Steps for a Complete Wind Integration Study

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Abstract

There have been many wind integration studies in recent years, and these efforts are expected to continue. Because power systems and data availability vary significantly, the results and methodologies used in these studies vary. This paper presents findings from international collaboration under IEAWIND Task 25 working towards Recommended Practices for Wind Integration studies. An overview of a complete wind integration study is presented as a flow chart. The set-up of a study and main assumptions are important because they have a crucial impact on the results. The main steps in the simulations are presented with methodologies, which include the increase in reserve requirements, estimating impacts on other generation and balancing, capacity value of wind power and increase in transmission due to wind power.

1. Introduction

General system impact studies are often the first steps taken towards defining wind penetration targets within each country or region. Wind power integration studies have been performed by numerous entities in an attempt to define, understand and quantify these impacts [1-3]. The studies typically simulate a future power system with high wind penetrations, and evaluate the impacts on the grid and the resultant incremental operating costs [4]. These studies have been maturing as the state of the art advances, with each study generally building on previous ones.

IEA WIND R&D Task 25 on “Design and Operation of Power Systems with Large Amounts of Wind Power” collects and shares information on wind generation impacts on power systems, with analyses and guidelines on methodologies. Task 25 participants are currently in the process of writing a first edition of Recommended Practices for Wind Integration studies, to provide research institutes, consultants and system operators with the best available information on how to perform a wind integration study. This paper presents the preliminary findings of the process. Section 2 gives an overview as a flow chart of a complete wind integration study. The rest of the sections follow this flow chart: Section 3 lists the main inputs, Section 4 presents issues in portfolio development, main set-up and system management assumptions, Section 5 in capacity value, Section 6 in flexibility and production cost simulation and Section 7 in transmission load flow and dynamics. Section 8 discusses analyzing and interpreting the results and Section 9 concludes.

2. Flow chart of a complete wind integration study

An overview of what an integration study should contain is given as a flow chart (Fig 1). Not all studies include all the components of the flow chart and it may not be realistic for all integration studies to go through each step proposed. A full study considering all the aspects and impacts is a quite complicated process especially taking into account all possible iteration loops. A wind integration study usually begins with a set of input data characterizing wind power and the remaining power system and a penetration level of wind power that is of interest (the blue boxes). The electrical footprint must be chosen, which may include a subset of, or the entire interconnection. Analysis of a synchronous system can characterise the full set of interactions that govern power systems. However, as it can greatly increase the complexity of the study and may not be relevant for the phenomena of interest, a part of the system is often studied, with careful modelling of interactions between boundaries of the study area and remaining synchronous system.

Portfolio development needs to set up the kind of system that is studied – current or future system, assumed generation fleet, demand and flexibility options available. The basic set-up assumptions will have a crucial impact on the results of the study. An important aspect is how wind power is added to the system; by replacing existing generation or by adding wind power to the existing system. Changes in system management methods may need to be made to accommodate large amounts of wind power. This involves checking the options for flexibility available in the power system through operational measures and through the transmission scenarios studied. Allocation,
procurement and use of reserves in a cost effective manner may also have to be changed.

Analysing and interpreting results of wind integration studies may also be challenging as the impacts of wind integration and the best options to remedy impacts can be difficult to determine. Significant wind penetration levels usually necessitate conducting studies that project 10-30 years in the future. The question of how best to prepare for the possible impacts of high penetrations of wind can also be extracted from simulations results: to allow changes to market structures and operating procedures to help ensure reliable and economic systems once high penetrations of wind power are realized.

3. Input data

Wind integration studies need data on wind power, load, conventional generation and transmission grid.

Figure 1. Wind integration study components. Flow chart showing a recommended route with iteration loops and possible routes when not all components are studied.
When the integration study is aimed at estimating potential impacts of large amounts of wind power in a future year, the assumptions regarding all of these data will impact the results considerably.

Different detail of data will be needed in different simulation parts. For example, the transmission grid is often modeled only as main interconnections of areas when simulating dispatch, and full time series of wind and load are replaced by some snapshots in grid simulations, where the transmission grid is modeled in detail.

Wind production time series data that realistically represents variability and uncertainty, can be obtained from a combination of actual or simulated data. It is crucial to use data that accounts for the smoothing effect, both spatially and on hourly and sub-hourly levels in order not to overestimate the variability. It is also important to have sufficient long term data to calculate the probability of rare events such as fast, steep ramps. Input data can be challenging to obtain especially for future systems and wind power production inputs can be most challenging part.

Time-synchronized wind and load data is crucial for estimating reserves and capacity value and simulating Unit Commitment and Economic Dispatch. Hourly data is sufficient for estimating capacity value, whereas more detailed data is valuable for dispatch simulations. For capacity value estimation several years (preferably 10 years) is needed [14], whereas for dispatch 1-2 years of data may be enough.

Time series (or distributions) of wind and load forecast errors are needed for estimating operating reserves, and more realistic unit commitment and economic dispatch, but not necessary in estimating capacity value or detailed grid simulations. It is also important to model wind forecast updates closer to real time. Wind forecasting accuracy will improve more in shorter time horizons than that of load. Wind forecasting accuracy is also likely to improve in the future.

For conventional generation units, forced outage rates are needed for capacity value estimates, and flexibility capabilities (ramp rates, start-up times and costs) for dispatch simulations. Grid simulations need to model more detailed capabilities of all power plants, also wind power plants. As most wind integration studies treat future scenarios, also the flexibility options available is important to model.

4. Portfolio development and system management

The (future) portfolio of generation plants, transmission capacity and operational practices are all important inputs to wind integration study calculations. There will also be important iterations from the last phases of integration study simulations back to this part, as changing generation and transmission, or operational practices (including how reserves are allocated) may be required to integrate larger amounts of wind power cost effectively.

There are several pathways to take in an integration study – some studies do not address all aspects. Usually the studies try to quantify wind impacts by comparing results from no (or little) wind with future higher amounts of wind power. Some studies try to estimate integration costs for the system. Quantifying the benefits of wind power to the system can also be made, and they should be larger to justify the wind energy targets.

4.1. Generation portfolio and transmission scenarios

Because most studies are limited in their scope, key scenarios are often chosen to provide insights on key issues or provide bookend values of interest. Generation and transmission portfolio, and institutional framework and markets will drive the results:

- what kind of system is studied – the current system or a future scenario or scenarios
- how wind power is added – replacing some existing generation or adding to an otherwise static system
- other assumptions regarding available flexibility, both technical and institutional

Meeting ambitious targets that have been set for wind energy may require upgrading existing transmission infrastructure and construction of new lines. Even if the main driver behind transmission needs is increasing installed wind power capacity, there will also be changes in load and other generation and possibly changes in electricity markets. Increasing transmission will also help security of supply. Transmission can contribute to more reliable and economic wind integration, providing a means to deliver the electricity to where it is consumed, but also enabling the sharing of flexibility between neighboring areas. Operational methods influence how much of the existing flexibility is accessible in practice.

4.2. Reserve allocation – estimating changes due to wind power

The impact that wind energy has on procuring operating reserves is a common focus of wind integration studies. This is an on-going area of research, taking the uncertainty of wind power into account while aiming for both reserve adequacy and economic provision.
System operators carry reserves to balance load and generation, and to respond to outages. The term "operating reserve" is defined here as the active power capacity that can be deployed to assist with generation and load balance and frequency control. Wind power output does not drop off fast enough and at large enough capacity to constitute a contingency event. For the discussion that follows we focus on additional reserve that is induced by wind power, and make no assumption regarding the use of contingency reserves to cover regulation or balancing with wind power.

Reserves are allocated (dimensioned and scheduled) for a diverse range of conditions. Reserve allocation also considers reserves responding across multiple timescales [5]:

- reserves that operate automatically (fast reserves, for example primary and secondary in Europe, and regulating reserve in the U.S.) and
- reserves that are activated manually when needed (from minutes to a few hours, for example tertiary reserves in Europe and load-following reserves in the U.S.)

The time steps chosen for dispatch and market operation can influence the reserve requirements. For example, markets that operate at 5 minutes time steps, can automatically extract balancing needs from the generators that must ramp to achieve proper position for the schedule for the next market period [6].

The computation of reserve requirements requires estimates of uncertainty and variability of demand, wind generation and other generation. For wind power, the forecast horizon time scale is a crucial assumption because the uncertainty at shorter time scales will reduce more significantly than for demand.

A common approach is to compare the uncertainty and variability before and after the addition of wind generation. Adding wind generation means allocating additional reserves to maintain a desired reliability level. Traditionally, the term "reliability" refers to assuring resource adequacy to accommodate rare events in long term planning, and also the ability to maintain the system operationally. In the context considered here, reliability concepts are applied to the operational planning horizon which spans a time frame from a few minutes to a few days ahead, and thus is referred to as short-term or operational reliability. There are several methods that can be used to calculate the impact of wind generation on operating reserves, but the general steps are:

1. The level of risk of insufficient reserve must be identified. For example, one might choose to cover 95% of the variations in net load (load minus wind power) output.
2. Operating reserves should be calculated for the appropriate time scales, matching existing operational practice. Although these may vary somewhat, there are typically different types of reserves associated with (a) automatically responding in seconds-minutes, (b) manually activated in minutes-hour to several hours. When dividing the reserves into separate categories, a common error is to double-count some variability or uncertainty; hence, care should be exercised in this process.

3. Simple statistical methods can be used, however assuming that load and generation errors can be represented by normal uncorrelated distributions and using standard deviation values (n-sigma method) will not be valid. Statistical methods can be altered to take this into account, for example using a desired level of exceedance or by performing analysis to determine the appropriate distribution.

4. Wind-related reserves should not be static. The variability and forecast uncertainties depend on meteorological conditions and vary over time. This means that using constant reserve levels will lead to varying risk levels, or that maintaining a constant reliability or risk level will require varying reserves. It has also been found that wind power variability is highest near the mid-range of its output, and dynamic reserve methods have been developed that build on this information [9].

4.3 Operational methods and markets

Operational methods and markets may need to be assessed as part of the study to determine whether current approaches to operate the system and current market practice allow for reliable and cost-efficient integration of wind power. Often, existing operational practice is used as a starting point, and additional scenarios or operating practices can be modeled as appropriate.

Large, fast energy markets, which significantly improve the ability of the power system to efficiently integrate wind energy, already exist in some regions and may require only relatively minor operational changes. Still, new markets for ancillary services may be evaluated.

Operational methods may change with the addition of new transmission and/or more flexible generation. For example, new transmission interconnection to neighboring systems may enable access to more flexible generation, and at the same time reduce the overall need for flexibility in the two combined systems. New quick-start, fast-ramping generation may enable shorter unit commitment time frames, or in the extreme, very short unit commitment periods because start-up time of units may no longer require longer periods of advance notice.

Changes may be made in forecasting practice. For example, individual wind plant operators may forecast
their own plant output or RTO/TSO can use its own forecasts, which can take into account the diversity of wind plants. In tandem with more accurate short-term wind forecasts, markets may be able to shorten the notification period [10]. Integration studies might investigate these issues to determine the value of these market characteristics on the ability to integrate wind power.

5. Capacity value

Capacity value estimation has often been done as a separate evaluation in wind integration studies. If the reliability (resource adequacy) target is not met by the power plant scenario, there is an iteration to change the portfolio to include more generation capacity or less load. The capacity value calculation should take the transmission limit impact into account when considering which area of the power system is studied.

Generation system adequacy (often called “resource adequacy”) refers to whether there is sufficient installed capacity to meet the electric load at some prescribed level of risk [11]. Capacity value (or credit) can be defined as the amount of additional load that can be served due to the addition of the generator, while maintaining the existing levels of reliability [12].

The metrics that are used for adequacy evaluation include the loss of load expectation (LOLE) and the loss of load probability (LOLP). LOLP is the probability that the load will exceed the available generation at a given time (in interconnected systems, this probability may instead refer to the probability of unintended import). This criterion only gives an indication of generation capacity shortfall and lacks information on the importance and duration of the outage. LOLE is the expected number of hours or days, during which the load will not be met over a defined time period. The effective load carrying capability (ELCC) is a common metric for capacity value [13].

The input data employed in the calculation is crucial - if sufficient data of the required quality is not available, the resulting answer cannot be relied upon. The ELCC method requires multi-year, synchronous hourly time series of demand and wind [14] and a complete inventory of conventional generation units’ capacity, forced outage rates and maintenance schedules. If there is a strong correlation with wind generation and peak load situations, this will have a strong impact on the results. This is why synchronous load and wind data are needed from many years. An important characteristic of wind power is its spatial diversity. This means that the capacity value increases relatively with larger region sizes [1] - larger areas decrease the number of hours of low wind output.

The reliability level can have a large impact on the capacity value of both conventional power and wind power [13]. When the reliability level is lower, and LOLE higher, there is relatively more value in any added capacity than in cases where LOLE is very low.

The recommended method for capacity value is ELCC as it calculates full net load effective load carrying capability:

1. Conventional generation units are modeled by their respective capacities and forced outage rates (FOR). Each generator capacity and FOR is convolved via an iterative method to produce the analytical reliability model (capacity outage probability table (COPT)) of the power system. The COPT is a table of capacity levels and their associated probabilities [11]. The cumulative probabilities give the LOLP for each possible available generation state.

2. The COPT of the power system is used in conjunction with the hourly demand time series to compute the LOLE without the presence of the wind plant.

3. Wind power cannot be adequately modeled by its capacity and FOR as wind availability is more a matter of resource availability than mechanical availability. Time series for the wind plants power output is treated as negative load and is combined with the load time series, resulting in a load time series net of wind power. In the same manner as above LOLE is calculated. It will now be lower (and therefore better) than the original LOLE.

4. The load data is then increased across all hours using an iterative process, and the LOLE recalculated at each step until the original LOLE is reached. The increase in the load is the ELCC or capacity value of the wind plant.

With modern computing power this method is not overly time-consuming for moderately sized systems. Approximation methods must therefore be justified on grounds of ease of coding or lack of data. This method contains approximations also but as it utilizes the datasets which capture the full relationship between load and wind it provides the best assessment of wind’s capacity value [11].

6. Flexibility assessment and production cost simulation

Flexibility can be described as the capacity of the power system to respond to change. For wind power integration, flexibility is required to manage the resulting variability and uncertainty to ensure that demand balance, security and reliability constraints are met. The capability to respond to changes is limited by
physical constraints on generation resources and of the power system in general. Thus, flexibility can also be understood as the absence of constraints on the system.

Typical sources of flexibility include conventional generation which can be dispatched up and down and provide ancillary services. Load is increasingly used to provide a degree of flexibility in the form of load shifting and load shaving. Transmission allows for the sharing of flexibility between interconnected regions. Storage is a valuable source of flexibility but with comparatively high capital costs for new installations. Wind power can also be a source of flexibility. However, as this requires energy to be held back to enable reserve and/or frequency response, this may be an expensive source.

Various methods have been proposed to assess the adequacy of power systems and to develop adequacy metrics with respect to flexibility. [16] describes a ramping resource expectation metric for use in power system planning studies. Broader system flexibility metrics are also proposed which consider a wide range of power system characteristics which can be used to quantify the inherent flexibility in power systems [17]. These methods are evolving and may become more important in systems with high levels of wind penetration where capacity adequacy type analyses are augmented by a specific assessment of flexibility. However, at the present time, flexibility assessment is generally conducted implicitly within Unit Commitment and Economic Dispatch (UCED) simulations.

UCED is the main type of study used to assess the impacts of wind power integration on flexibility, operating costs and emissions. UCED involves optimizing the scheduling of load and generation resources to meet expected demand over various time frames with consideration of cost and constraints (system, physical, and operational) and wind power. The constraints in the optimization ensure the physical feasibility of short term operational plans and reliability under uncertainty.

To assess the true capacity of the system to respond to change, the limitations and constraints of the system must be accurately modeled. Otherwise, a higher level of flexibility than exists in reality is assumed and the true impact of wind power is not captured. Wind power also introduces additional uncertainty which needs to be considered. Thus, with increasing levels of wind energy it is important to capture more detail and the current constrained optimization paradigm may need to be adapted.

- Impact of uncertainty on dispatch decisions in UCED: In [18] a stochastic optimization and rolling planning method explicitly considers a range of possible future outcomes. Other approaches include increased reserve targets which capture the additional requirements brought about with increased wind energy, using wind forecasts [19] dynamic reserves, faster markets and increased market resolution.
- Increased levels of variability on the power system mean there is a greater need to accurately model physical temporal limitations such as minimum generation levels, ramp rates, minimum up/down times, start times, load times etc. To accurately model these, it may be necessary to use mixed integer programming (MIP). For large systems or for very high level studies, it may be adequate to use linear programming approximations but this is unlikely to result in feasible operational schedules and should be expected to significantly underestimate costs and impacts. Smaller studies can be used to compare the differences between both approaches.
- Transmission: it is important to consider congestion and N-1 security within UCED. Explicit inclusion of grid congestion significantly increases the computational requirements especially in large systems or where stochastic optimization is used. As an approximation, net transfer capacities between areas as defined by the TSOs can be used. Recent work has attempted to combine stochastic multi-area UC with a more detailed grid model [20]. Iterative solutions could also be used.
- Interconnections with neighboring regions: One approach is to assume full availability of interconnectors. This approach may be too optimistic. Another approach is to assume fixed flows on interconnectors with flows obtained from other studies or based on assumed market prices in neighboring regions. This approach is possibly too pessimistic. More accurate would be to explicitly model the neighboring regions and include them in the study. This could be difficult to implement in practice owing to the data, effort and computational requirements for such.
- In systems with very high levels of renewable generation, it may be necessary to model additional stability constraints. Thus, the results of the studies described in section 7 may need to be incorporated into UCED models.
- Data quality can be another issue. Oftentimes, UCED studies can reveal implicit levels of flexibility that are assumed but which do not exist in practice owing to omission or over estimation of plant capabilities.
- Selection of the non-wind case as a basis for comparison is not straightforward – and will be needed especially if estimating integration costs. A
suitable comparative case must be chosen carefully along with the assumptions regarding the types of generation wind power will displace. A scenario with equivalent wind energy but with a perfectly flat profile can be used but may result in impacts not entirely related to wind energy [4].

7. Transmission grid simulations: load flow and dynamics

Once market simulations, including unit commitment (UC) and economic dispatch (ED) studies, have indicated that a given wind integration scenario is feasible, steady-state load flow and often also dynamic system stability analyses are performed. With appropriate data, these analyses can:

- Confirm the steady-state adequacy and utilization of the transmission system infrastructure, and the value of network expansion options.
- Determine if the plant portfolio and grid is sufficiently strong to sustain both temporary disturbances and significant failures, and stable enough to recover satisfactorily from those events.
- Evaluate the chosen deployment of wind generation (including different wind turbine technologies and wind distributions) against existing grid code requirements, and consider different mitigation or participation options that the regulatory regime allows.

DC grids will be a main driver for future European wind studies, either as part of connecting offshore wind farms or as trading capacity between different market regions. As more wind generation is placed offshore meshed VSC-HVDC grids, rather than point-to-point connections, become viable with multiple offshore and/or onshore termination points. A range of technical options remain to be resolved, including adequate network protection schemes, with different network topologies and control schemes being considered.

7.1 Transmission system studies

Typical steps in transmission system studies are:

1. Creating a number of credible load flow cases that represent high penetration of wind (and solar) generation expected. Traditional dynamic stability and transmission planning methods apply a worst-case approach. Snapshots chosen can include peak demand situations (e.g. check the dynamic voltage control provided by wind turbines) as well as low demand situations (e.g. voltage regulation and frequency control). Situations with high non-synchronous generation (wind, solar, HVDC) can be critical. The high wind situations are compared with low wind or no wind cases.

2. Deterministic steady-state security analysis. In compliance with N and N-I security criteria, and the capabilities of network elements based on local TSO rules, load flow analyses are performed to identify transmission network bottlenecks (congestion), and to assess the system’s ability to control the voltage profile. The effect of wind energy production on the voltage profile differs according to a generic power chart (PQ) derived from the connection rules and the operational agreements (constant power factor, voltage control). Therefore, an appropriate level of reactive power absorption/production shall be simulated to determine the reactive compensation requirements and to ensure conformity of the voltage profiles to the security criteria.

3. Network loading (congestion) assessment. Based upon yearly analysis of wind generation and demand patterns, network branch loadings can be determined both for normal and contingency situations. Subsequently, criteria for prioritizing bottlenecks can be developed together with a method for ranking them according to a risk-based severity index. Bottlenecks can be identified in a probabilistic manner, so that by analyzing the risk of overload and the aggregated severity index, planners can decide whether bottlenecks are severe or whether they can be solved (temporarily) via operational measures. A probabilistic approach allows uncertainty factors such as the forced outage of transmission equipment, generation units and wind generation variability to be considered. The effect of different wind penetration scenarios on the severity indices of different grid elements can also be considered, such that the frequency of network overloads (hour/year), the volume of overloads (MWh/year), and the risk of wind farm curtailment (MWh/year) arising due to system constraints can be quantified. Reliability metrics (like EENS, LOLP and LOLE) may also be incorporated within the analysis.

4. Short circuit levels. The maximum short circuit level is typically used to assess if breaker limits are violated. At high wind penetration scenarios synchronous generation will not be dispatched which may lead to a reduction of the minimum short circuit level. The reduced short circuit level may affect the power quality, voltage step changes after shunt switching and the operation of line commutated HVDC converters.

5. Dynamic analyses. Subject to particular system concerns, transient / steady-state / frequency and voltage stability analyses may be completed (see section 7.2). Ideally, studies should be performed with different wind turbine technologies, but often
it is sufficient applying generic models which captures the minimum performance required in the connection code. Preferably, different wind penetration and demand levels shall be included to best understand the dynamic system limits. Power system recovery after a disturbance is studied by simulating the impact of system failures.

Grid investments should be economically justified. This is measured by the proportion of benefits divided by the cost (investment + operational). The benefits are the sum of producer plus consumer benefits plus congestion rent. Additional criteria can be adopted referring to environmental benefits (CO₂ emission reduction), variation in system losses, etc. [21]. Transmission adequacy needs associated with wind power integration may be of concern for only a small fraction of the year. In these cases network investments can potentially be postponed using several means (for example curtailment/redispatch, dynamic line ratings to increase transmission line capacity and co-ordinated control using FACTS devices).

7.2 Dynamic stability analyses

The need to assess the impacts of wind generation on power system dynamics will be important, especially at higher penetration levels. Of particular interest will be those periods of time when there is a high penetration of non-synchronous generation. The grid code requirements and control capabilities of wind power plants should be recognized within any study.

System dynamics studies can address:

- transient stability (i.e. angle stability): ability to maintain generator synchronism when subjected to a severe transient disturbance
- small-signal (oscillatory) stability: ability to maintain synchronism when subjected to a small disturbance
- frequency stability: ability to maintain system frequency following a major imbalance between generation and load
- voltage stability: ability to maintain an acceptable voltage profile after being subjected to a disturbance.

Dynamic analyses should be executed for the same expected operating conditions (peak and low load conditions, and other scenarios, as appropriate) considered at the steady-state security stage, to ensure coherency, while taking into account the correlation between wind generation and demand patterns.

Stability studies require much greater detail than unit commitment – economic dispatch (UCED) simulations:

- The dynamic characteristics of all generators and the load are required, as well as more detail on the configuration and electrical parameters of the transmission and distribution networks. The modeling complexity will depend on the nature of the analysis. For example, boiler / steam turbine models would not be required for transient stability analysis, while a reduced network representation may be appropriate for frequency stability studies.
- Frequency stability studies will require the inertia, droop and governor settings of all units to both simulate individual unit responses and the combined system response to major load and generation contingencies, and assess changes in frequency regulation capacity.
- Small-signal stability studies will require automatic voltage regulator (AVR) including power system stabilizers (PSS) settings for synchronous generation. Additionally, transient stability analysis has to consider the effect of protection devices for network and converter-interfaced generating equipment.
- The technical performance of both renewable and non-renewable generation to support high levels of wind generation is clearly important. Particularly, at higher wind penetration levels, validated and comprehensive wind turbine / wind power plant models will be required to accurately assess the dynamic power system characteristics.
- In large simulation models comprising hundreds of dynamic models it is vital that specific models are not too detailed in order not to jeopardize overall model performance. Especially, for installations involving power electronics simplifications are required. For example, a current control loop may be so fast that it can be ignored, or rotating machine dynamics can be left out if connected via an inverter.

The stability issues of concern for a particular system will depend on system size, and underlying characteristics, although they are likely to be first seen during night-time or seasonal low demand periods when instantaneous wind penetration may be high, but annual energy contribution is somewhat lower:

- For frequency response, the fraction of generation participating in governor control is a good metric for expected performance [22]. The maneuverable capacity, i.e. headroom, of such generation, is also important, with resources that provide significant incremental power before the frequency nadir being more valuable.
- Reduced inertia at times of high non-synchronous penetration will alter the system response for both faults and contingencies, which can be particularly important for smaller power systems or those connected by HVDC links. Modern wind turbines...
can provide a synthetic response, but it is not always available and changes with turbine operating point [23][24]. Fast acting load response, or injection of power from energy storage are also beneficial.

- To mitigate transient stability problems, fast acting reactive power response devices during and following disturbances is required, e.g. installing FACTS, synchronous compensators, and/or requiring all wind plants and conventional generators to incorporate that specific capability.
- Current grid code requirements regarding wind turbine fault behavior are not a guarantee of transmission system stability and proper network modeling within simulation studies is crucial.
- Generalized fault mitigation design for offshore wind power plants connected by VSC-HVDC has proven challenging, being dependent on the installed wind turbine type [25].
- Wind turbine reactive power controls can help manage voltage and improve voltage stability margins particularly in weak parts of the electric system [26].

Small signal (oscillatory) and voltage stability have in many cases been found to be unaffected or enhanced by the presence of wind turbines [27], although the wind turbine converter controls complicate such analyses.

8. Analyzing and interpreting the results

When performing the analyses from the simulations it should be noted that also at this stage it is possible to take the iteration loop in the flowchart in Fig 1 back to change assumptions. This may be desired if the impact of wind power would be difficult or costly to manage, and more flexibility in operational practices is needed.

The main set-up chosen will have crucial impacts on the results. Many studies take the current system as a starting point. Both technical flexibility and operational flexibility can change for future systems. Successful wind integration may mean changing the operation of the power system from how systems have been traditionally operated. These changes can include things like incorporating wind forecasts into operations and on-line generation level monitoring in control rooms. At higher penetration levels the methods and tools used for planning and operation, like allocation of reserves, need to be adapted.

Integration cost is a concept that covers additional costs that are required in the power system to keep customer requirement (voltage, frequency) at an acceptable reliability level (and do not include the costs for installing the new power plants and connecting them to the grid). However, correctly extracting such costs is very difficult and should be undertaken with great care [28]. The need for transmission capacity and balancing resources will increase with high amounts of wind power. It is challenging to draw out system cost for a single form of generation because system services are there for all loads and generators. In case of transmission costs induced by wind power (except in the case of a radial connection), allocation is challenging also because additional transmission typically provides a reliability benefit beyond the benefit of connecting the generator in question.

Although it is difficult to extract the cost of variability and uncertainty from wind integration, it is relatively straightforward to assess total operational cost in both no-wind and wind cases, and these operational costs can be compared.

The impact of wind power on transmission losses and grid bottleneck situations can be significant in some cases and therefore may need to be assessed.

An increased level of reserves caused by wind power may be supplied by conventional generators that are used to supply energy in the non-wind case, and are used to supply less energy and more reserve in the wind case. This is a critical distinction, and failure to understand this basic principle can lead to erroneous statements. During times when wind power output increases, other generating units must back down, allowing them to provide up-reserve if needed.

The comparison of results for different methods is challenging. This is why it is important to present results in metrics that other studies have used, stating also penetration level of wind and size of power system, as well as all relevant assumptions and limitations of the methodology [1].

9. Conclusions

Wind integration studies have been maturing continuously as the state of the art advances, with each study generally building on previous ones. This paper presents an overview of a complete wind integration study as a flow chart. The portfolio selection and main assumptions are important as they will have crucial impact on the results. There are important iteration cycles from portfolio set-up to operational practices that ensure reliability of the system and also to enable more cost effective integration. The recommendations for the main steps and methodologies are intended to be updated as the integration study methodologies evolve and new experience of real wind integration emerge.
10. References


