.Liu@tudelft.nl

Abstract— **The growing share of electricity generated from intermittent renewable energy sources as well as increasing market-based cross-border flows and related physical flows are leading to rising uncertainties in transmission network operation. This paper presents the current and possible future operational challenges from TSOs' experiences, and provides a comprehensive overview of expected features that a toolbox should contain for the stable operation of the transmission network. In addition, it outlines the research vision of the UMBRELLA project, namely better use of renewable energy forecasts, optimization of transmission system operation, and risk-based security assessment, as the possible solution to tackle the aforementioned challenges. In the end, a brief introduction to the UMBRELLA project has been incorporated.**

Keywords: System operation, wind integration, renewable energy forecasts, optimization of transmission system operation, risk-based security assessment, TSO experiences.

I. INTRODUCTION

The growing share of electricity generated from intermittent renewable energy sources (RES) as well as increasing market-based cross-border flows and related physical flows are leading to rising uncertainties in transmission network operation. In the central-European synchronous area, the difference between actual physical flows and dynamic market exchanges can be very substantial due to large installations of renewable energy generation, such as wind and solar plants and the impact of market coupling and introduced cross-border intraday mechanisms. Transmission System Operators (TSOs) are already experiencing issues due to additional loop flows caused by this restructuring of energy exchange. The analysis of the 2015 time horizon identified [1]: a) High power flows starting from large wind power installations to the remote load centres (higher than previous national studies had anticipated and existing planned reinforcements can accommodate). b) Substantial loop flows through many borders. Both high power flow situations are higher than expectations of network reinforcement and market transactions.

As a result, further development of common grid security tools is one of the major challenges that European TSOs will face in the mid-term. The methods to be applied will have to take into account all technological measures to enhance flexibility of power system operations.

Additionally, the framework is to be used to assess the influence of different operational and market rules on system security. The concepts to be developed namely will contribute to more efficient use of the available transmission capacity. On the one hand this is achieved by explicitly modelling the stochastic behaviour of a large number of critical optimization parameters. On the other hand defence actions and methods are systematically analysed and redesigned in view of a risk-based assessment. This is to achieve European-level coordination of defence and restoration plans, including blackstart, taking also into account the possibilities of cascading events.

Many of the projects accomplished so far have been focusing on the needs for grid development, including more or less detailed simulations of future operation. The REALISEGRID project [2] aimed at establishing a framework to support the optimal development of the transmission infrastructure. At a more practical level, the "Working group for Offshore/onshore grid development" (Adamowitsch Working Group) or the Ten-Year Network Development Plan proposed by ENTSO-E [3] identified in detail needs for the future grid infrastructure. The EWIS project [1] has focused on the immediate network related challenges by analysing detailed representations of the existing electricity markets and network operations as well as the resulting physical power flows and other system behaviours. Similarly, the TradeWind project [4] aimed at facilitating the dismantling of barriers to the large-scale integration of wind energy in European power systems, on transnational and European levels, and to formulate recommendations for policy development, market rules and interconnector allocation methods to support wind power integration. The PEGASE project [5] focused on the improvement of real-time system state estimation, as well as the steady-state optimal power flow optimization that is designed to support off-line dynamic simulations.

This paper has been organized in the following manner. Section II presents the TSOs' operational experiences and challenges, covering current situation and foreseen future challenges with large renewable integration to the system. Section III presents a comprehensive list of features that a toolbox should have in order to cope with the afore-mentioned challenges. Section IV actualises the TSO's' expectation to the scientific level by outlining the research vision of the UMBRELLA consortium [6], as the possible solution to the challenges. Section V briefly introduces the UMBRELLA project.

II. TSO'S CHALLENGES AND RISKS

Challenges reported by TSOs concerning system operation with a significant contribution from RES relate to:

- Coordinating the operation of flow controlling devices across Europe.
- Coordinating system arrangements to adjust power flows in the event of faults and other events.
- Developing and using dynamic equipment ratings reflecting ambient conditions, loading, and conductor temperatures.
- Shared intelligence on developing generation and load conditions (including wind forecasts).
- Suitable monitoring and control facilities.
- Procedures for using enhanced operational measures so that maximum benefit is achieved across each region.

In terms of the operational risk, almost all major TSOs in continental Europe with large wind power installations and increasing solar power installations are already experiencing huge difficulties to operate the network. TSOs are already facing today operational challenges due to these loop flows but analysis of the 2015 snapshots identified high power flows starting in the areas with large wind power installations in Germany and directed to the remote load centres, substantial loop flows through Poland and the Czech Republic, and increasing flows significantly above those that are currently expected to result from market transactions. Also high loop flows through Benelux countries with similarly increasing flows have been found. There is hence a substantial risk of cascading failures and disruption should a fault event occur. E.g. on the German-Czech Republic border, flows could exceed line capacities even with all circuits in service, risking network failure without an initiating fault event. On the German- Poland border, flows reach line limits with all circuits in service, risking network disruption in the event of a fault.

Moreover, other identified risks include imbalance, frequency instability (frequency response), voltage instability (voltage control options and short-circuit power ratio), and overall stability due to transit flows in emergency cases. Such identified risks lead to lack of system adequacy, security, and financial risks.

As the share of RES increases in the generation mix every year, TSOs expect the future challenges such as a) Increasing uncertainties due to the growing share of electricity generation from intermittent renewable energy sources as well as increasing market-based cross border flows, b) Enhancement of grid capability and grid flexibility, c) New planned interconnections including new technologies, devices for power flow control, and FACTS for system services will offer new possibilities in network operation, d) Better system coordination and cooperation by using common tools.

III. TSOS' EXPECTATION

All mentioned above leads to a strong desire of further development of common grid security tools, which has been considered one of the major challenges that European TSOs will face in the mid-term. Not only should such tool be able to cope with these challenging system security research issues, but also enable TSOs to ensure secure grid operation also in future electricity networks with high penetration of intermittent renewables.

The ultimate goal of the toolbox is to be usable for the operational purposes, which means that the computational time is crucial in the short-term and real-time operation. The idea is to develop a prototype can be used for Day Ahead Congestion Forecast (DACF) and Intra-Day Congestion Forecast (IDCF) datasets to detect critical situations regarding voltage and high load flow problems under consideration of uncertainties during day-ahead and intraday stage. Analysis of the critical situations to find and to coordinate the best remedial actions for the supra-regional transmission grid in Continental Europe Region is essential. Keeping the general criteria in mind, the toolbox should provide the following.

A. Forecast

The toolbox that provides a risk-based assessment for system security analysis should be able to be used in different operational timeframes:

- Planning environment
- *D*-7 (week-ahead – planned outages analysis)
- *D*-2 (2-day ahead) congestion forecast
- *D*-1 congestion forecast
- Intraday congestion forecast (computational time may be critical – re-dispatch takes around 90 minutes to be implemented in the Dutch system)
- On-line (close to real time, highly dependent on the computational speed of the algorithm)

The results should also be used to give feedback in the long-term planning process. The forecast with uncertainties for the intra-day, day-ahead, and two-day ahead schedule based on the previous data, as well as the indication of power plant dispatch and import/export are necessary for decision of capacity allocation and planning of maintenance (deactivation of lines), also for the planning of day-ahead re-dispatch due to congestion management, even the further enhancement of current congestion forecasting procedures. To be specific, a step-by-step congestion forecast is highly desired for an hour H in the day D beginning (D-1) and closing (H-1). The forecast for this hour H should contain multilateral (also between balancing areas or different countries if necessary as the result of an optimization process) remedial actions for a (N-1) secure system operation.

B. *Risk and Uncertainties*

In terms of risk assessment, the toolbox should be able to provide the critical loadings of lines with ranges and probability/ uncertainty, hint for critical trading direction, intraday-market reaction capability per power plant type (related to forecast uncertainty), improved (*N*-1)-analysis for detection of risk of cascading events (e.g. when very high overload in (*N*-1)-case → outage of this overloaded element → development of dynamic outage simulation), and suggestion for best preventive and curative remedial actions (phase shifting transformer tap positions, power plant re-dispatch, etc.) Uncertainty should be specifically modelled including wind forecasts with time shift (ascent, descent) and absolute level in different forecast horizon – related to data sets, power plant outages, photovoltaic forecast uncertainties, fault in hydro power forecast (time shift and level, gambling (of market participants 'parked energy'). Reducing the forecast failures is also of importance to ensure the reliable uncertainty forecast. Needs/ requirements for a toolbox to achieve the aim (additional to today's practice):

- The multilateral remedial actions should also include preventive re-dispatch (physical and economical aspects) and corrective measures in relevant neighbouring systems.
- The (*N*-1) analysis should also focus on parts of neighbouring systems with significant relevance on the own system.
- The (*N*-1) analysis should also focus on critical voltage situations.
- Identification of key-locations for power plants to ensure a stable system operation under changing infeed scenarios (more intermittent renewable energy infeed, less conventional power plants with rotating parts). These power plants should be and stay available as strategic reserve for remedial actions ordered by TSO.
- Enhanced transparency of the generation data concerning to, e.g., operation forecasts, blackstart capabilities including the availability of information regarding reserves of primary energy to enable the TSO to plan adequate measures in each cases of system operation problems.
- Taking into account real time voltage conditions for defining remedial action scenarios.
- Possibility to consider future grid designs like the integration of DC-overlay grids in the existing AC-infrastructure.

When performing such forecast and security analysis, the input data are normally assumed to be complete and homogeneous. This might not be the case in practice where incomplete and inhomogeneous data may only be available from different TSO data exchange. The toolbox should be able to deal with such incomplete dataset if it is necessary with reasonable level of accuracy.

IV. UMBRELLA'S APPROACH

In order to understand and tackle the aforementioned challenges, joint effort of research and synthesis in the industrial scale is of importance. Specifically speaking, the research activities lay the key foundation in terms of scientific breakthroughs. Meanwhile the industrial scale of synthesis and prototyping serves as the feasibility study that the scientific content is subjected to in the harsh reality. To this extend, three major research interests are identified, namely forecasting, optimization, and risk-based security assessment. Industrial support of supervision, synthesis, and prototyping not only points out the direction of research activities, but also guarantees the practical usability of the proposed solutions.

A. *Forecast*

Due to the increasing penetration of renewable energy such as wind and solar power into the power system, as well as the increase of intra-day energy trading, more uncertainties associated with such trends can be expected. In this regard, accurate forecasting of generation, load, and renewable energy infeed is highly desirable, mainly to reduce the operational cost and to maintain the system balance. The UMBRELLA consortium proposes the following guideline to initiate the analysis of forecasting studies. Before performing forecasting methodology, the scope of uncertainties needs to be identified. This identification process includes a) Analysis of uncertainties in the transmission grid operation, mainly focusing on the renewable power forecasts, short-term trading, load forecasts, and power plant outages, b) Time-adaptive forecast of uncertain parameters and critical system state parameters, which contribute to the derivation of forecast distribution for the system state, especially critical system states.

1) *Wind and Solar Power Forecasts:*

Accuracy improvement: Two sets of data are desirable to perform the detailed analysis, namely spatio-temporal information for wind and solar power infeed forecasts, and IDCF data for providing time-adaptive intra-day wind and solar power forecast.

Probabilistic forecasts: Stochastic nature of renewable energy needs to be modelled precisely. Moreover, quantiles can be integrated into the DACF dataset.

Refine spatial resolution: Renewable energy forecasts could be generated for each grid node, providing higher resolution of the renewable power infeed.

2) *Prediction of intra-day trading:*

The proposed approach is to use the merit order model that incorporates the stochastic behaviour of renewable energy infeeds in order to anticipate future trades, subject to operational constraints.

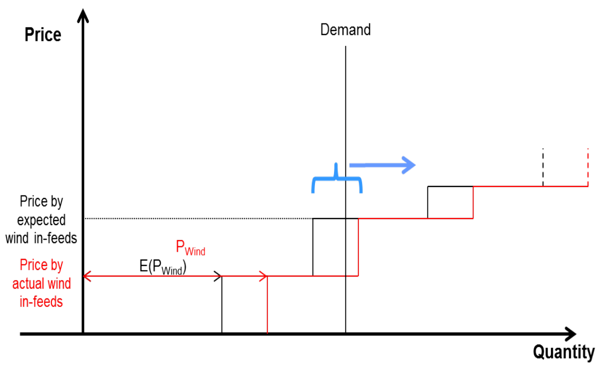

Figure 1 Overview of merit order intra-day trading modelling

Figure 1 depicts how the forecast error of renewable energy infeeds (in Figure 1 only wind power) influences the merit order and, thus, intra-day trading. By knowing the uncertainty of such events, TSOs are able to anticipate future intra-day trades. In Figure 1 are the wind power infeeds higher than expected. By constant load, conventional power plants have to diminish their power generation, which leads to respective intra-day trades.

3) Load forecast and power plant outages:

The assessment focuses on the two challenges associated with the state-of-art prediction tools, including the unobservable differences between the vertical grid load and total grid load, and the variations in the vertical grid load caused by subordinate grids to which the power plants are connected.

4) Critical system state forecast:

The main objective is to prevent an actual critical system state from happening by performing remedial actions beforehand. The state estimation requires definition of system state parameters, which condense key information of the system, and their impact on the system security.

B. Optimization

Unlike the conventional Optimal Power Flow (OPF), which minimizes losses or maximizes social welfare for instance, the objective of the Enhanced Optimal Power Flow (EOPF) framework is to determine optimal topologies as well as set points for load flow control devices in order to minimize re-dispatch volumes while maximizing possible power transports in critical system states and avoiding overloading of lines while taking into account the uncertainty of the system state's development. To substantiate the objective, the EOPF modelling consists of two time-frame analyses. Proactive EOPF aims at anticipating the critical system states, and short-term/ real-time EOPF is subject to additional constraints related to short-term/ real-time operating conditions. Moreover, the forecasting methodology applied to the uncertainty assessment should also be incorporated to the EOPF modelling to ensure the secure system operation against predicted uncertainties.

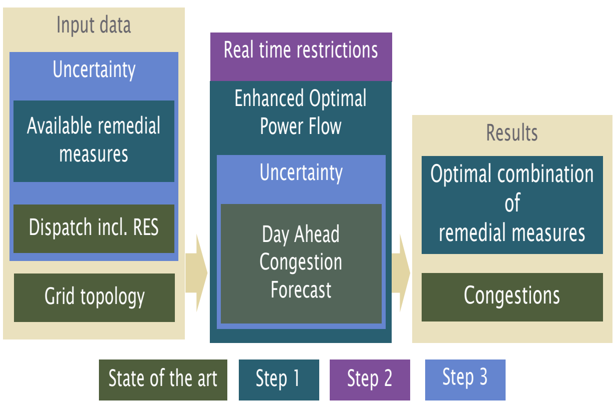

Figure 2 EOPF modelling framework

- Step 1: Optimization algorithms supporting operational planning process
- Step 2: Short-term optimization methods for real time grid operation
- Step 3: Optimized uncertainty accounting in operational planning

The EOPF approach is based on state of the art congestion forecast methods [7] that are incorporated in the operational planning process as well as in real-time grid operation. The extension by optimization algorithms in a first step allows calculating optimal combinations of remedial measures based on current grid topology, dispatch and availability of remedial measures. Based on this approach a further enhancement of computational algorithms will take place considering the special requirements of real time grid operation in terms of computational speed and quality of results. This development providing a rather fast and reliable method will then be used for an additional integration of uncertainties into the optimization algorithms for use in the operational planning phase. These uncertainties on the one hand consist of uncertain infeeds being assessed by forecasting algorithms described in the previous paragraph and on the other hand affect network security calculations taking into account risk-based concepts within the congestion forecast. This concept guarantees a reliable estimation of remedial measures for next day grid operation by an uncertainty accounting optimization toolbox and additionally assists the network operator in real-time situations that cannot be covered by day-ahead optimization methods.

Previous work in this field in [4] shows challenges in the integration of all available remedial measures in a security constrained OPF. Therefore, in the optimization modelling, special emphasis concerning computational speed is crucial due to the large scale and the complexity of the problem, and thus should be considered in the formulation of both the objective function and constraints. To be specific, several possible approaches in the modelling are suggested, depending on the trade-off between accuracy and computational effort.

- Impact of remedial measures limited to the surrounding region [4]
- Neglecting measures with little effect on observed congestions
- Linear approximation in operating point [8]
- Limiting the amount of simultaneously applied remedial measures
- Neglecting dispensable constraints [4]
- Simplified approximation of load flow in (N-1) situations [9]

In the real-time EOPF modelling, additional simplification can be adopted:

- Reduced number of remedial measures available
- Reduced requirements regarding accuracy
- Initial solution available from proactive EOPF
- Negligible uncertainty studies

C. Risk-based security assessment concept

The goal is to develop strategies for keeping the system secure while facilitating market operations and integrating additional renewable energy sources. To achieve this, the use of a risk-based security assessment is proposed as a supplement of the traditional *N*-1 criterion.

Risk encompasses both the probability and the severity of events. The probabilistic measure carries more information than the deterministic criterion and helps to distinguish situations, which are considered to be equal in the deterministic criterion. For example, a situation with one slight violation and a situation with many severe violations are treated as equal with the deterministic N-1 criterion, but have different risk levels. An overview of different risk zones as defined in the UCTE handbook [10] is given in Figure 4.

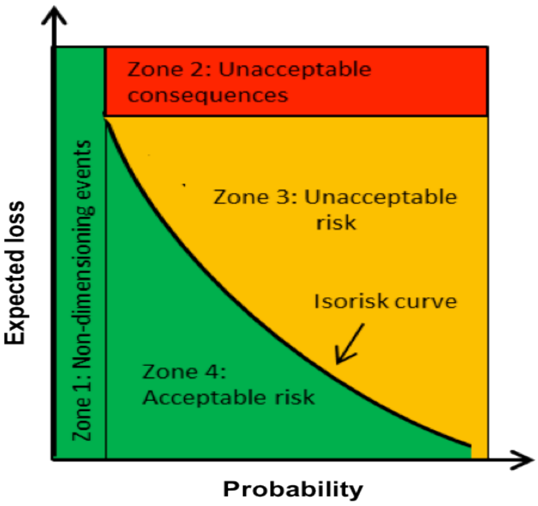

Figure 3 Risk zones in operation based on different risk levels [10]

The advantage of the risk-based security assessment is to have a quantitative measure and an explicit formulation of the acceptable risk level. Furthermore, it allows for a direct trade-off between security and cost and for the incorporation of different sources of uncertainty.

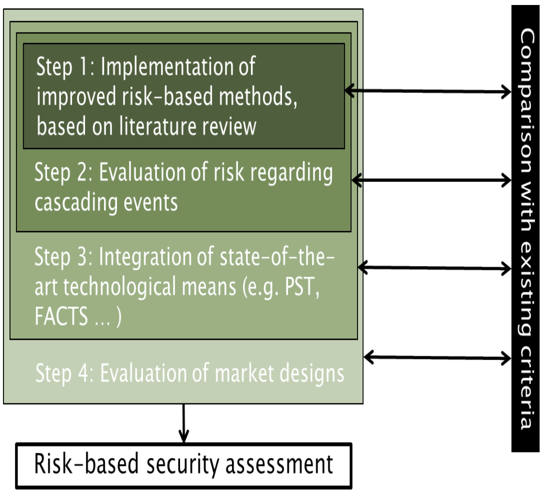

Figure 4 Overview of risk-based security assessment

However, these advantages come along with three main challenges: First, a proper modelling of the outage probabilities and the severities in order to come up with a meaningful risk measure; second, the computational requirements involved in carrying out the risk-based security assessment; and third, the condensation of risk information for a user-friendly visualization in control centres.

The development of an appropriate risk-based security assessment will be done in four steps as described in Figure 4. Step 1 consists of the implementation of improved risk-based methods based on a literature review. In Step 2 these methods are evaluated with regard to cascading events. Step 3 encompasses the integration of state-of-the-art technological measures in the developed methods. Determination of operational rules and coordination procedures among TSOs by evaluation of market designs are considered in Step 4.

V. UMBRELLA PROJECT

The full title of the UMBRELLA project is 'Toolbox for Common Forecasting, Risk assessment, and Operational Optimisation in Grid Security Cooperations of Transmission System Operators (TSOs)'. It answers the call from European Commission 7th Research Programme aiming at a comprehensive prototype toolbox development encompassing forecasting and optimization tools to ensure secure grid operation in future electricity networks. The consortium consists of 15 members, including nine European TSOs, five universities and one research institute. R&D activities will be mainly conducted at universities with support from the industry. Synthesis prototyping, demonstration and testing will be conducted at the TSO level to ensure the scientific solution is technically feasible in the power system operation. This toolbox will be extensively tested in a large-scale cooperation of TSOs in mainland Europe. The area covered by the TSOs is particularly affected by increasing uncertainties from intermittent renewable infeed (notably wind, but also solar) and increasing market-based cross border flows. An overview of the different work packages of the project is given in Figure 5.

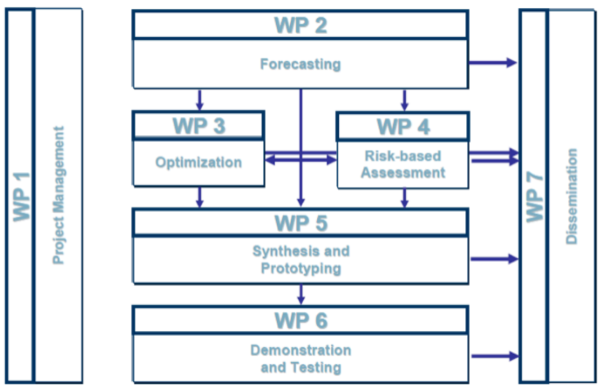

Figure 5 Overview of UMBRELLA organizational structure

Upon the aforementioned TSOs' challenges in operating the transmission grid, and possible approaches to tackle the problems, the final results from the UMBRELLA project are expected in December 2015. The expected results consist of a toolbox that enables European TSOs to operate their grid in a more secure and efficient way to maximize power transit taking into account uncertainties caused by intermittent renewable energy integration. Forecasting methodology, optimization of maximum power transit, and risk-based security assessment will be studied in depth, and further synthesized and tested by TSO members within the consortium. The work performed will notably allow deriving conclusions for operational requirements in TSO cooperation rules on the following issues:

- European level strategies to limit extent and impact of major system disturbances
- Type and amount of data that needs to be shared among individual transmission systems and the data that needs to be obtained from market participants (e.g., generators, retailers) in order to implement the above approaches
- Recommendations for operational planning tools that will also support further operational rule harmonization

ACKNOWLEDGMENT

The research has been conducted under the EC Research Framework 7 programme (FP7). The authors thank the UMBRELLA consortium members for the valuable review work and discussion.

REFERENCES

[1] EWIS final report online available at http://www.wind-integration.eu/downloads/.

[2] Realisegrid Project online available at http://realisegrid.rse-web.it/

[3] TradeWind Project online available at http://www.trade-wind.eu/index.php?id=13.

[4] PEGASE project online available at http://www.fp7-pegase.eu.

[5] Umbrella Project online available at http://www.e-umbrella.eu.

[6] ENTSO-E Operation Handbook Chapter 4: Co-ordinated Operational Planning.

[7] ENTSO-E Operation Handbook Chapter 4: Co-ordinated Operational Planning.

[8] Linnemann, C.; Echternacht, D.; Breuer, C.; Moser, A. 'Modeling Optimal Redispatch for the European Transmission Grid', Proceedings of the IEEE Powertech, Trondheim, 2011.

[9] Hug-Glazmann, G., Andersson, G, 'An Accurate and Efficient Current Injection Method for the Determination of the System State during Line Outages',. 16th PSCC, Glasgow, 2008.

[10] UCTE Operation Handbook.