ADVANCES IN WIND INTEGRATION, RECENT FINDINGS FROM INTERNATIONAL COLLABORATION IEAWIND TASK 25

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The main challenges of integrating variable renewables to power systems are discussed. The recent advances in methods and results of integration studies are summarised, based on the reports published in 2018 from IEA WIND Task25. The summary reports by Task 25 contain information on the most recent findings from both experience and studies on how to integrate large amounts of wind and solar energy to the power systems. In 2018, Task 25 updated the Recommended Practice 16: Wind Integration Studies in 2013 to cover solar PV and distribution system studies though collaboration with IEA PVPS Task 14. The Recommended Practices details the knowledge on how to perform an integration study, and can be used as a benchmark for studies.

Keywords: renewable energy, solar energy, wind power, integration

INTRODUCTION

The lack of reliable and comparable knowledge about the effects of variable renewable generation (i.e., wind and solar PV), including operational practices, can limit the large-scale development of renewable energy due to uncertainties about its impact. With the growth of wind and solar deployment and their tremendous potential, it is crucial that commonly accepted methodologies are applied to accurately assess integration issues.

IEA WIND Task25 is working on enhancing the knowledge and methods to assess impacts of higher shares of wind and solar energy to power systems. It is a Research Collaboration Task on Design and Operation of Power systems with Large Amounts of Wind Power under International Energy Agency (IEA) Technology Collaboration Programme (TCP) Wind (https://community.ieawind.org/home).

Wind power has several impacts on electric power systems: long-term planning issues and short-term operational impacts. Long-term planning issues include grid planning and generation capacity adequacy. Short-term operational impacts include reliability, stability, reserves, and maximising the value of wind in operational timescales (balancing related issues).

Ongoing experience from countries and regions that already integrate 20-50% of yearly electricity from wind power, as well as integration studies of wind and solar in future power systems are helping to evolve integration study methods. Wind/PV integration studies usually involve simulations of the power plants in the system and investigations of grid and generation capacity adequacy. A more detailed level includes dynamic simulations and a flexibility assessment, which are necessary when studying higher shares of wind and solar energy in the system.

This paper presents results of two recent reports. The summary report, to be published later in 2018, will highlight the main findings of recent integration studies, as well as experience, in the 18 countries participating in the international collaboration (the previous summary reports [1]-[4]). The newly updated Recommended Practice 16: Wind/PV Integration Studies details the knowledge on how to perform an integration study, and can be used as a benchmark for studies [5]-[6].

HIGHLIGHTS FROM RECENT WIND INTEGRATION STUDIES AND EXPERIENCE

The share of wind energy of annual electricity demand is growing. In Europe, already more than 11 % of all electricity consumption was covered by wind power in 2017. The pioneering country Denmark covered 43 % of its demand and Ireland and Portugal about 25 %. There is more and more real life experience from the countries integrating higher shares of wind and solar.

Experience from system operators

In Denmark, wind power covers more than the demand in many hours of the year and a recent highlight is that the system operator has been operating the system without any central power plants during several occasions, the first time being in December, 2015. During these hours, the frequency and voltage control is provided by the neighbouring areas through HVDC lines, and also by some local small scale combined heat and power plants.

In Texas the average wind power share is close to 20 % and wind power plants are actively used in frequency control. The fast response available from wind power plants has reduced the overall need for frequency support services in the system. Grid support from wind power plants have been shown to improve the frequency stability in studies from Ireland, the Netherlands, Denmark, Norway and US.

In Spain the average wind energy share is about 20 %, and during the last years a tertiary and imbalance management reserve market has opened for wind power. About half of the wind power plants have already conducted the operational capability tests with the system operator, proving the 15 min and 30 min response times required for these markets. In 2017 wind power provided 6.1 % of the downward tertiary reserves and 2.5 % of the upward tertiary reserves in Spain.

Variability and uncertainty of wind power generation

The European wide, hourly wind generation data has been analysed to vary between 5 and 52% of installed capacity. Maximum duration of low generation (below 10 % of installed capacity) was 38 hours in 2017.

The forecast accuracy is still improving. In Germany, detailed analyses of the events where the variability and forecast error of wind is high shows that these happen during times of stormy weather.

Congestion management

Congestion management in transmission grids is a challenge in Germany. Forecasting methods have been adapted to provide network operators with input data and information on uncertainty for real-time and anticipatory grid security calculations. Transmission and distribution system operators applied the system in grid management, also considering explicit measures for reducing power generation that are not weather-dependent.

Dynamic line ratings are used in Italy, and studied in Portugal, Sweden and US, to alleviate the bottlenecks when lower temperatures and more wind is cooling the overhead lines.

Curtailments and flexibility

Curtailing wind energy is a big challenge in China. Grid reinforcements and renewable certificates with quotas for provinces to ensure wind priority in transmission grid are the mitigation measures currently worked at.

In Texas and Italy, the curtailments have been an issue due to lack of grid in 2009-11 after which the curtailments have been less than 5 % of annual wind generation. Ireland, Germany and UK have had curtailments that are more than 4 %, other countries have very low, even close to 0 curtailments even in countries where share of wind is very high (Demnark and Portugal).

Increasing flexibility in the power system is a topic in many studies. In China, the curtailment rates have been estimated to decrease from 17 to 4 % using flexibility from the heat sector. The transmission and demand side flexibilities resulted in similar order of magnitude results.

In Finland the heat flexibilities have been estimated to be the second most cost effective flexibility, after increased transmission lines, in the North European system.

In Ireland the CAES (compressd air energy storage) builds an attractive flexibility option, and in Norway the large hydro power reservoirs, complemented by pumped storage could add to the flexibility needs of Northern Europe.

Co-locational storages at wind power plants are also emerging, making wind power plants more flexible - approximately 400 MW of co-located projects were identified by Wind Europe in 2017.

Market design

A set of recommendations for market design was the outcome of EU project Market4RES: faster markets with shorter lead times, larger markets with cross border participants, smaller products and efficient pricing to enable wind power producers joining the day-ahead, intraday and balancing markets.

RECOMMENDATIONS FOR INTEGRATION STUDIES

The phases of a complete integration study are illustrated in a flow chart (Figure i). Figure i shows the main setup of the study, input data needed, links between simulations and iterations to change main assumptions and finally analyzing the results. A full integration study is a complicated process, especially taking into account all possible iteration loops. Not all integration studies need to look at all aspects presented here. Integration studies can also be made in phases. In this case, the first phase usually looks at the short-term impacts for lower shares of wind/PV for the current power system—mainly impacts on other power plants in production cost simulations or local distribution networks. More elaborate studies look at transmission network adequacy and congestion, as well as generation capacity adequacy for higher shares of wind/PV in future systems (including the capacity value of wind/PV).

The set-up phase can be iterative, taking results from generation/network adequacy simulations when forming scenarios. Iteration between network simulations and production cost simulations may also be needed. Network dynamics need to be assessed for larger shares of wind and solar. What is considered a small or large share of wind/PV will depend on the power system studied, how large the area is where wind/PV is added, and how distributed it is built. Solar PV will tend to impact the system at lower shares than a well distributed wind power fleet. In most systems, 5-10% share of yearly electricity demand is considered a small share.

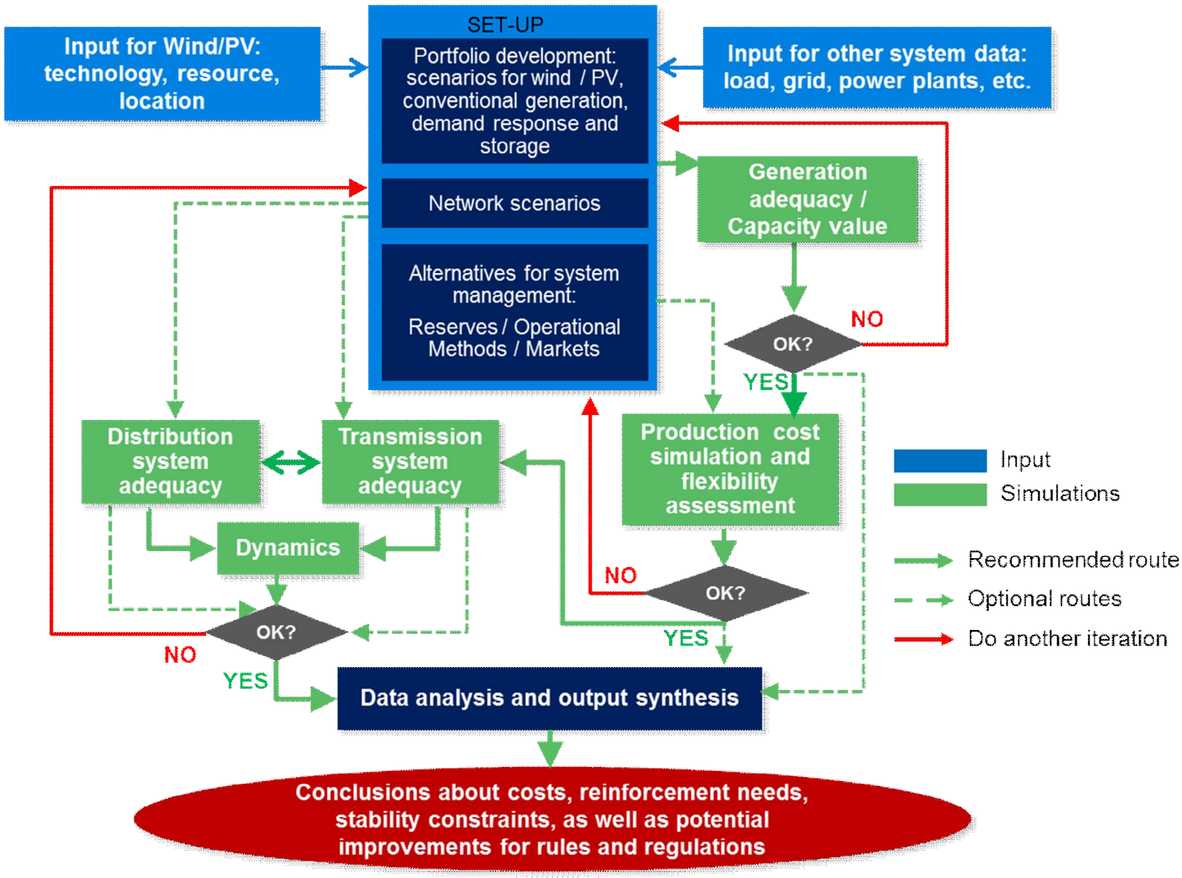

Fig. 1. Contents of a wind/PV integration study.

Portfolio development - set-up of the study

When studying small amounts of wind/solar power, or short-term studies, integration can be studied by adding wind/solar to an existing, or foreseen system without major inaccuracies. Also the operational practices can remain as is.

For larger wind/solar shares and long-term studies, the changes to the remaining system—generation portfolio and network infrastructure—become increasingly beneficial and necessary. Additional scenarios or operating practices should be studied, capturing potential sources of flexibility (demand response) and technical capabilities of power plants (dynamic stability responses).

Reserve requirements/allocation methods

To estimate the impact that wind/solar have on the short term operational reserves that the system needs to carry, the input data includes wind/PV and load time series (at least hourly) and wind/PV/load forecast error distributions. These time series should be time synchronized (co-incident). Also generation outage distribution and be used. First a level of risk is chosen based on existing operating practice; for example, to cover 95% of the variations in load and net load (load minus wind/PV power) output.

Calculate for the appropriate time scales, corresponding to existing operational practice (like automatically responding in seconds-minutes, and manually activated in minutes-hour to several hours). Split the input data for these categories with care not to double-count sources of variability or uncertainty.

Variability and uncertainty from wind/PV and load (and generation) are combined keeping the same risk level before and after adding wind/PV. Whatever statistical method applied, take into account that variability and uncertainty are not normally distributed. Using a desired level of exceedance, or determining the appropriate distribution is therefore recommended instead of using standard deviation.

With increasing shares, dynamic, not static allocation methods for committing reserves should be used, this means not using the same requirement for all hours of the year, but according to load, wind and PV levels anticipated.

Capacity value

Wind and solar energy have also capacity value - they add to the reliability of the power system to meet the load at all times, also at highest peaks. To estimate this the recommended method is effective load carrying capability (ELCC) method:

Gather chronological, time-synchronized wind/PV and load data that captures the correlation between wind/PV and load data. The robustness of the calculations is highly dependent on the volume of data collected–10 to 30 years is recommended. Data on generation unit installed capacity and forced outage rates is also required.

Convolve generator capacity and forced outage to produce a capacity outage probability table (COPT) of the power system, which is a table of capacity levels and their associated probabilities. Loss of load expectation (LOLE) for each hourly demand level calculated from the COPT table, first without the presence of wind generation—wind/solar is added as negative load, and load is increased until the same LOLE is reached as the one without wind/solar power.

Impacts on power system dispatch and ramping

Time-synchronized (co-incident) input data for wind, PV and load with at least hourly resolution and one year is required. Capturing the spatial smoothing of wind/PV power production time series for the geographic diversity assumed is important. For hydro dominated systems the hydrological changes (wet/dry year) need to be captured and co-incident data is needed for run of the river hydro. Wind/PV forecasting best practices should be used for the uncertainty of wind/PV power production.

Capture system characteristics and response through operational simulations (Unit commitment and economic dispatch, or UCED). Model the flexibility options, as well as any constraints of flexibility. This includes generation unit ramping, minimum up/down times, minimum stable levels, start-up and shutdown limitations. The operational practices that may enable or limit flexibility to be used should also be taken into account. Take into account the possibilities of flexibility that exist in neighboring regions. To accurately model the limitations of interconnections, the neighboring system should be explicitly modelled, including also the wind/PV power installed there. Alternative approaches include assuming fixed flows obtained from other studies or based on assumed market prices in neighboring regions. To capture the limitations from the transmission network, congestion and N-1 security can be included directly within UCED. To reduce the computational burden for large systems or where stochastic optimization is used, net transfer capacity, or iterative methods can be used. Also, transmission systems limitations can be modeled in other dedicated tools and the resulting limitations included as constraints within the UCED model.

Study results and conclusions are particularly sensitive to the non-wind/PV case used as a basis for comparison and assumptions regarding the types of generation that wind/PV power will displace. Just adding wind/PV power, or using a scenario with equivalent wind/PV energy, but with a perfectly flat profile, may result in impacts not entirely related to wind/PV energy. The use of generation planning models to ensure consistent scenarios should be considered. For higher wind/PV shares, a scope that acknowledges and/or includes new potential sources of flexibility is recommended.

Network simulations - steady state analyses

In addition to the peak load and low load situations traditionally studied, a number of credible power flow cases including critical situations regarding wind and solar power should be chosen, such as periods with high non-synchronous generation (wind/solar) and import via HVDC. An evaluation of the snapshot's statistical relevance is beneficial as an input to the cost-effectiveness of implementing corrective actions—for example as part of a multi-year analysis. Moving towards probabilistic analysis, full year with cost benefit analysis is recommended for network reinforcement.

<u>Deterministic steady-state security analysis</u>: in compliance with N and N-1 security criteria, power flow analyses are performed to identify transmission network bottlenecks (congestion), and to assess the system's ability to maintain the voltage profile.

<u>Network loading (congestion) assessment</u>: network branch loadings should be determined for wind/solar generation and load combinations, across a year, both for normal and contingency (N-1) situations. Bottlenecks can be identified in a probabilistic manner, so that by analyzing the overload risk and the aggregated severity index, planners can identify whether bottlenecks should be considered 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 and solar generation variability to be considered.

<u>Time-series power flow and operation of discrete controllers</u>: reducing the number of online conventional power plants will also reduce the number of continuously acting automatic voltage regulators, unless the plants are converted to synchronous compensators. Wind and solar variability may require more frequent operation of discrete controllers, e.g., shunt reactors, with a detrimental effect on plant lifetime and the viability of such an approach.

<u>Power transfer fluctuations on cross-border lines</u> caused by the variable production of wind/PV power plants should be examined to help determine the steady-state cross-border transmission power margins (net transfer capacity, while taking into account wind/PV energy production).

<u>Short circuit levels</u>: for high wind and solar shares, some synchronous generation will not be dispatched, which may lead to a reduction in the minimum short circuit level in some locations (the presence of wind and solar generation in other non-traditional locations may actually improve the fault level in those areas). This, in turn, may affect the power quality, voltage step changes after shunt switching and the operation of line commutated HVDC converters, leading to the mal-operation of protection systems.

<u>Protection systems</u>: increased generation capacity at lower voltage levels may lead to reverse power flows from distribution buses (former load buses), such that correct operation of protection systems should be ensured.

Network simulations - dynamic analyses

Different systems may experience totally different dynamic issues (e.g., frequency stability, voltage stability, or transient stability challenges), dependent on the underlying correlation between wind/PV production and system demand, the underlying flexibility and capabilities of the conventional generation portfolio, relative location of generation assets and major load centres, etc., implying that specific system studies may be required. Usually dynamic analyses are made at higher shares of wind/PV. Studies should recognize that wind turbine/PV controls, as part of a coordinated control strategy(s), may offer system advantages.

Snapshot cases should include ranges of wind share, solar share, and demand levels to best understand system dynamic limits. These need not be the same as those chosen for steady-state power flow analysis. Understanding the new commitment and dispatch patterns with the addition of wind and solar is important, as several (conventional) generators could be reducing their output but remain online to provide stability.

Dynamic models for power plants and load: Appropriate model complexity will depend on the study application. Using generic RMS models for strong systems; EMT models for weak systems; and manufacturer-specific detailed RMS models for systems of intermediate strength is a general recommendation. Validation of all models (conventional generators, PV and wind turbine, and load) is important. PV and wind turbine models should recognize (evolving) technology capability and grid code requirements. Load characteristics will more strongly influence system performance with power systems becoming 'lighter' due to the displacement of conventional generation (reduced inertia).

Transient stability analysis: It can be important to include the effect of protection devices for both network and converter-interfaced generating equipment; however, boiler/steam turbine models are not required. Wind and solar generation can provide system support during voltage dips, and help to dampen oscillations, although the level of support provided is network sensitive. Proper representation of the impedance connecting the wind power plants is crucial within simulation studies. To mitigate any issues discovered, fast acting reactive power response devices during and following disturbances can be applied, e.g., installing FACTS devices, synchronous compensators, and/or requiring all wind plants and conventional generators.

Voltage stability studies: At low wind/solar shares it is probably unnecessary to perform studies, as system stability is likely to be unaffected or even enhanced by the presence of wind turbines/PV panels. This argument is particularly true if the reactive power control capabilities of the wind turbines (PV) are deployed to manage voltage, and if they are connected at transmission level. As conventional generation is displaced at higher shares of wind and solar, voltage security levels may be affected in certain locations, which may require requiring more detailed analysis.

Frequency stability studies: The fraction of generation participating in governor control is a good metric for the expected performance. The maneuverable capacity of such generation is also important. Particularly for larger systems, the self-regulating effect of the load can also ameliorate severe disturbances: simulation results can be sensitive to how the load is modeled. Modeling inertia as well as droop and governor control settings of all units (both individual unit responses and system response to faults or contingencies) is important. Reduced inertia at times of high non-synchronous (wind, PV and/or HVDC input) shares will alter the system response for both faults and contingencies, particularly for smaller power systems. A reduced network representation may be sufficient, focusing on demand-generation imbalances and active power flows, with reduced consideration of voltage variations and reactive power requirements. However, under-frequency load shedding can provide system support during frequency drops, and proper representation of the frequency disconnection rules is crucial. Wind turbines can provide a fast frequency response, depending on their operating point, and PV plant can provide a similar response if their output has previously been curtailed. Fast-acting load response or storage may also be included. Mitigation measures include disabling/replacing aspects of distribution connected protection schemes for wind plants, while ensuring that conventional generators provide appropriate reserve in a timely manner following an energy imbalance. In addition, the capability of all generators to withstand high rates of change of frequency should be reviewed.

Small-signal stability studies: Wind and solar generation do not generally introduce small-signal oscillatory modes, but as their presence may displace conventional generation (and associated power system stabilizers) and alter the magnitude and direction of transmission line power flows, it follows that small signal stability may be impacted.

Sub-synchronous oscillations: Sub-synchronous torsional interaction (SSTI) and sub-synchronous control interaction (SSCI) should be investigated as part of small-signal stability analysis, particularly in relation to doubly fed (type 3) wind turbines. A range of mitigation measures including bypass filters, FACTS devices, auxiliary (damping) controls are available.

Common-mode fault events: Network faults and/or loss of a major infeed can result in widespread voltage depressions and/or large frequency deviations and the common-mode tripping of local wind and solar generation. Consequently, the operation of associated protection systems may play a crucial role in determining system outcomes, requiring sophisticated modeling methods. Delayed active power recovery from grid code compliant generation following a widely seen network fault may similarly lead to a common-mode power reduction and frequency stability issues—voltage dip induced frequency dips.

Distribution grid analyses

The integration of wind and PV systems at the distribution level entails both challenges and opportunities for distribution grid planning and operation. Stronger coordination of transmission and distribution grid studies will be required with higher shares of wind/PV to access the full capabilities and flexibilities of distributed resources for the overall bulk power system.

For grid planning, the measures should be considered in this order: grid optimization before grid reinforcement, before grid expansion. Based on available input data and the scope of the study, the analyses can either be performed using representative grid data or actual data, if available. For comprehensive system-wide distribution grid studies, a high degree of automation for data handling is required and recommended.

A detailed study of the grid losses for a certain number of representative distribution grids, combined with statistical analysis or data-driven methods, is recommended to recognize the large variation in the network characteristics of distribution grids. It is also essential to consider both the location and generation pattern of wind/PV when representing distribution grids, as they both have a significant impact on the grid losses. In order to partially validate the implemented model of the grid area, the energy flow in the studied grid area can be investigated in comparison with real measurement data available at transmission level bulk supply points.

Analyzing and presenting results

If the results show unexpectedly high and costly impacts of wind/PV power to the system, consider the iteration loops. Changing operational practices may prove cost effective, or generation or transmission scenarios may be in adequate.

When extracting results for the impacts, select the cases to compare with care and report the methodology and possible caveats in the findings. Assessing integration costs is especially challenging both in capturing the increases in costs that are due to wind power and allocating a part of system costs for a single technology.

The results should be presented stating share of wind/PV, size and type of power system and the main assumptions and limitations arising from the methods used. The recommendations on the methodology could be used as a benchmark when doing this.

CONCLUSIONS

Ongoing experience from countries and regions that already integrate 20-50% of yearly electricity from wind power, as well as integration studies of wind and solar in future power systems are helping to evolve integration study methods.

The advances in wind power technology and short term forecasting of wind energy allow for modern wind power plants to provide grid support and help in integrating the variability and uncertainty of wind energy. The power system transformation towards deeper decarbonisation means linking the energy sectors of power, heat, transport and gas. This will bring more opportunities of flexible power demand that will help integrating high shares of variable generation.

The recommendations on the methodology for integration studies could be used as a benchmark when presenting the limitations and strengths of an individual study. The assumptions and setups of the study (such as investments in the remaining system) are crucial to determining the integration impacts. Because system costs are difficult to allocate to any single plant or technology, it is recommended to quantify increases in power system costs, and instead of allocating system costs to use total cost comparisons and cost- benefit analysis. Adding wind and solar energy to power systems will reduce total operating costs and emissions as wind and PV replace fossil fuels.

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