Recommended Practices for wind/PV integration studies from international collaboration IEA WIND Task 25 and IEA PVPS Task 14

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17.12.2018 VTT – beyond the obvious
Contents

Introduction: On Task 25/Task14 work

Recommendations for how to perform integration studies
- Impact on balancing
- Impact on generation adequacy
- Impact on grid adequacy and resiliency
  - Damian Flynn, UCD: Transmission systems
  - Markus Kraiczy, Fraunhofer IEE: Distribution system
IEA-PVPS Task 14
Solar PV in the 100% RES Power System

- Promote the use of grid connected PV as an important source in electric power systems also on a high penetration level where additional efforts may be necessary to integrate the dispersed generators in an optimum manner.

- Develop and verify technical requirements for PV and electric power systems to allow for high penetrations of PV systems interconnected with the grid.

- Discuss the active role of PV systems related to energy management and system control of electricity grids.

- Reduce the technical barriers to achieve high penetration levels of distributed renewable energy systems on the electric power system.
IEA-PVPS Task 14: Outcomes

- Prepare the technical base for Solar PV to become an integral part of the future 100% RES supplied power system through
  - guidelines and best practices for industry, network operators, energy planners as well as authorities
  - transparent technical analyses
  - comprehensive international studies for high penetration PV

- Develop key methodologies for large scale PV integration
  - Grid interconnection studies and planning
  - Technical standards and interconnection requirements
  - Integration with the Smart Grid

- Active dissemination of objective and neutral high-quality information
  - Task 14 Reports
  - Task 14 Workshops at national and international events
  - National information networks of Task 14 members

- Further information: http://www.iea-pvps.org/
IEA Wind Task 25 – What Does It Do?

- Started in 2006, now 17 countries + WindEurope participate to provide an international forum for exchange of knowledge
- State-of-the-art: review and analyze the results so far: latest report end 2018
- Formulate guidelines- Recommended Practices for Integration Studies: Update published in August
- Fact sheets and wind power production time series. Literature list.

https://community.ieawind.org/task25/
Experience of wind integration is increasing

- Hourly maximum wnd shares in European countries
  - Denmark and Portugal > 100%
  - Germany 80 %
  - Ireland > 60 % of demand

- Wind energy in Europe:
  - Ranges 5-52% of installed capacity,
  - max duration of low generation: hours < 10% of capacity
**Recommended Practices for wind/PV integration studies**

- A complete study with links between phases
- Most studies analyse part of the impacts – goals and approaches differ

Conclusions about costs, reinforcement needs, stability constraints, as well as potential improvements for rules and regulations.
What to study - Portfolio Development and System Management

- Set-up of study
- Main assumptions – Critical for results!
- Future system, how wind/PV is added, what is remaining generation mix, operational practices

For larger shares and longer term studies:

- changes in the assumed remaining system become increasingly necessary, and beneficial: generation portfolio and network infrastructure, taking into account potential flexibility and technical capabilities of power plants. Additional scenarios for operating practices recommended
## Input data

<table>
<thead>
<tr>
<th></th>
<th>Capacity Value / Power (resource) Adequacy</th>
<th>Unit Commitment and Economic Dispatch (UCED)</th>
<th>Power Flow</th>
<th>Dynamics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wind/PV</strong></td>
<td>Hourly generation time series for distributed wind/PV energy covering the area. Especially for wind, more than 10 years recommended</td>
<td>5-minute to hourly generation time series of at least 1 year for distributed wind/PV power covering the area</td>
<td>Wind/PV capacity at nodes, high and low generation and load snapshots, active and reactive power capabilities</td>
<td>Wind/PV capacity at nodes, high and low generation and load snapshots, dynamic models, operational strategies</td>
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<tr>
<td><strong>Wind/PV Short-term Forecasts</strong></td>
<td>Not needed</td>
<td>Forecast time series, or forecast error distribution for time frames of UCED</td>
<td>May be needed in future</td>
<td>Not needed</td>
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<tr>
<td><strong>Load</strong></td>
<td>Hourly time series coincident with wind/PV data, at least 10 years recommended</td>
<td>5-minute to hourly time series coincident with wind/PV, of at least 1 year</td>
<td>Load at nodes, snapshots relevant for wind/PV integration</td>
<td>Load at nodes, high and low load snapshots, dynamic capabilities</td>
</tr>
<tr>
<td><strong>Load Forecasts</strong></td>
<td>Not needed</td>
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<td>May be needed in future</td>
<td>Not needed</td>
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<tr>
<td><strong>Network</strong></td>
<td>Cross border capacity, if relevant</td>
<td>Transmission line capacity between neighboring areas and/or circuit passive parameters</td>
<td>Network configuration, circuit passive and active parameters</td>
<td>Network configuration, circuit parameters, control structures</td>
</tr>
<tr>
<td><strong>Other Power Plants</strong></td>
<td>Rated capacities and forced outage rates</td>
<td>Min, max on-line capacity, start-up time/cost, ramp rates, min up/down times, efficiency curve, fuel prices</td>
<td>Active and reactive power capabilities, system dispatch</td>
<td>Dynamic models of power plants</td>
</tr>
</tbody>
</table>
Synchronous wind/PV and load time series + forecast error distributions + generation outage distribution

2. Calculate for appropriate time scales, f.ex. automatically responding (secs-mins) and manually activated (mins-hour). Split data for categories with care not to double-count

3. Combine uncertainty keeping the same risk level before and after wind/PV

4. With increasing shares, use dynamic, not static reserves

Operating reserve allocation with wind/PV

PDD of generator outages
PDD of load forecast errors
PDD of wind power forecast errors

PDD of power deficits and surplus

LOLP = 0.0025 %
Generation capacity adequacy

Needed for making consistent future scenarios (how much capacity will wind/PV replace), as integration study result: capacity value of wind or solar PV

Recommendations:
- How much increase in load will bring same reliability/LOLP in the system when adding wind or solar (ELCC method) recommended
- Input data – synchronous wind/PV/load data. Number of years critical for robust results, more than 10 years
Impact of wind/PV on other power plants’ operation. Simulated with Unit Commitment and Economic Dispatch (UCED) tools

- Iteration loops /sensitivities often needed: results sensitive to base case selection (non-wind/PV case of comparison)

- Input data: one year of hourly wind/PV data – synchronous with load (and hydro) and capturing smoothing impact and forecast accuracy

Production cost simulation – flexibility assessment
Recommendations for Unit Commitment and Economic Dispatch (UCED)

1. Impact of uncertainty on commitment decisions with possibilities to update forecasts (rolling planning)
2. Increased operating reserve targets
3. Flexibility limitations and constraints: min.generation levels, ramp rates, part load efficiency,..
4. Possible new flexibilities (power2heat, EVs, storages, demand response, dynamic line rating)
Recommendations for Unit Commitment and Economic Dispatch (UCED)

5. Possibilities and limitations of interconnections
   - model neighbouring system or mention assumption (over- or underestimating transfer possibilities)

6. Limitations from the transmission network require modeling of congestion and N-1 security
   - Net transfer capacity, or iterative methods can be used. Additional stability constraints for very high wind/PV shares.
Transmission Grid and System Dynamics
Recommended Practices for Wind / PV Integration Studies

Damian Flynn, University College Dublin
High Wind / PV Share Concerns

- Displacement of synchronous machines
  - Low online inertia levels / regional inertia? $\approx$ frequency stability
- Reduced fault levels $\approx$ system strength
  - Impact on voltage stability / PE controls performance / power quality / ...
- Reduced synchronising torque $\approx$ rotor angle stability
  - Exchange of surplus wind / PV power across wide areas
- Reduced Q / voltage regulation capability (static & dynamic)
  - Negative effect on voltage and transient stability
- Harmonic injections introduced by PE converters
  - Resonance amplification introduced by the new HV/EHV cables
  - Harmonic distortion at PoC, and wider network, within planning levels?
Locational Shift in Generation

- Large share of PE generation connected to Dx network
  - Voltage regulation capability from dx connected generation?
  - Operating at leading pf? Voltage profile on long + low X/R lines?
  - Reactive power requirements at TSO / DSO interface?

- Loss of mains protection for distributed generation
  - RoCoF relays for low inertia systems?

- Spatial distribution of old / new generation relative to load
  - *Old* generation near high capacity transmission circuits
  - *New* generation in remote, electrically weak locations?

- Buildout of network much slower than wind / PV growth
  - Network congestion / stability issues / ...
  - Real-time operational challenges?
Growth of PE based Loads

- Voltage & frequency dependent behaviour of evolving load
  - Constant power loads ≈ frequency stability?
- Proximity of load to distributed generation
- Growth of large data centre connections
  - Short project delivery times
  - Strict power quality and reliability requirements
  - Limited knowledge of dynamic behaviour (+ protection)
  - Limited knowledge of harmonics emissions
Stability Analysis

• **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 steady-state conditions on voltage, current, and power magnitudes after being subject to a small disturbance

• **Frequency stability**
  – ability to maintain the 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
Scenario Selection

- High / low demand – winter / summer
  – Extracted from production cost simulations
- High / low wind and / or solar power output
- High / low import / export
- Recognise correlation between inputs
- Multi-year evaluation of wind / PV scenarios
- Static scenarios ≠ dynamic scenarios
- Likelihood of scenario occurrence
Scenario Selection

- Reverse power flows
- Full / empty (energy) storage
- High / low (synchronous) inertia
- High / low online headroom (P & Q)
- Displacement of stabilising controls
- ...

- Revisit scenario selection as results emerge
  - High-level scanning & in-depth focus
  - Selection of before vs. after scenarios?
Ireland - Synchronous Inertia 2020
Loadflow Assessment

- Modified unit commitment / economic dispatch
  - Incorporation of *must run* and *locational* plant constraints?
  - Inclusion of DC network + assessment of N-1 security?
- Network expansion / reinforcement
  - Dynamic line rating + High temperature low sag conductors
  - Power flow controllers / line compensation
  - SVC / STATCOM / FACTS devices / ...
- Probabilistic assessment of event occurrence and consideration of severity of outcomes
  - Time series loadflow – switching operations
Dynamic Modelling

- Increasing array of (bespoke) PE control structures
  - Modelling assumptions + Grid code compliance?
  - Utilisation of generic wind / PV models

- Offshore HVDC connected wind
  - Power control and system frequency support
  - HVDC controls, individual turbine controls and overall plant controller

- Assess existing (conventional) generator models
- Assess (regional) dynamic load models
- Inclusion of protection devices ... potentially larger frequency & voltage variations
Dynamic Load Models

WECC – Western Electricity Coordinating Council
WWSIS- 3 - Midway-Vincent Fault

WWSIS-3 – Western Wind and Solar Integration Study, Phase 3
Generic Wind / PV Models

- WECC and IEC models capture minimum performance required by most grid codes for basic wind turbine types
- PV models based on type 4 wind plant models
Evolving Wind / PV Plant Controls

- Plant models should be linked with evolving wind / PV capabilities and grid codes
- Fault ride through requirements
  - emphasis placed on MW or MVAr response?
- Fast frequency (emulated inertia) response
- High wind ride through ...

![Graph showing time (s) vs. percentage for different countries]
Wind Turbine Controls

High Wind Shutdown

<table>
<thead>
<tr>
<th>Wind Speed (m/s)</th>
<th>Power (kW)</th>
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<tbody>
<tr>
<td>20</td>
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<tr>
<td>25</td>
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<tr>
<td>28</td>
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10min 30s 1s

High Wind Ride Through

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<td>39</td>
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</tbody>
</table>

10min 30s 1s
Horns Rev 2 – 30th January 2013
Demand / Storage Response

- Configurable under / over response curves
- Configurable reserve / recovery curves

FFR – Fast frequency response
Stability Analysis – Additional Options

- Distribution of generation across network
- Voltage dip induced frequency dips
- Sympathy (distribution) tripping due to transmission-level events
  - Voltage trip vs. voltage ride through settings
- Sub-synchronous interactions
  - Sub-synchronous resonance, sub-synchronous torsional interactions and sub-synchronous control interactions
Voltage Dip-Induced Frequency Dips
Voltage Dip-Induced Frequency Dips
System Modelling Analysis – 3φ Fault

![Graph showing RoCoF against Frequency Nadir (Hz) for different cases. The graph includes markers for different cases with a load shedding zone highlighted.](image-url)
Enhanced Distribution Network Model
Concluding Comments

• Trade-off with transmission planning and operational policies requires multiple studies
• At higher wind / PV shares, stability issues can take precedence over UC / flexibility / market issues / ...
• Accurate assessment requires validated wind turbine / PV / load / generator models + proposal of control strategies
• Relative importance of voltage / transient / small-signal / frequency stability issues can be system dependent
  – Network topology, underlying plant portfolio including renewables, e.g. solar, wind turbine types + location, grid code requirements
  – Studies should evolve from "what are my problems?" to "how can I take advantage of my new control options?"
Contributors: B. Mather (NREL), M. Kraiczy, C. Ma, M. Braun (Fraunhofer IEE) and S. Meinecke (University of Kassel)
**Distribution grid**

Distribution grid modelling

- **Challenge**: Scarce input data, high complexity and regional diversity of distribution level
- Example - Grid modelling in state-wide/ system-wide distribution integration studies:
  1. Analysis of representative grids in detail, i.e. via clustering/ taxonomy
  2. Automated (simplified) analysis techniques, possibly with assumptions of simplified distribution grid data
    † Reduce complexity of distribution level, but preserve diversity and relevant characteristics of distribution level
- Best-practice of distribution grid modelling depends on detailed study objective and available input data.

Data acquisition, data handling and distribution grid modelling is still a major challenge for distribution integration studies. For comprehensive system-wide distribution grid studies, a high degree of automation for data handling and analysis is required.
Distribution grid
Objectives of distribution integration studies

- DER integration and other impact factors (e.g. digitalization) are main drivers for the development of new planning procedures and tools in the distribution level
- Selected objectives of distribution integration studies:
  - Hosting capacity analysis
  - Distribution network reinforcement analysis
  - Voltage variability analysis and test of control algorithms
  - Grid losses analysis
- Further objectives, e.g.: protection and unintentional islanding studies, flicker and harmonics studies, development of dynamic DER and distribution grid equivalents and several more.
Hosting Capacity Analysis

Objective:
- Analyze the maximum amount of wind or PV interconnections on an existing network without the need of any grid reinforcements.
- Screening method for PV/wind interconnections
- Benchmark of mitigation methods to avoid grid reinforcements

Example - Deployment scenario independent hosting capacity:
- Provides the maximum amount of wind/PV that can be integrated on a circuit regardless of where the wind/PV interconnects to the system
- Valuable for distribution utilities and developers in the interconnection process of many wind/PV systems (e.g. residential roof-top PV)

Fig: Example Calculation of Hosting Capacity (Source: Alternatives to the 15% Rule: Modeling and Hosting Capacity Analysis of 16 Feeders. EPRI, Palo Alto, CA: 2015. 3002005812)
Distribution grid
Objectives of distribution integration studies

Distribution grid reinforcement analysis

Objective:
- Estimate the DER grid integration costs in the distribution level
- Benchmark of different grid integration measures

Best practice example/recommendation:
- A comprehensive catalogue of grid planning measures should be considered, i.e. grid optimization before grid reinforcement before grid expansion (e.g. [1]).
- Based on available input data and the scope of the study, the analyses can either be performed using representative or actual grid data.
- Presentation of results: important to put the wind/PV integration driven reinforcement costs in contrast with generally necessary reinforcements, such as replacing outdated grid assets.

Fig.: Simplified flow chart for system-wide distribution grid reinforcement studies

Distribution grid
Objectives of distribution integration studies

Variability analysis and test of control algorithms

**Objective:**
- Analyse the impact of wind and PV interconnections on the operation of voltage regulators in the distribution level
- Test and benchmark of voltage regulator and DER control strategies

**Best practice example:**
- Variability analysis can be completed through the full-scale quasi-static timeseries simulation of a distribution circuit over an entire year with relatively high temporal resolution (e.g. [3])
- Simplified methods available (e.g. [2])

Fig.: Example variability analysis (Source: IEA PVPS Task 14 Report, High penetration PV in local distribution grids, 2015)

**Grid losses analyses**

**Objective/ Motivation:**
- Interconnection of wind/PV and other DER can have a significant impact on the distribution grid losses
- Grid losses are often a key efficiency indicator of DSO by regulators in different countries

**Best practice example/ Recommendation:**
- Conventional methods for loss estimation are usually not suitable for power systems with DER
- Consideration of PV/Wind location and generation pattern important for grid loss analysis
- 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
Distribution grid
Summary distribution integration studies

**Modelling and data handling**
- Best-practice of distribution grid modelling depends on detailed study objective and available input data.
- Data acquisition, data handling and appropriate distribution grid modelling still a major challenge for distribution integration studies. For comprehensive state-wide and system-wide distribution grid studies, a high degree of automation for data handling is required.

**Scope and Methodologies**
- Scope, tools and methodologies for distribution integration studies will continue to expand and develop.
- Well established best-practice examples and advanced planning procedures for distributed Wind/PV integration studies partly still required.

**Transmission-Distribution coordination**
- 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.
Analysing and Presenting the Results

- Iterations provide significant insights
- Comparisons to base case selected may impact results. Integration cost contradictory issue – so far no accurate methods found to extract system cost for a single technology
- Present the share of wind/PV for easier comparison with other studies
Future work: integration studies are still evolving, towards 100% renewable studies

- **Metrics and tools for flexibility needs** of the power system, and ways to achieve flexibility
- **Simulation tools that consider uncertainty** of wind in different time scales, and combine network constraints with UCED constraints
- Ways to set up simulation cases to efficiently extract impacts and system costs – from cost of integration to cost of inflexibility
- Stability issues with very high penetration cases. Future grids with more DC transmission.
- Implications of market design and/or regulatory processes for wind/PV integration.

Link to report RP16 Ed.2 at Recommended Practices site: [https://community.ieawind.org/publications/rp](https://community.ieawind.org/publications/rp)
Questions/experience in using the bullet point lists: hannele.holttinen@recognis.fi
Transmission part: damian.flynn@ucd.ie  Distribution part: Markus.Kraicz@iee.fraunhofer.de
## IEA Wind Task 25

**Design and operation of power systems with large amounts of wind power**

17 countries + Wind Europe participate

<table>
<thead>
<tr>
<th>Country</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
<td>Hydro Quebec (Alain Forcione, Nickie Menemenlis); NRCan (Thomas Levy)</td>
</tr>
<tr>
<td>China</td>
<td>SGERI (Wang Yaohua, Liu Jun)</td>
</tr>
<tr>
<td>Denmark</td>
<td>DTU (Nicolaos Cutululis); Energinet.dk (Antje Orths, Peter Börre Eriksen)</td>
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<tr>
<td>Finland (OA)</td>
<td>VTT (Hannele Holttinen, Juha Kiviluoma)</td>
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<tr>
<td>France</td>
<td>EdF R&amp;D (E. Neau); TSO RTE (J-Y Bourmaud); Mines (G. Kariniotakis)</td>
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<tr>
<td>Germany</td>
<td>Fraunhofer IEE (J. Dobschinski); FeE (S. von Roon); TSO Amprion (P. Tran)</td>
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<tr>
<td>Ireland</td>
<td>Energy Reform (J. Dillon, M. O'Malley); UCD (D. Flynn); SEAI (J. McCann)</td>
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<td>Italy</td>
<td>TSO Terna Rete Italia (Enrico Maria Carlini)</td>
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<td>Japan</td>
<td>Tokyo Uni (J. Kondoh); Kyoto Uni (Y. Yasuda); CRIEPI (R. Tanabe)</td>
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<tr>
<td>Mexico</td>
<td>INEEL (Rafael Castellanos Bustamante, Miguel Ramirez Gonzalez)</td>
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<td>Wind Europe</td>
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