Grid codes and wind farm interconnections
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Purposes of grid codes

- Grid codes are designed to ensure stable operating conditions and to coordinate the response of generating units during disturbances.
- Grid codes will provide for the protection of people and equipment.
- Grid codes will provide for high power quality.
- These requirements will vary for grid authorities in different regions.
Publishers of grid codes

Grid codes are published by:

- Utility Companies.
- State Public Service Commission (PSC).
- Regional Transmission Organizations (RTOs).
- Independent System Operators (ISOs).
- Regional Coordinating Councils.
- Regional Interconnections.
- North American Electric Reliability Corporation (NERC).
Industry Standards also affect interconnections:

- IEEE Std 1159, IEEE Recommended Practice for Monitoring Electric Power Quality
  - IEEE Std 1547a, Amendment 1
- IEC Std 61400-21 Measurement and assessment of power quality characteristics of grid connected wind turbines
Grid code requirements and wind turbine responses

- Undervoltage conditions
- Overvoltage conditions
- Frequency variations
- Voltage regulation and power factor
- Frequency control
- Active power control
- Power quality: harmonics and flicker.
System analysis of wind farms

- Basic analysis can be done with standard tools:
  - Short circuit
  - Load flow
  - Harmonics

- Dynamic analysis with transient stability programs (PSLF, PSSE)

- Transient analysis (EMTP, PSCAD)

- Modeling is specific to turbine manufacturer and type.

- Both require proprietary “black box” models of wind turbines and wind farms, if models are available at all.
Typical causes are faults, load energization, and faulty wiring.

Fundamental frequency phenomena
- Short duration rms variations
- Interruptions: <0.1 pu voltage
- Sags: 0.1 to 0.9 pu voltage
- Instantaneous: 8.3ms-0.5s
- Momentary: 0.5-3.0s
- Temporary: 3-60s

Long duration rms variations
- Sustained interruptions: 0.0pu
- Undervoltages: 0.8-0.9pu.
Fault Ride-Through

- When wind farms were a relatively small proportion of generation, they were required to disconnect from the transmission system when a fault occurred.

- With increasing proportions of wind generation in the overall generation mix, it has become necessary to retain wind turbines during faults.

- Wind farms must have protective systems to take them offline in extreme situations where they may be subject to damage.

- Capability of the wind-turbine generator to withstand the fault for its duration and then to recover to normal operation.
Fault Ride-Through: LVRT and ZVRT

Two types of ride-through characteristics exist:

- **Low-voltage ride-through (LVRT)**, where the turbine must stay connected for a terminal voltage no lower than a certain limit, such as 15% of nominal voltage, for a given time, such as 0.625 s.

- **Zero-voltage ride-through (ZVRT)**, which is similar to LVRT, but the turbine must remain connected during a zero-voltage fault of a given duration.

- ZVRT and LVRT capabilities of wind turbines are dependent upon grid strength.

- Rate of recovery to normal voltage is important.

- Wind turbines generally have a published fault ride-through characteristic.
Fault Ride-Through at Transmission Interconnections

- The grid code requirements for transmission interconnection are at the high side of the wind-farm step-up transformer. This is the Point of Interconnection (POI).

- Different voltage levels for the same event at the POI and the wind turbines.

- A zero-voltage fault at the transmission level may be a low-voltage fault at the wind turbine.

- A power system study would be required to determine the exact relationships.

- Some grid codes specify additional requirements for remote faults in the transmission system.
Types of overvoltage events

- Impulsive transients lightning protection.
- Oscillatory transients: 5μs-50 ms, 0-8pu
  - Switching surges
  - <5 kHz to >500 kHz
- Short duration rms variations, 8.3ms-60s, 1.1-1.8pu
  - Fundamental frequency
  - Single line to ground faults (SLGF), load switching, load shedding, capacitor switching
  - Instantaneous: 8.3ms-0.5s, 1.1-1.8pu
  - Momentary: 0.5-3.0s, 1.1-1.4pu
  - Temporary: 3-60s, 1.1-1.2pu
- Long duration rms variations, >60s, 1.1-1.2pu
- Impulsive (lightning) transients: <50ns to >1ms
- Oscillatory transients: <33ms, <1.4pu
  - Open ended upper limits are difficult
  - Control systems and relay protection
- Voltage swells
  - Tripping not allowed when the disturbance will subside normally
  - Tripping permitted when expected limits are exceeded
  - Typically within the range of the various types of swells
- Long duration overvoltages: >3 s, >1.1pu
  - Tripping required in all of the codes evaluated
Over- and Under-Voltage requirements of selected standards.
Frequency variations.

- Not generally an issue with stiff systems unless large scale changes occur in the grid.

- With increased penetration of renewable energy, reduced inertia of synchronous generators in system may lead to frequency instability.

- Islanding: Frequency depends on ratio of load to generation.
  - Frequency droop is used to control frequency versus power.

- Typical variations: ±0.1 Hz, <10s

- Grid codes may specify minimum inertia, $H(s)$, in system
  - Wind turbines may have “synthetic inertia” from rotor blades and capacitors.
Examples of Frequency variation requirements.
Frequency response during disturbances
- Maintain connection with grid
- Inertia constant, minimum H
- Islanding
- Load sharing between generators

Frequency droop, $\Delta P/\Delta f\ %$
- $\Delta P/\Delta f\ %$
- deadband $\pm 0.06\% \leftrightarrow \pm 0.036\ Hz$
Frequency droop – over and underfrequency.

- ERCOT Droop control, %Power/Frequency (Hz)

Frequency droop of 5% and deadband of ±0.017 Hz.

NERC BAL-001-TRE-1
Voltage regulation (VR) and power factor (pf).

- Regulate the terminal voltage at the point of interconnection (POI)
- Acceptable voltage range typically 90-110%
  - Setpoint adjustment
  - Accuracy, e.g. ±0.5%
  - Voltage droop, typical range 0-10%
- Voltage control by power converter
- Reactive power control:
  - Power converter
  - Capacitor and reactor banks
  - STATCOM
  - Synchronous condensers
pf requirements of selected grid codes.

“Each Transmission Operator shall specify a voltage or Reactive Power schedule (which is either a range or a target value with an associated tolerance band)…”

NERC VAR-001-4.2 — Voltage and Reactive Control
However, in some cases (in Canada and Europe) both voltage and reactive power must be met at once, while maintaining acceptable frequency. This can be difficult.
Reduced power output may be required due to contingencies

Curtailment commands sent to wind farm control system

Minimum up/down ramp rates may be required (MW/min)
Power quality - harmonics.

- Most distributed generation interface with the grid using power electronic converters.
  - Typically VSI with a high switching frequency.

- By their nature these devices switch the current, resulting in distorted non-sinusoidal waveforms.
  - These are resolved by Fourier Series into currents at multiples of the fundamental frequency.

- Wind turbine harmonics may be exacerbated by system resonances.
  - Large cable systems have significant capacitances. There may be shunt capacitors on the power system.

- Harmonic remediation combines:
  - Active control schemes in the inverter.
  - Passive filters.
In this example, the wind turbine harmonics peak at the 27th harmonic = 1620Hz

Frequency range depends on switching frequency and power electronic controls.

Wind turbine harmonics can be at the range where the requirements are lowest.
Filter connected at AC output of inverter.
- Small capacitor bank good for high power factor operation.
- Significantly reduces THD. Typically in 0.5-2% range.
- More effective than DC Link Choke or AC Line Reactor.
Flicker is the variation in voltage such that a perceptible variation in the intensity of lighting is observed.

Most used references are: IEC Standards 61000-2-2, 61000-3-3, 61000-3-7, 61000-4-15.

$P_{st}$ (short term variation) is defined as variations over a 10-minute period.

$P_{lt}$ (long term variation) is defined as variation measured for 12 consecutive $P_{st}$ measurements.

Compatibility is complex among the different standards. A general guideline is:
- Short term $P_{st} = 1.0$
- Long term $P_{lt} = 0.8$
Various flicker curves have been used over the years.

The flicker curve most generally used is from IEC Standard 61000-3-7, 2008.

Figure A.1 – $P_{st} = 1$ curve for regular rectangular voltage changes [13]
Conclusions

- Grid codes are designed to ensure stable operating conditions and to coordinate the response of generating units during disturbances.
- These requirements will vary for grid authorities in different regions.
- The capabilities of wind generators are specified at the individual turbine, while grid requirements are specified at the point of interconnection.
- Power system studies for wind plants generally require models specific to the wind turbines being studied.
- Grid code specification of combined ranges, such as the required power factor range being applicable across the voltage range requires careful evaluation.
Discussion

- What is the purpose of grid codes?
- At what point in the system does the grid code apply?
- What constraints can affect reactive power control?
- What ranges of wind farm harmonics are most likely to cause trouble with IEEE 519?
  
  (a) \( h < 11 \)
  (b) \( 11 \leq h < 17 \)
  (c) \( 17 \leq h < 23 \)
  (d) \( 23 \leq h < 35 \)
  (e) \( 35 \leq h \)
Any questions?