International
ESBI Energy Innovation

Harmonic Design Considerations for Wind Farms

To Ensure Grid Code Compliance

Liam Breathnach
Power System Studies Group
ESB International

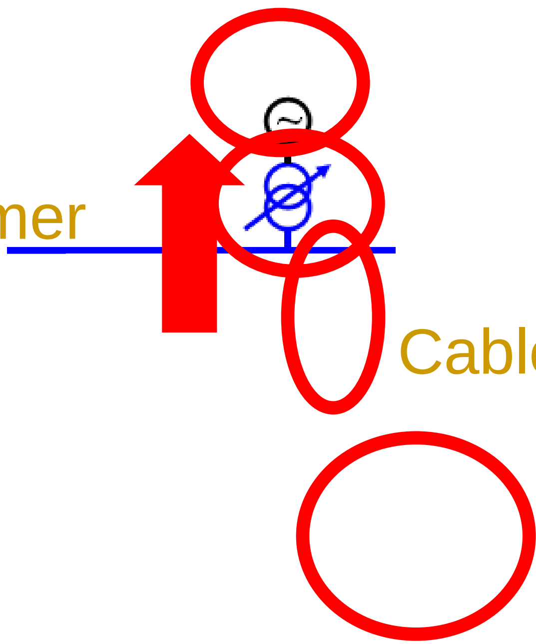
Agenda

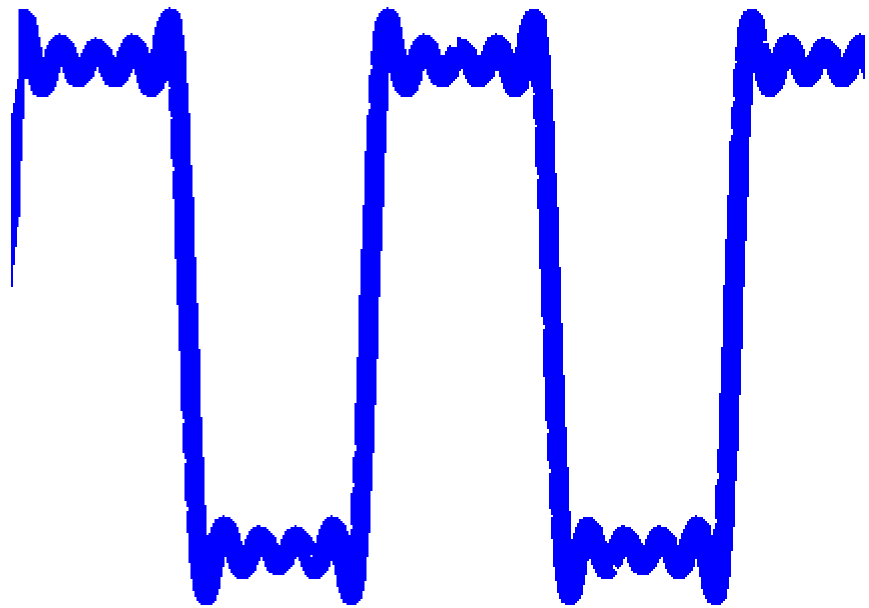
- Introduction
- Harmonic Theory and Concepts
- Grid Code Requirements
- Modelling and Simulation
- Case Studies
- Mitigation Measures

Introduction

- AC Power systems
  - sinusoidal voltages / currents
- Non-linear devices
  - Power electronic equipment
  - Saturable devices
- May cause distortion
- Unwanted effects on equipment and system

Introduction



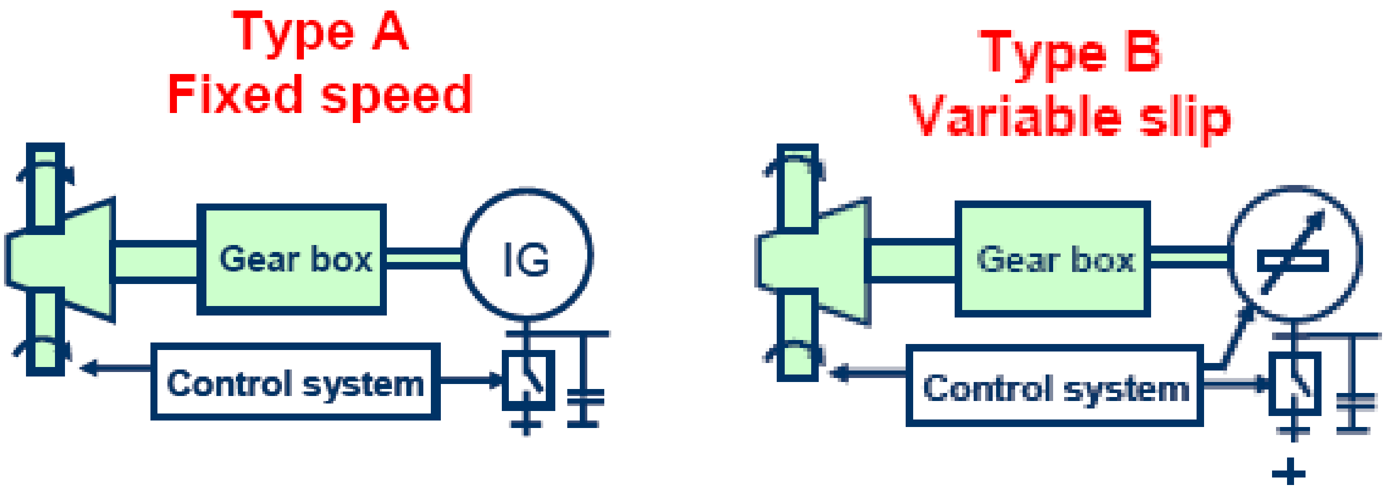


Introduction

Examples of Unwanted Effects:

- Conductors
  - Increased losses
- Transformer
  - Increased losses and excessive heating
- Circuit Breakers
  - Nuisance tripping
- Capacitors
  - Permanent failure

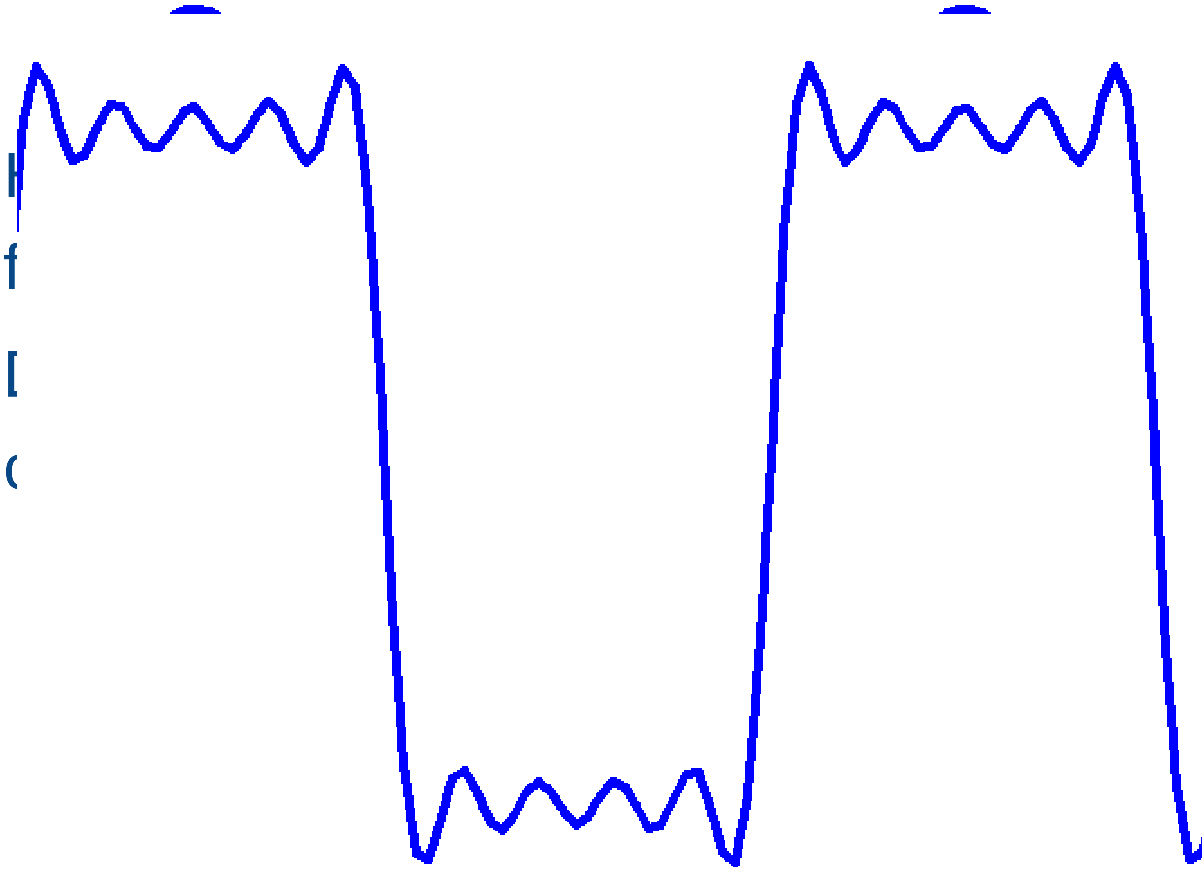
Introduction



- Squirrel Cage Induction Generator
- Doubly Fed Induction Generator
  - No harmonics
  - Harmonic currents
- Synchronous / Induction generator with Full Converter
- Induction generator with Variable resistance
  - No harmonics
  - Harmonic currents

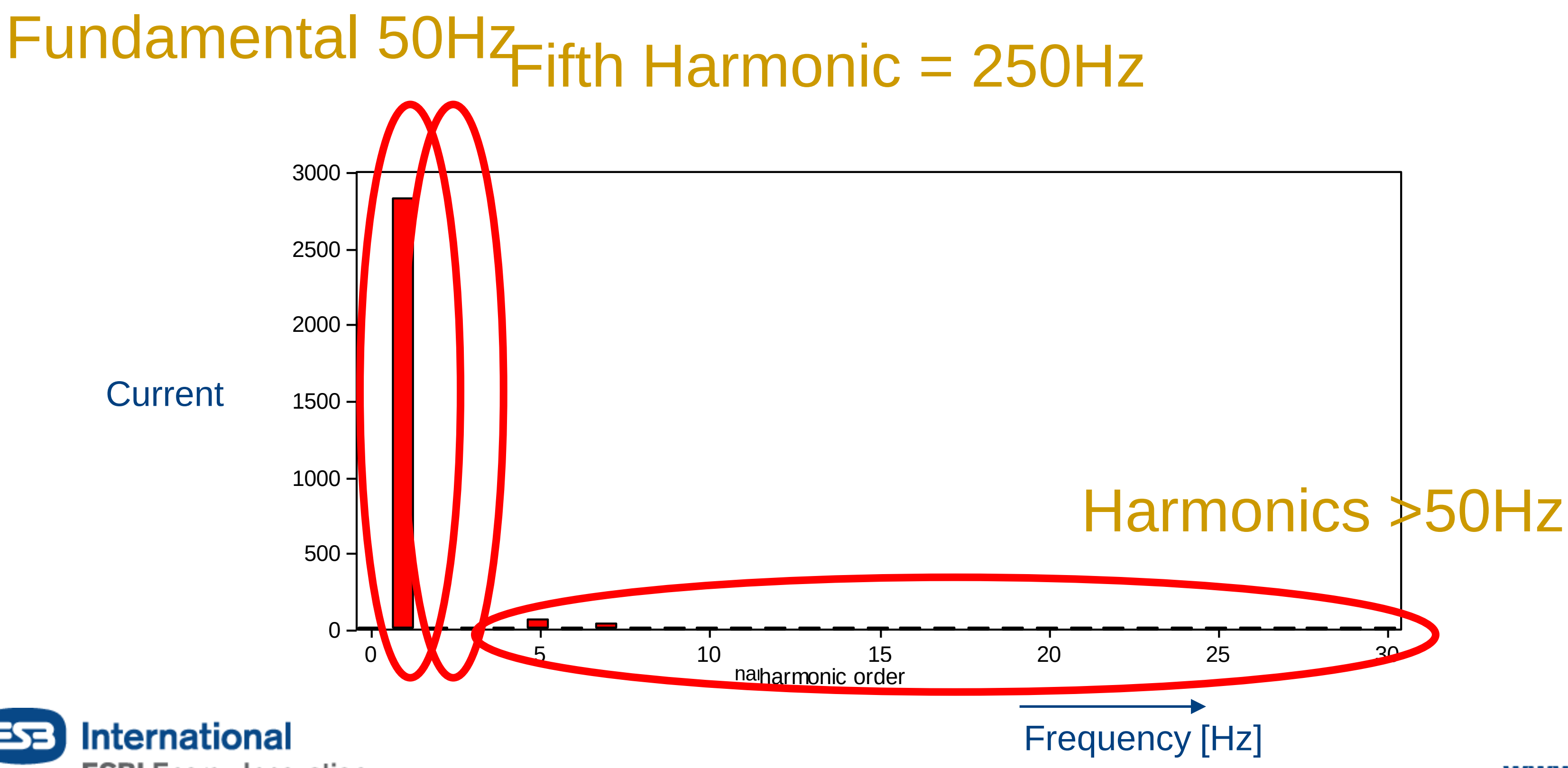
Harmonic Theory and Concepts

- H... nental f...
- D... erms of it's c...



Harmonic Theory and Concepts

- Harmonic currents produced by a wind turbine



Harmonic Theory and Concepts

- Voltage Distortion:

System Impedance

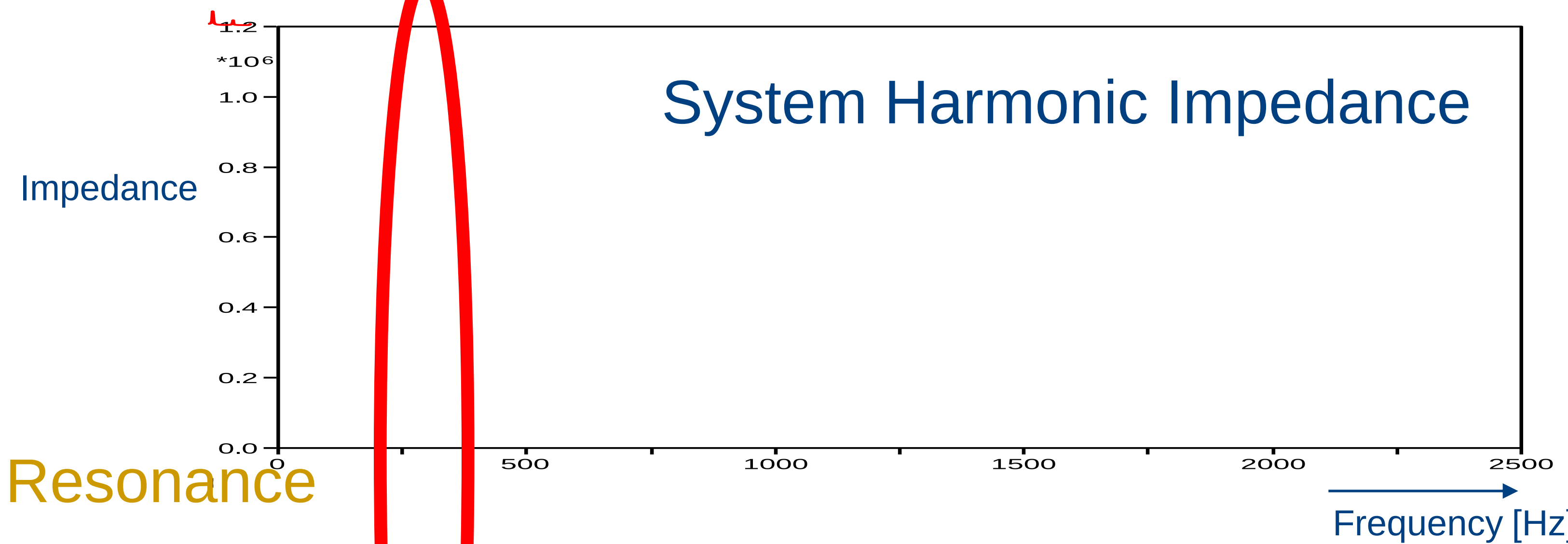
$$Vh = Zh * Ih$$

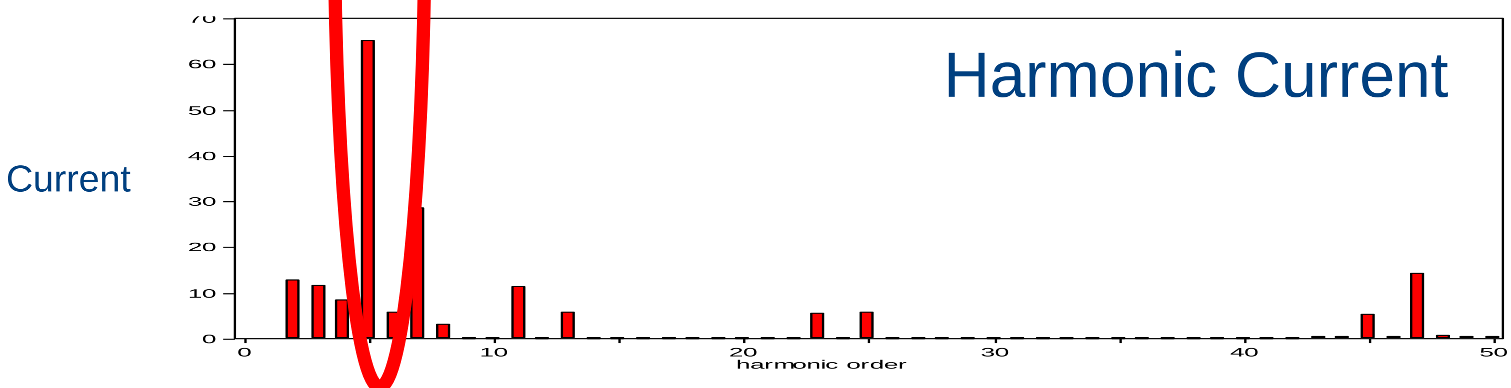
- Impedances varies with frequency

$$X_L = 2\pi f L \qquad X_C = \frac{1}{2\pi f C}$$

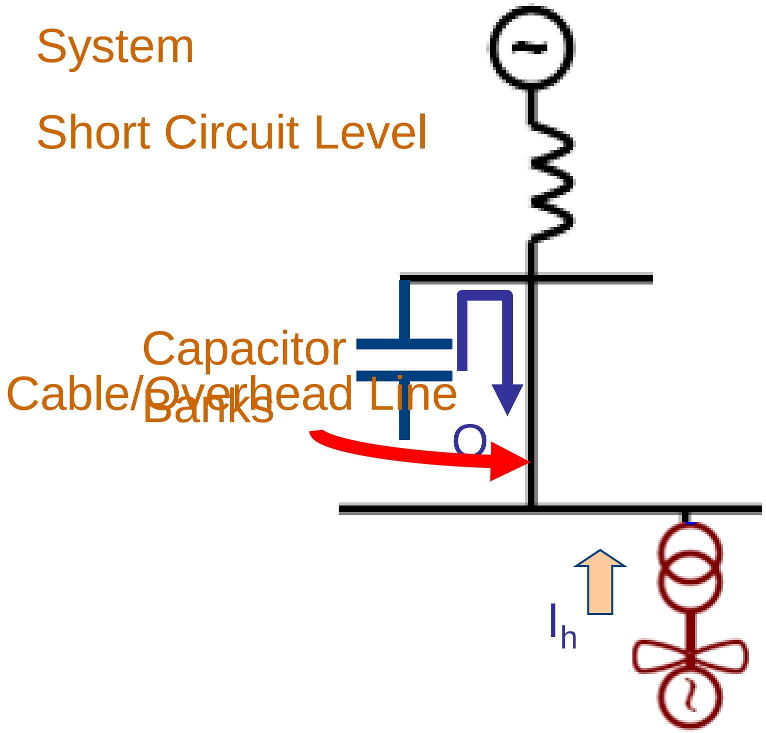
- May result in harmonic voltages
- Total Harmonic Distortion (THD)

Harmonic Theory and Concepts





Harmonic Theory and Concepts



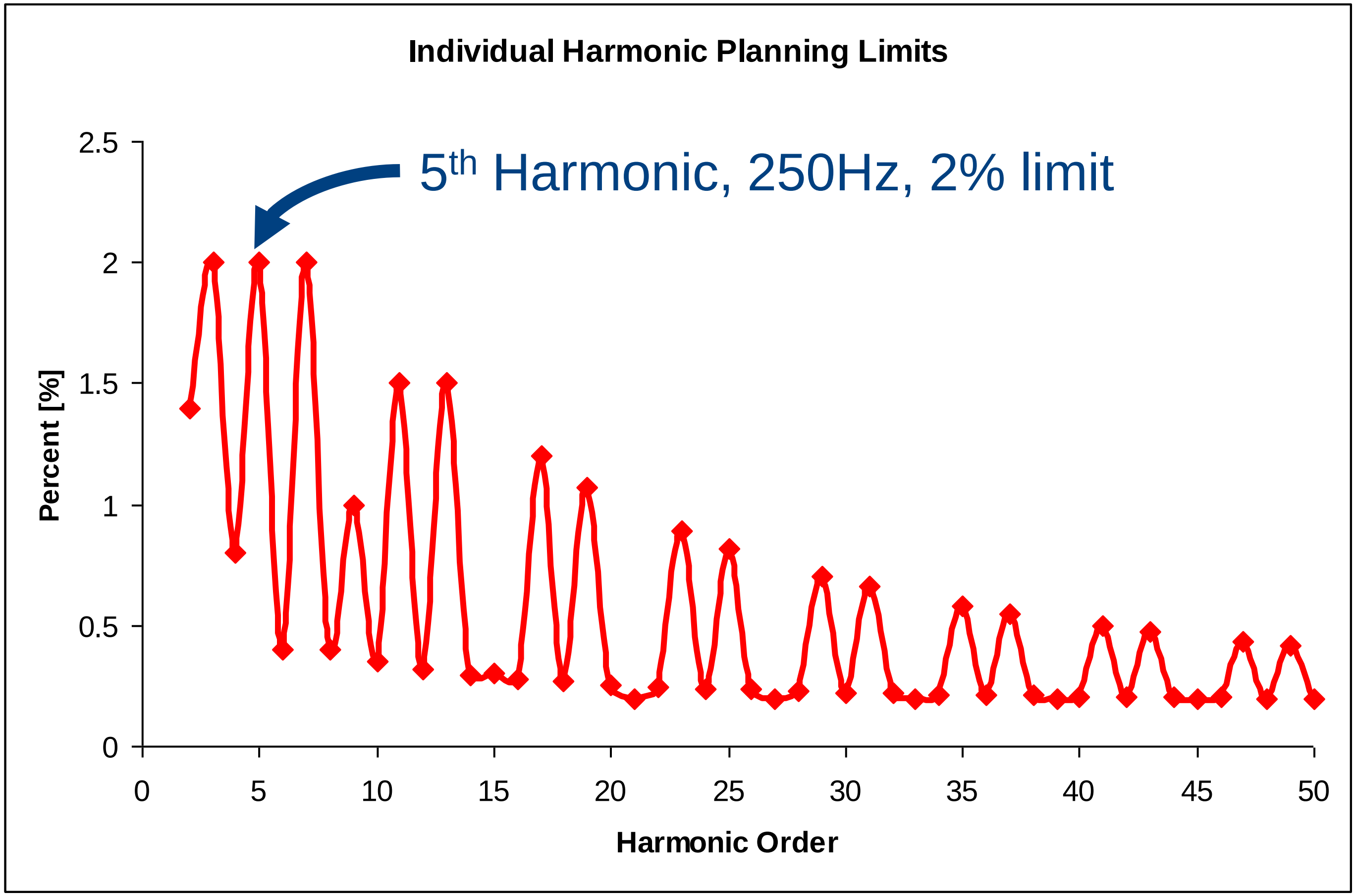
System Harmonic Impedance affected by:

- Short Circuit Level
- Capacitor banks
  - lower the resonant frequencies
- Connection
  - Cable/ Overhead Line
- Transformers/ Reactors

Grid Code Requirements

- Distortion limits outlined in IEC 61000-3-6
- High Voltage THD planning level is 3%
- Limits for individual harmonic magnitudes

Grid Code Requirements



Modelling & Simulation

- Build model
  - Represent harmonic source
  - Wind Test Report (IEC 614(
- Frequency scan analysis
  - Identify potential resonance
- Processing techniques
  - individual harmonic distortic
  - THD

WINDTEST
[redacted]

Laboratory accredited by DAP Deutsches Akkreditierungssystem Prüfwesen according to DIN EN ISO/IEC 17025. This accreditation is valid for the test and measurement procedures given in the certificate.
DAP-PL-1556.00

Excerpt of the test report
"Measurement of the electrical characteristics acc. to IEC61400-21 with regard to utility interconnection of the [redacted]

Report No.: [redacted]
Page 2 of 2

Switching operations:

Case of switching operation	Start-up at cut-in wind speed			
Max. number of switching operations, N_{10}	1			
Max. number of switching operations, N_{120}	6			
Grid impedance angle	30°	50°	70°	85°
Flicker step factor, $k_f(\psi_k)$	0.05	0.06	0.07	0.07
Voltage step factor, $k_u(\psi_k)$	0.17	0.21	0.27	0.31

Case of switching operation	Start-up at rated wind speed			
Max. number of switching operations, N_{10}	1			
Max. number of switching operations, N_{120}	1			
Grid impedance angle	30°	50°	70°	85°
Flicker step factor, $k_f(\psi_k)$	0.09	0.08	0.06	0.06
Voltage step factor, $k_u(\psi_k)$	0.82	0.58	0.29	0.19

Harmonics:

Order	Output power	Harmonic current	Order	Output power	Harmonic current	Order	Output power	Harmonic current
	[kW]	[% from I_n]		[kW]	[% from I_n]		[kW]	[% from I_n]
2	73	0.4	13	988.2	0.2			
3	1306.9	0.4	23	1867.3	0.2			
4	135.1	0.3	25	2318.3	0.2			
5	2134.1	2.3	45	618.7	0.2			
6	425	0.2	47	214	0.5			
7	42.8	1.0						
8	2189.1	0.1						
11	1588.4	0.4						

Maximum THD [% from rated current]	2.42
Power at maximum THD [kW]	2134.05

Exceptional details:

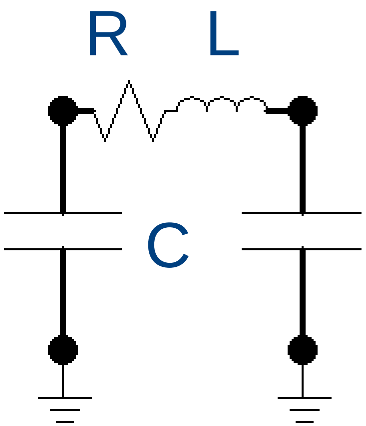
[1]Reactive power at p_{max} has been estimated with the existing data of reactive power (10-min-maximum-average-values), because no values at P_{max} have been recorded.

This report is only valid in conjunction with the report [redacted]

[redacted]

Modelling & Simulation

- Loads not producing harmonics
  - Damping
- Phase angles of sources
- Transformer connections
- Modelling of lines and cables
  - PI equivalent model (multiple sections)
- System representation
  - How far back?
  - Capacitor banks
- Short circuit capacity



Case Studies – Short Circuit Capacity

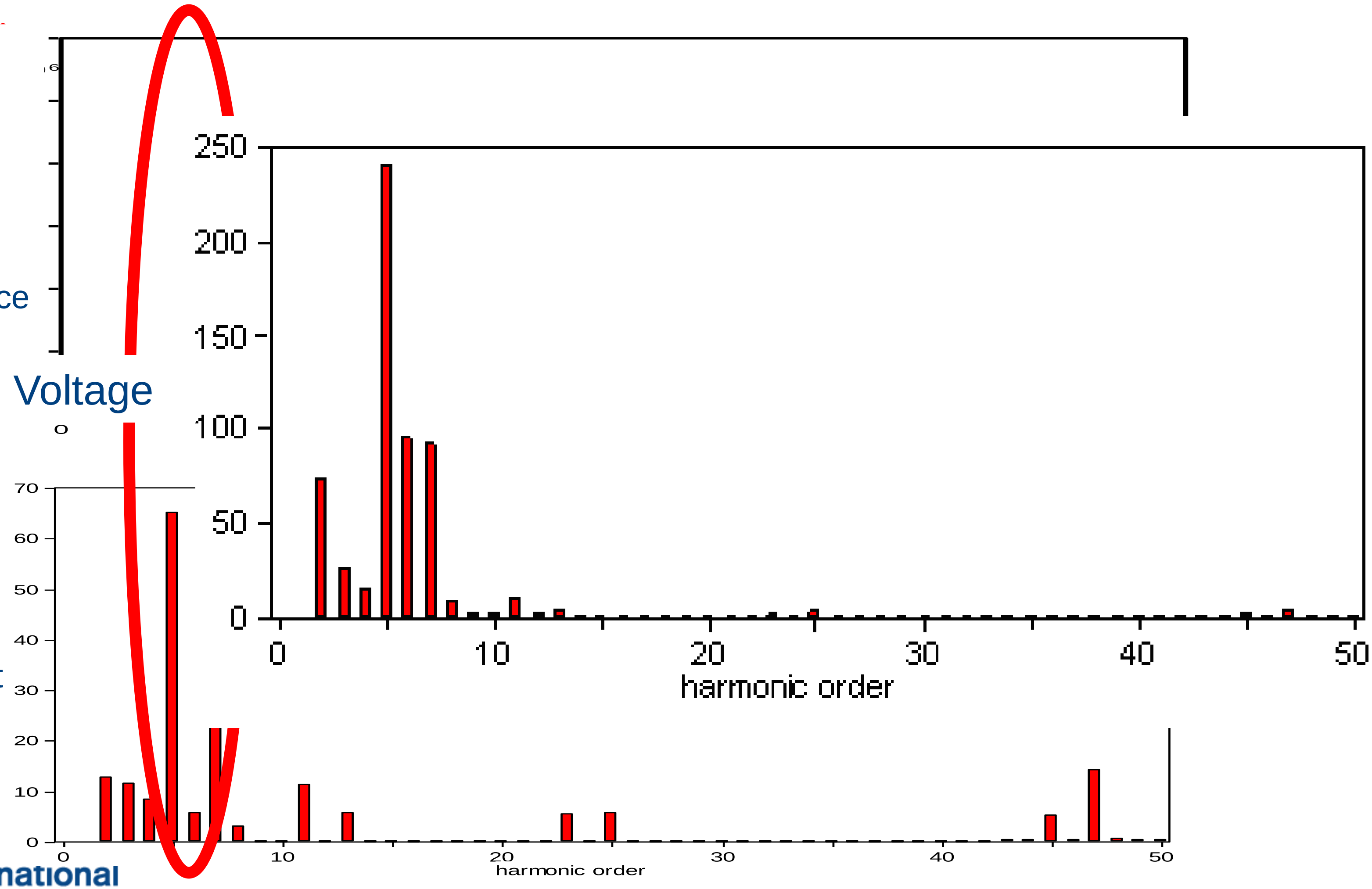
- High Short Circuit Level
  - Typically lower harmonics
- Lower Short Circuit Level
  - Weaker system
  - More pronounced resonance peaks

Case Studies - Cable vs Overhead Line

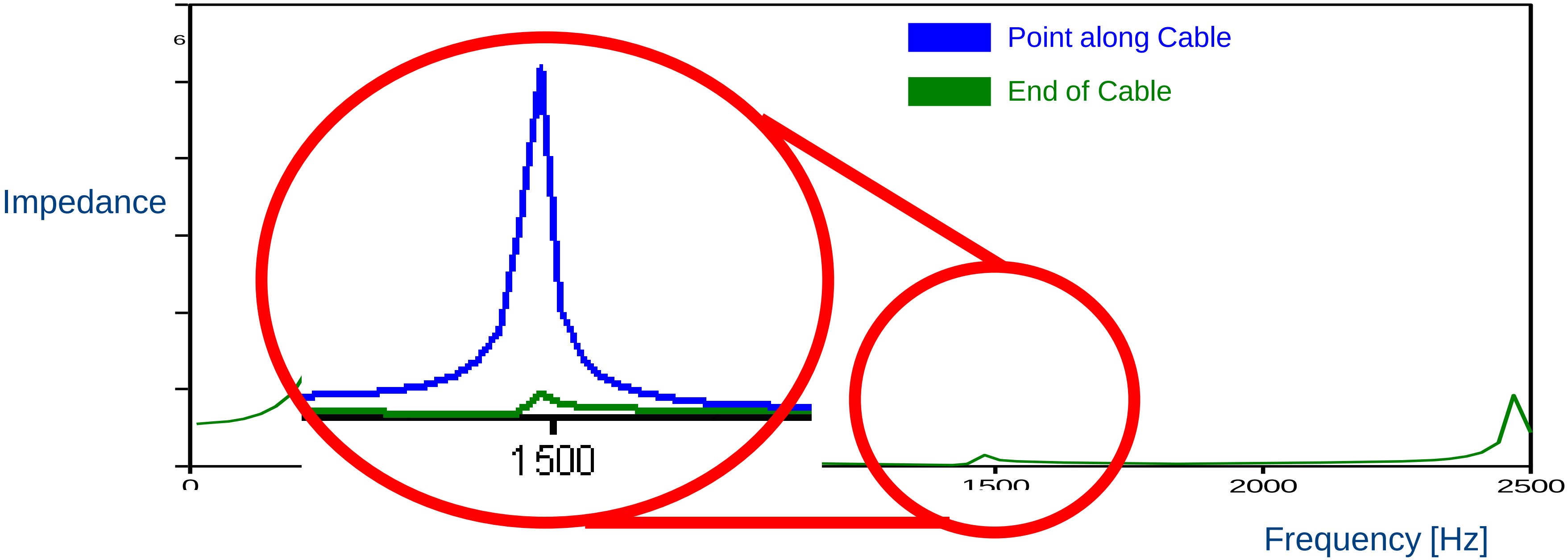
Impedance

Voltage

Current



Case Studies – Distance Along Cable

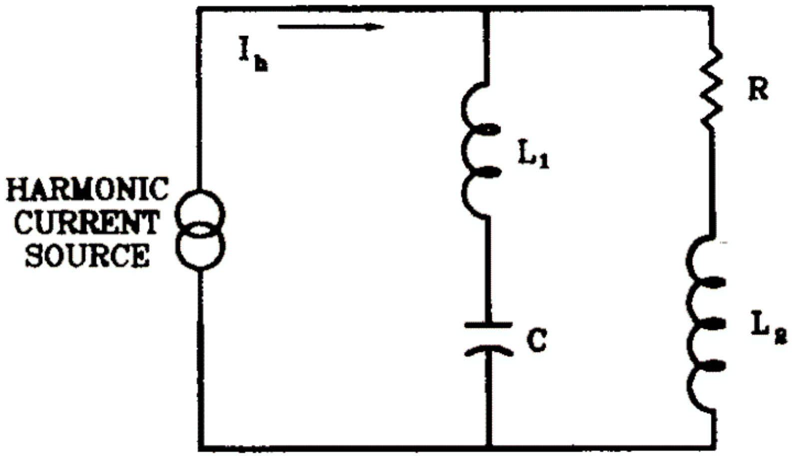


- Cable capacitance distributed along its length
- Point to connection important

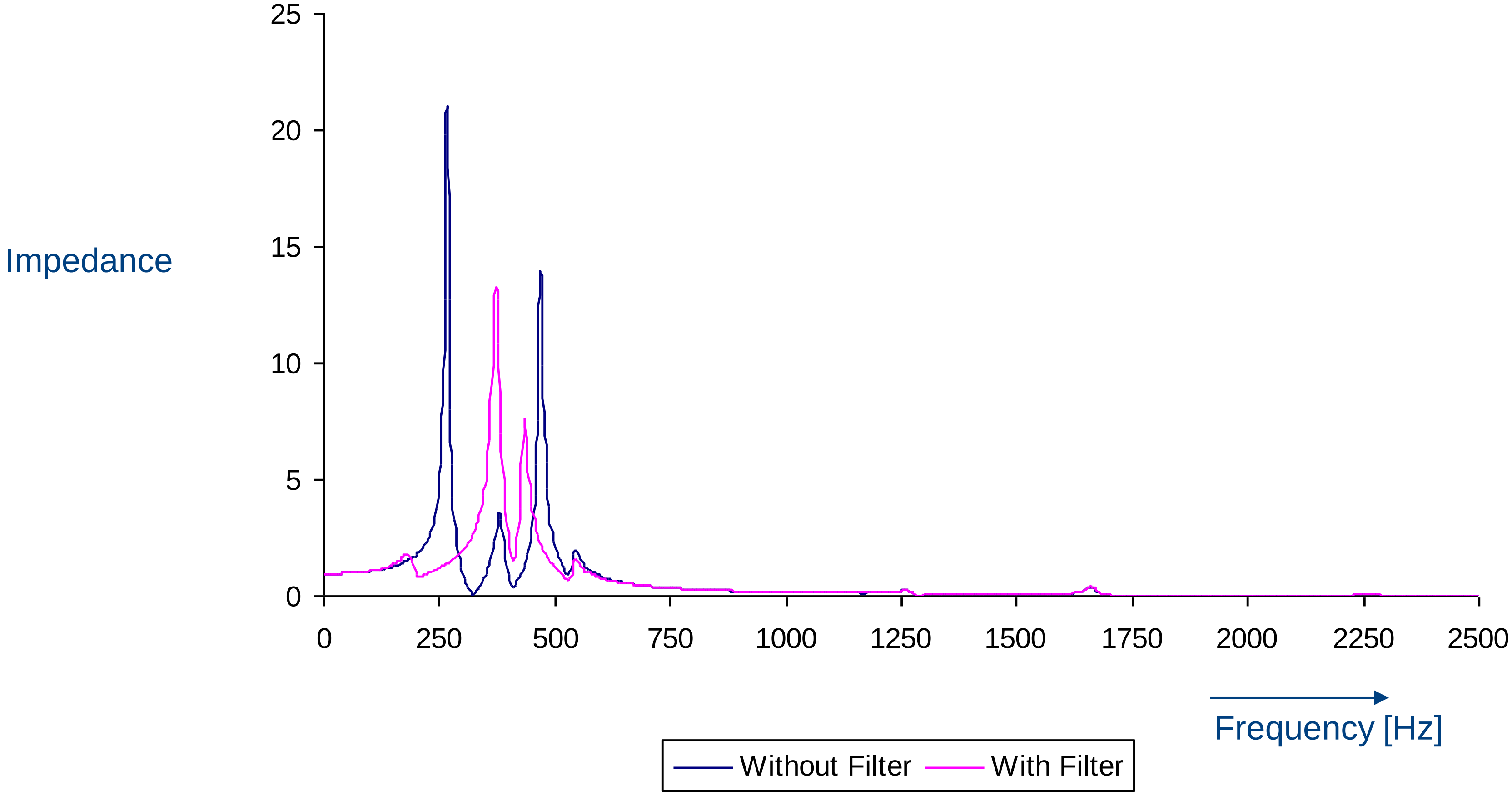
Harmonic Mitigation

- Active Filters
  - Mitigate multiple harmonics
  - Complex and costly

- Passive Filters
  - Simple and reliable
  - Relatively inexpensive
  - Cannot mitigate multiple harmonics



Harmonic Mitigation



Summary

- Wind turbines may be source of harmonics
- May interact with system impedance
- Resulting distortion may:
  - Damage equipment
  - Increase losses
- Mitigation measures
  - May prove costly
- Identify potential issues early