ECE 566: Grid Integration of Wind Energy Systems

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Reminders and notifications

1. Homework 4 is assigned
2. Project: Information on team membership and topic is DUE

Power Quality (PQ)

What is power quality? [1]

- Definition?

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- PQ means different things to different entities: utility; manufacturer; and customer

Power Quality (PQ)

What is power quality? [1]

- Definition?
- PQ means different things to different entities: utility; manufacturer; and customer
- It may be defined as the faithfulness of a voltage waveform at the point of common coupling to a perfectly sinusoidal wave oscillating at the given power frequency without interruptions.

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Power Quality

What is power quality? [1]

- *Lack of* power quality is an expensive proposition
- E.g.: compromised supply reliability; malfunctioning equipment; overheating.
- Interface issue
- Any switching in the grid will introduce harmonics, transients, or disruptions to the said voltage waveform
- Accentuated by the proliferation of switching elements interconnected to the grid

Classification of power quality [1]

- Based on magnitude, frequency, and continuity attributes
- Common PQ phenomena:
  1. Transients: impulsive and oscillatory
  2. Long-duration voltage variations: over-voltage, under-voltage, and sustained interruptions
  3. Short-duration voltage variations: swell, sag, and momentary interruptions
  4. Voltage imbalances
  5. Distortions: harmonics, DC offset, interharmonics, notching, and noise
  6. Voltage fluctuations: Flicker
  7. Power frequency variations

Some definitions [1]

Transients

- Transients are the result of a sudden change in the steady state operation conditions of a system that may produce an undesirable and momentary response. Also called *spikes* or *surges*.
- Impulsive transients are sudden, non-power frequency changes in the steady state operation condition (V or I) which is **unidirectional** in polarity and is characterized by very fast rise and decay times [1].
- Oscillatory transients are sudden, non-power frequency changes in the steady state operation condition (V or I) which is **bidirectional** in polarity and is characterized by relatively slower rise and decay times [1].

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Transients [1]

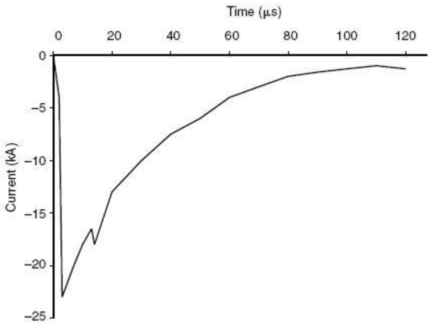

Figure : Impulsive transient following a lightning strike. Figure from [2]

Transients [1]

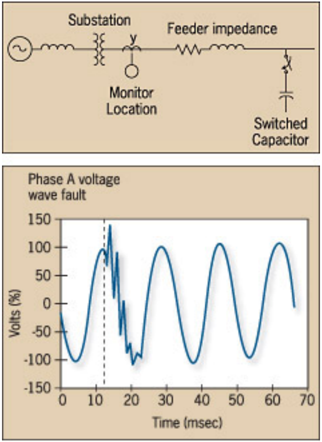

Figure : Oscillatory transient following a cap switching. Figure from [3]

Some definitions [1]

Long-duration voltage variations

- Typically refers to RMS deviations at power frequencies which last for at least 1 minute.
- Over-voltage refers to the increase in $V_{rms} \geq 110\%$ at power freq. for longer than 60 seconds [1].
- Under-voltages refers to the decrease in $V_{rms} \leq 90\%$ at power freq. for longer than 60 seconds [1].

Some definitions [1]

Long-duration voltage variations

- Not caused by faults in the system; rather, caused by load variations and switching operations
- Over-voltages are produced by switching OFF a large load or switching ON a cap bank or incorrect transformer tap settings, especially on weak grids with inadequate voltage regulation controls
- Under-voltages are produced by events opposite to over-voltages causing ones. Colloquially termed **brownout**.

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Some definitions [1]

Long-duration voltage variations

- When a supply voltage magnitude value is fixed at zero for a time that exceeds 60 seconds, that long-duration voltage variation is termed as a **sustained interruption.**
- Such interruptions usually require manual intervention for repair
- Utilities use this for quantifying reliability for reporting purposes
- Metrics include: SAIFI, SAIDI, CAIFI, CAIDI, ASAI

Some definitions [1]

Short-duration voltage variations

- Typically refers to RMS deviations at power frequencies which last for **no more than** 1 minute.
- Designated as *instantaneous*, *momentary*, or *temporary* [1]
- Most usually caused by faults in the system
- Includes sags, swells, and interruptions

Some definitions [1]

Short-duration voltage variations

- Interruptions are events during which the $|V| \leq 10\%$ for no more than 60 seconds
- Caused by system faults, equipment and control failures/malfunctions
- Interruptions may be preceded by a voltage sag due to the causal event (fault). Then, breakers may isolate a part of the system leading to interceptions
- Automatic reclosers are set to operate in 0.5 seconds when the fault is non-permanent
- Interruptions due to control or equipment failure/malfunction may have irregular duration

Momentary interruption [1]

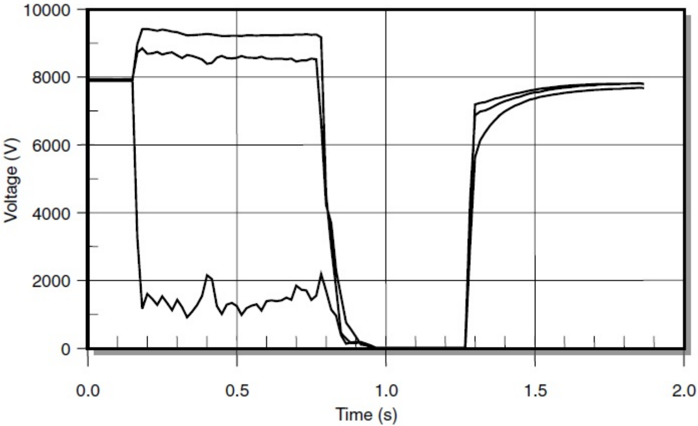

Figure : 3-ϕV_{rms} for momentary interruption due to a fault and recloser action. Figure from [1]

Some definitions [1]

Short-duration voltage variations

- A voltage sag (or dip) is a condition when $.10 \leq V_{rms} \leq .90$ pu
- Causes: system faults; motor starting; energization of heavy loads leading to heavy current draw
- Sags are quantified using CBEMA or ITIC [4]
- Sags lasting less than $\frac{1}{2}$ cycles are classified as *transients*, since it is difficult to measure their RMS
- Sags lasting longer than 60 seconds are grouped under under-voltages, and attributed to causes other than faults

Some definitions [1]

Short-duration voltage variations

- A voltage swell is a condition when $1.10 \leq V_{rms} \leq 1.80$ pu for $0.033 \leq t_{dur} \leq 60$s
- Causes: system faults, typically unsymmetrical
- Swells are quantified using CBEMA or ITIC [4]

Voltage sags [1]

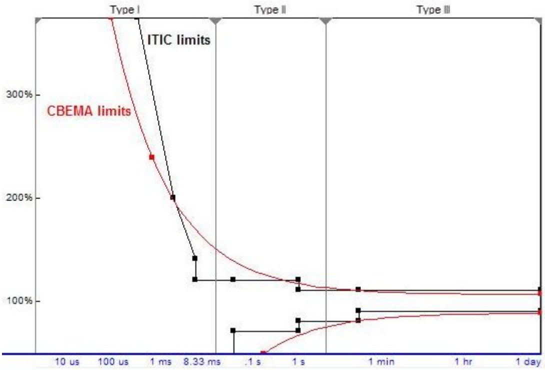

Figure : CBEMA and ITIC curves. Figure from [4]

Some definitions [1]

Voltage unbalance

- Defined as the ratio of the maximum deviation from the average 3ϕ voltage (or current) to the average 3ϕ voltage (or current), expressed in %
- The main source of voltage unbalances ($\leq 2\%$) is 1ϕ loads on a 3ϕ circuit
- Also caused by blown fuses in one phase of the three phases
- Severe imbalance ($\geq 5\%$) is caused by single-phasing conditions, i.e., when one phase of the connecting supply to a 3ϕ motor or transformer is cut-off [5].

Some definitions [1]

Waveform distortions

- DC offset
- Harmonics
- Interharmonics
- Notching
- Noise

Some definitions [1]

Waveform distortions

- DC offset
  - When a DC bias (i.e., average value $\neq = 0$) is present in an AC waveform, a DC offset is said to occur
  - Causes: geomagnetic disturbance or asymmetry of power electronic converters (i.e., $\frac{1}{2}$-wave rectifiers)
  - Can lead to transformer saturation during normal operation
  - Can lead to increased heating and loss of transformer life
  - Can also cause electrolytic erosion of grounding & and other connectors

Some definitions [1]

Waveform distortions

- Harmonics

$$V_{THD} = \frac{\sqrt{(V_2^2 + V_3^2 + V_4^2 + ...)}}{V_1} \quad (1)$$

- Harmonics are sinusoidal components of voltages (or currents) with frequencies that are integer multiples of the power frequency (i.e., V_2 has a frequency of 2×60)
- Presence of harmonics distorts the ideal sinusoid; Can be studied by Fourier decomposition of the time-series
- Caused by inherent non-linearity in the loads, switching devices, etc.
- May impact loads by heating, increased losses, malfunctions, etc.

Voltage waveform distortions [1]

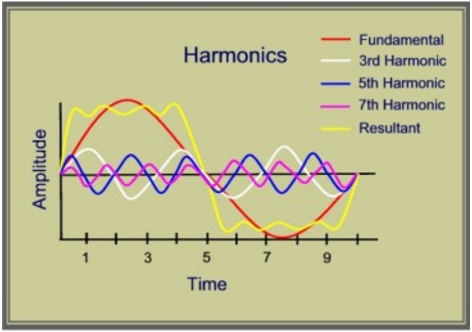

Figure : An FFT based decomposition of a distorted waveform. Figure from [6]

Some definitions [1]

Waveform distortions

- Inter-harmonics
  - Are frequency components of voltages (or currents) with frequencies that are **non-integer** multiples of the power frequency (i.e., $V_2.5$ has a frequency of 2.5×60)
  - Causes: static frequency converters, cyclo-converters, induction furnaces, arcing devices
  - Impacts: can excite severe resonant modes, affect power line carrier signals, & introduce flickering.

Some definitions [1]

Waveform distortions

- Notching
  - Periodic voltage disturbances caused by normal operation of power electronic devices when current is commutated from one phase to another
  - During the current commutation, there is a momentary short circuit between the 2 associated phases. This causes the voltage to drop closer to zero as allowed by the system impedances. This manifests as a *notch*.
  - Due to its continuous nature, it can be characterized through the harmonic spectrum of the affected voltage
  - The associated freq. components can be pretty high and not easily captured by harmonic analysis equipment

Voltage waveform distortions [1]

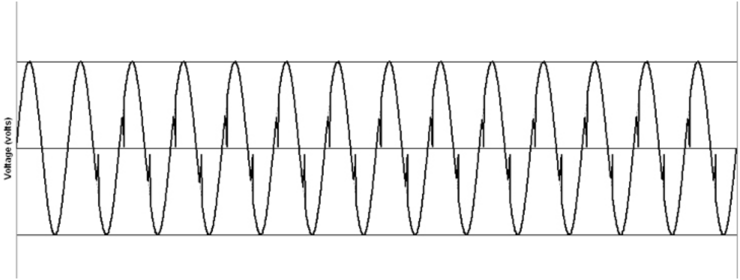

Figure : A waveform distorted by notches. Figure from [7]

Some definitions [1]

Waveform distortions

- Noise
  - When unwanted electrical signals with broadband spectral content lower than 200 kHz distorts the system voltage (or current), then it is called *noise*
  - Cause: power electronic devices, control circuits, arcing eqpt., solid-state rectifiers, switching power supplies, etc.
  - Problem accentuated by improper grounding circuit. This eliminates a safe and easy path for high freq. components to leave the circuit
  - Impact reduced by using filters, isolation transformers, line conditioners, etc.

Some definitions [1]

Voltage fluctuations

- These are systematic variations of the voltage envelope or a series of voltage changes, the magnitude of which does not normally exceed the ranges specified by standards such as the ANSI C84.1 ($.9 \leq |V| \leq 1.1$ pu)
- *Flicker* is a visual manifestation of an electromagnetic phenomenon, i.e., the voltage fluctuation
- Loads can exhibit continuous and rapid variations in the load current magnitudes (i.e., in arc furnaces) that can cause voltage fluctuations
- Flicker exists in the low frequency voltage modulation of the voltage at the system frequency

Voltage fluctuation [1]

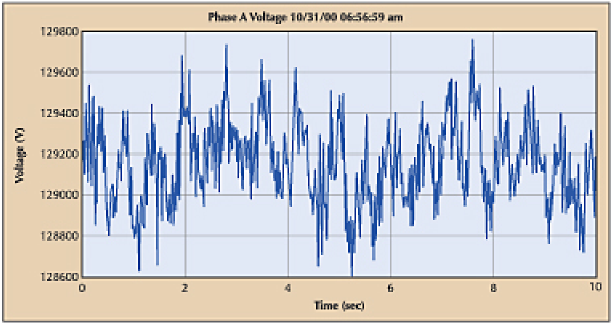

Figure : Voltage fluctuation characteristic of an arc furnace load. Figure from [8]

Some definitions [1]

Voltage fluctuations

- Flicker is measured subjective to the sensitivity of the human eye
- IEC 61000-4-15 is the standard that defines the methods and specifications of instrumentation for measuring flicker
- The measurement method simulates the lamp/eye/brain function and produces a fundamental metric called short-term flicker sensation (Pst)
- Pst is normalized to 1.0 to represent the level of voltage fluctuation required to cause noticeable flicker to 50% of a sample observers

Some definitions [1]

Voltage fluctuations

- Plt is the long-term flicker sensation
- Used for verifying compliance with compatibility limits established by standards bodies and used in utility contracts
- Obtained as an average of Pst samples

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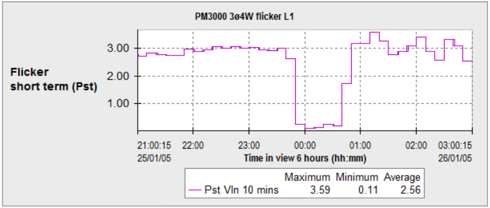
Voltage fluctuation [1]



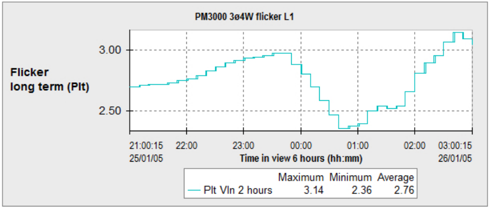


Figure : Pst and Plt plots. Figures from [9]

Some definitions [1]

Power frequency variations

- Defined as the deviation of the power system fundamental frequency from the specified nominal value
- Power system freq. is directly related to the rotational speed of the generators in the system
- Any variation in this value is largely due to imbalances between the demand and supply
- In interconnected systems, the accepted limits for system frequency are tight
- In isolated systems, freq. deviations are expected to be more profound. Here, the governor responses to abrupt load changes may not be adequate to regulate within the tight bandwidth reqd. by freq. sensitive eqpt.

Introduction [10]

The need

- When wind power is injected into the grid, it will alter the power quality
- These changes to PQ must comply with requirements else they may cause loss of supply, $, and comfort
- PQ is an interface issue—hence, wind turbines/farms connecting to grid is where the PQ should be assessed

Introduction [10]

The need

- PQ standards for the grid exist: IEEE 519, etc.
- Wind turbines are not manufactured to site specifications, rather to manufacturer specifications
- Need for consistency in assessment of PQ characteristics of such a challenging set up led to the development of the IEC 61400-21

Introduction [10]

The need

- History of IEC 61400-21 (‘Measurement and assessment of power quality characteristics of grid connected wind turbines’)
    - Work began in 1996
    - First publication in 2001
    - Second (revised) edition including recent experiences, technical needs, and harmonizing with grid codes, was published in 2008
- IEC 61400-21 describes procedures for determining the PQ characteristics of wind turbines
- We will look at the application rather than the procedures themselves in our scope

Introduction [10]

PQ chars. of wind turbines as described by IEC 61400-21

- Rated data
- Emission of voltage fluctuations and flicker
- Emission of current harmonics, *interharmonics, and higher freq. components*
- *Response to voltage dips*
- *Active power capabilities and control*
- *Reactive power capabilities and control*
- Grid protection and reconnection times

PQ chars. of wind turbines as described by IEC 61400-21 [10]

Rated data [11]

Rated data is used for normalizing purposes in IEC 61400-21 [10]

- Active power at the wind turbine terminals, P_n
- Reactive power at the wind turbine terminals, Q_n
- Apparent power at the wind turbine terminals, S_n
- Rated voltage (phase-to-phase) at the wind turbine terminals, U_n
- Rated current at the wind turbine terminals, I_n

PQ chars. of wind turbines as described by IEC 61400-21 [10]

Emission of voltage fluctuations and flicker

- Flicker is the visual manifestation of voltage fluctuations
- This can be measured using a flickermeter
- Input to this instrument is the voltage; output is the severity of the flicker (i.e., Pst)
- So long as a $Pst < 1.0$, customers are generally frustrated/affected
- Since voltage fluctuations are caused by changes in load or generation, wind turbines are especially credited with causing them
- IEC 61400-21 differentiates between continuous and switching operations for flicker quantification

PQ chars. of wind turbines as described by IEC 61400-21 [10]

Emission of voltage fluctuations and flicker

- Continuous operation—Flicker coefficient
- Flicker coefft. is a normalized measure of the max. flicker emitted (99 percentile) from a wind turbine in continuous operation

$$c(\psi_k, \nu_k) = Pst \times \frac{S_k}{S_n} \tag{2}$$

ψ_k is network impedance phase angle
ν_k is the annual wind speed average
Pst is the flicker emission from the wind turbine
S_k is the short crkt. apparent power of grid

PQ chars. of wind turbines as described by IEC 61400-21 [10]

Emission of voltage fluctuations and flicker

- Continuous operation—Flicker coefficient
- Flicker coefft. of a wind turbine is given as the 99 percentile for specified values of:
- $\psi_k = \{30^\circ, 50^\circ, 70^\circ, 85^\circ\}$ and
- $\nu_k = \{6, 7.5, 8.5, 10\}$ m/s
- Variable speed machines are commonly expected to have lower flicker coefficients
- Fixed-speed machines may have high value (pitch controlled) to average values (stall controlled).

PQ chars. of wind turbines as described by IEC 61400-21 [10]

Emission of voltage fluctuations and flicker

- Switching operation
  - Some switching events that may cause voltage fluctuations:
  - turbine start-up at cut-in speed
  - Turbine start-up at rated speed
  - Pole switching in fixed-speed generators
- Acceptance depends on:
  - grid voltage
  - number of times of occurrences: max. number of switching operations within a 10 minute period (N_{10}) and a 2 hour period (N_{120}) must be specified.
  - N_{10} and N_{120} depend on control system settings

PQ chars. of wind turbines as described by IEC 61400-21 [10]

Emission of voltage fluctuations and flicker

- Switching operation—Flicker step factor
- Flicker step factor is a normalized measure of the flicker emitted due to a single switching operation of a wind turbine

$$k_f(\psi_k) = \frac{1}{130} \times \frac{S_k}{S_n} \times Pst \times T_p^{1.31} \tag{3}$$

$k_f(\psi_k)$ is the flicker step factor
T_p is the duration of the voltage fluctuation

PQ chars. of wind turbines as described by IEC 61400-21 [10]

Emission of voltage fluctuations and flicker

- Switching operation—Flicker step factor
- Flicker step factor of a wind turbine is given for specified values of:
- $\psi_k = \{30°, 50°, 70°, 85°\}$ and for specified switching actions
- Variable speed machines are commonly expected to have lower flicker step factor
- Fixed-speed machines may have average value (pitch controlled) to high values (stall controlled).

PQ chars. of wind turbines as described by IEC 61400-21 [10]

Emission of voltage fluctuations and flicker

- Switching operation—Voltage change factor
- Voltage change factor is a normalized measure of the voltage change due to a single switching operation of a wind turbine

$$k_u(\psi_k) = \sqrt{3} \times \frac{S_k}{S_n} \times \frac{U_{max} - U_{min}}{U_n} \quad (4)$$

$k_u(\psi_k)$ is the voltage change factor
U_{max} & U_{min} are the max. & min. RMS (phase-to-neutral) voltages due to switching

PQ chars. of wind turbines as described by IEC 61400-21 [10]

Emission of voltage fluctuations and flicker

- Switching operation—Voltage change factor
- Voltage change factor of a wind turbine is given for specified values of:
- $\psi_k = \{30^\circ, 50^\circ, 70^\circ, 85^\circ\}$ and for specified switching actions
- Variable speed machines are commonly expected to have lower flicker step factor
- Fixed-speed machines may have average value (pitch controlled) to high values (stall controlled)
- $max(k_u) = k_i$, where k_i is the ratio between the max. inrush current and the rated current

PQ chars. of wind turbines as described by IEC 61400-21 [10]

Current harmonics, interharmonics, and higher freq. components

- These are to be stated for the operation of a wind turbine within the active power bins of $P_n = \{0, 10, 20, ..., 90, 100\}\%$
- THD (current) is derived from the individual harmonics

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PQ chars. of wind turbines as described by IEC 61400-21 [10]

Current harmonics, interharmonics, and higher freq. components

- Interharmonics are specified up to 2kHz according to Annex-A of IEC 61000-4-7,2002
- Higher freq. comp. specified for $2 \leq f \leq 9$kHz according to Annex-B of IEC 61000-4-7,2002
- All freq. comp. for stated for wind turbine operating at zero reactive power draw/injection
- IEC 61400-21 does not require specification of harmonics at start-up or switching operations

PQ chars. of wind turbines as described by IEC 61400-21 [10]

Response to voltage dips

- Voltage dips or sags are due to faults in the system and modern turbines are required to stay online to ride through the fault (LVRT, ZVRT requirement)
- IEC 61400-21 requires wind turbines to be tested to withstand certain sags stating the response by the time-series of the following:
  - P_n
  - Q_n
  - U_n
  - I_n

PQ chars. of wind turbines as described by IEC 61400-21 [10]

Response to voltage dips

- Tests are carried out for the turbines operating at low ($0.1P_n - -0.3P_n$) and high power ($0.9P_n$) outputs
- Tests include symmetrical 3ϕ sags at $\{0.9, 0.5, 0.2\}$ pu voltage with duration of $\{0.5, 0.5, 0.2\}$ s respectively
- Same holds true for two-phase sags
- Test verifies response of wind turbine to voltage sag

PQ chars. of wind turbines as described by IEC 61400-21 [10]

Active power capabilities and control

- IEC 61400-21 considers max. measured power, ramp rate limits, and set-point control
- Max. measured power is stated for $\{P_{600}, P_{60}, P_{0.2}\}$, measured as a $\{600, 60, 0.2\}$s average respectively
- These are relevant data for load-flow studies and protection setting studies
- Variable speed turbines may typically provide for $P_{0.2} = P_{60} = P_{600} = P_n$, whereas
- In fixed-speed turbines (stall or pitch controlled) $P_{0.2} > P_n$

PQ chars. of wind turbines as described by IEC 61400-21 [10]

Active power capabilities and control

- Ability of wind turbine to operate in ramp rate limitation mode or set-point mode is germane to situations in grids with high penetration of wind energy
- This ability is verified by two 10min test periods showing the time-series of the available and measured $P_{0.2}$ output
- Test on ramp rate limit is conducted for operation at a ramp rate of 10% or P_{rated} per minute
- Test on set-point control is conducted for operation adjustments from 100% to 20% of P_{rated} with 2min operation at each set-point

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PQ chars. of wind turbines as described by IEC 61400-21 [10]

Reactive power capabilities and control

- Reactive power is tested as the maximum 1min average inductive and capacitive Q of the wind turbine for $\{0, 10, 20, ...90, 100\}$% of rated active power output
- Ability to control Q is verified by two tests:
  - Allowing the reactive power set-point to zero and the measuring the 1min average reactive power for $\{0, 10, 20, ...90, 100\}$% of rated
  - Operating at about 50% of rated power, the reactive set-point is to be changed from 0 to maximum capacitive value and after 2min to its maximum inductive value, and the measured $P_{0.2}$ shall be known

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PQ chars. of wind turbines as described by IEC 61400-21 [10]

Grid protection and reconnection times

- IEC 61400-21 requires the functionality of grid protection to be verified by testing
- Actual disconnection levels and times are determined for over-voltages (frequencies) and under-voltages (frequencies)
- Reconnection time after disconnection of the turbine due to grid failure shall be state for cases where the grid has failed for $\{10, 60, 600\}$s
- Reconnection time is the time from the instant when the grid service is available again to the instant when the turbine start producing power.

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