PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

Poul Sørensen & Behnam Nouri

Test and validation of multifrequency models

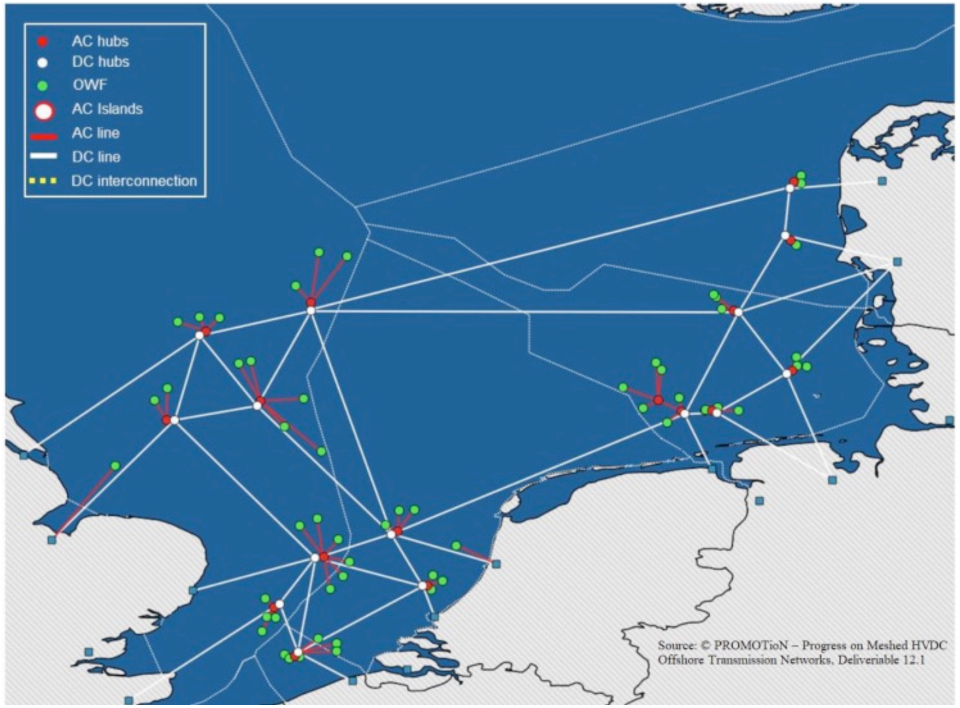
Outline

- EU PROMOTioN
  - The project DNA
  - The harmonization and standardization work package

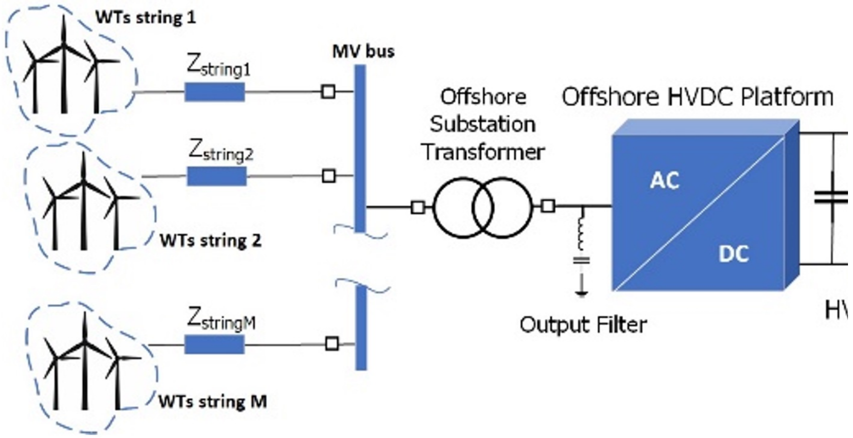
- Multifrequency PhD
  - Challenges
  - Frequency and sequence couplings
  - Empirical type 4 wind turbine and PV inverter model
  - Type 3 wind turbines rotor speed dependency
  - Extended empirical model (incl type 3)

PROMOTioN scope

- Meshed HVDC in the North Sea



- Connection of offshore wind power plants



PROMOTioN partners

TSOs

TenneT – Taking power further
Rte
SVENSKA KRAFTNÄT
sse
EIRGRID
ENERGINET.DK

Consultants

DNV·GL
TRACTEBEL Engineering GDF SUEZ
DEUTSCHE WINDGUARD

Academia

DTU
TU Delft
RWTH AACHEN UNIVERSITY
KTH VETENSKAP OCH KONST
University of Strathclyde
UNIVERSITAT POLITÈCNICA DE VALÈNCIA
rijksuniversiteit groningen
European University Institute
KU LEUVEN
1495 UNIVERSITY OF ABERDEEN

Vendors

ABB
SIEMENS
MITSUBISHI ELECTRIC
GE
MHI VESTAS OFFSHORE WIND
SCiBreak Enabling the Supergrid
Prysmian Group

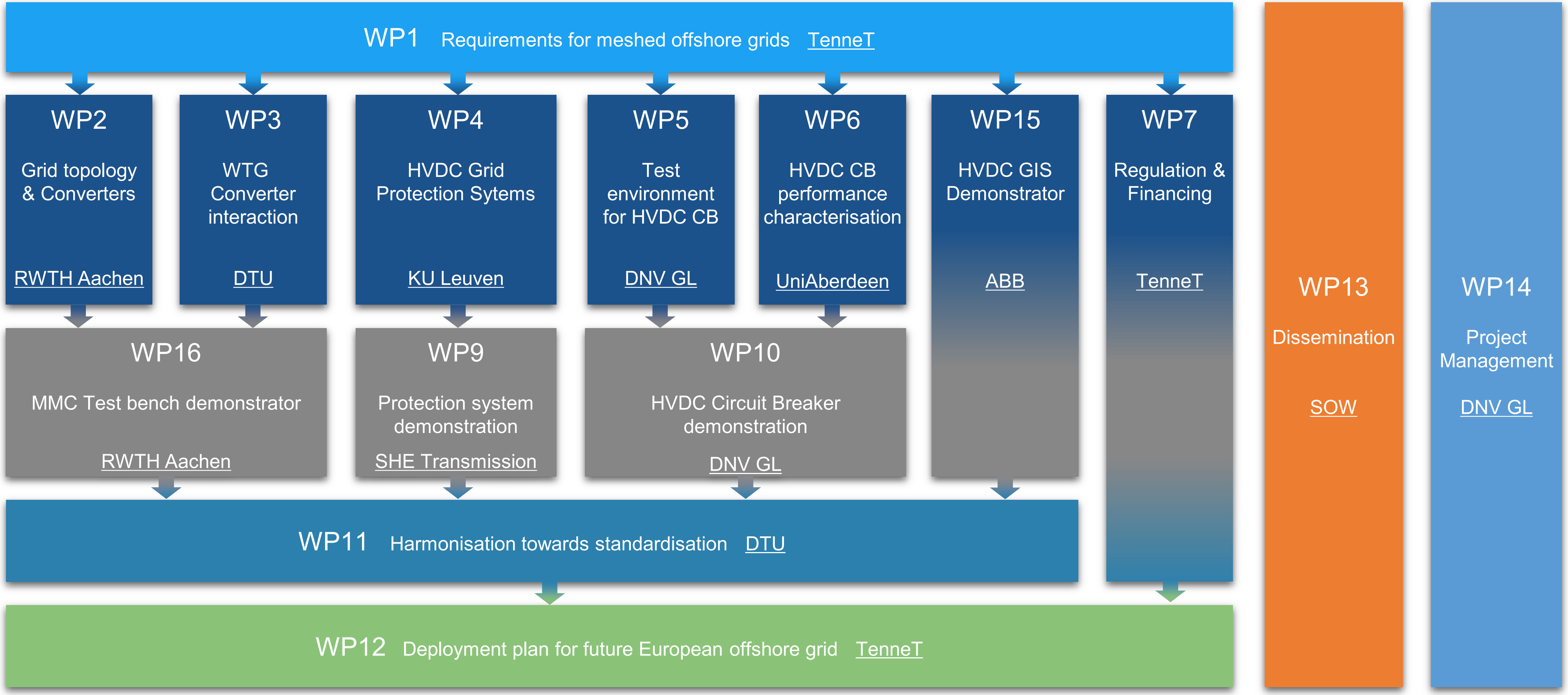
Developers

Ørsted
equinor

Other stakeholders

STIFTUNG OFFSHORE WINDENERGIE
FGH
T&D europe
CARBON TRUST
SuperGrid Institute

PROMOTioN work packages



Standardization WP11 partners

WP11

11.1 Coordination of harmonization activities

11.2 Contributions to harmonization of HVDC systems

11.3 Contribution to harmonization of wind power plants connected to HVDC systems

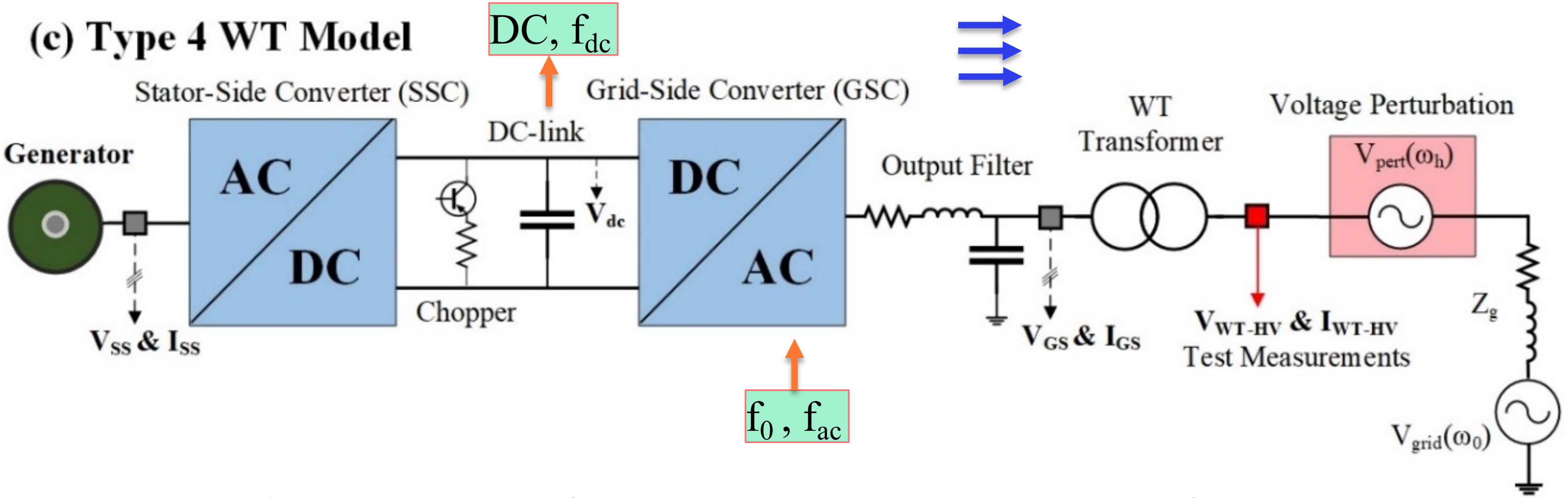
11.4 Harmonization of grid codes and compliance evaluation

Multifrequency modelling – Behnam Nouri's PhD

- Challenges:
  - Converters' design and control details are required in analytical models
  - Existing models are averaged and linearized
  - Frequency and sequence couplings are not addressed fully
  - The models need to be validated properly
  - System-level applications are under development

- This PhD Thesis:
  - Proposes an **empirical multi-frequency modelling and model validation** methods to solve/ eliminate/ facilitate these challenges!
  - The focus is on modelling of **a single** converter-based renewable generator (wind turbine or PV system with converter).

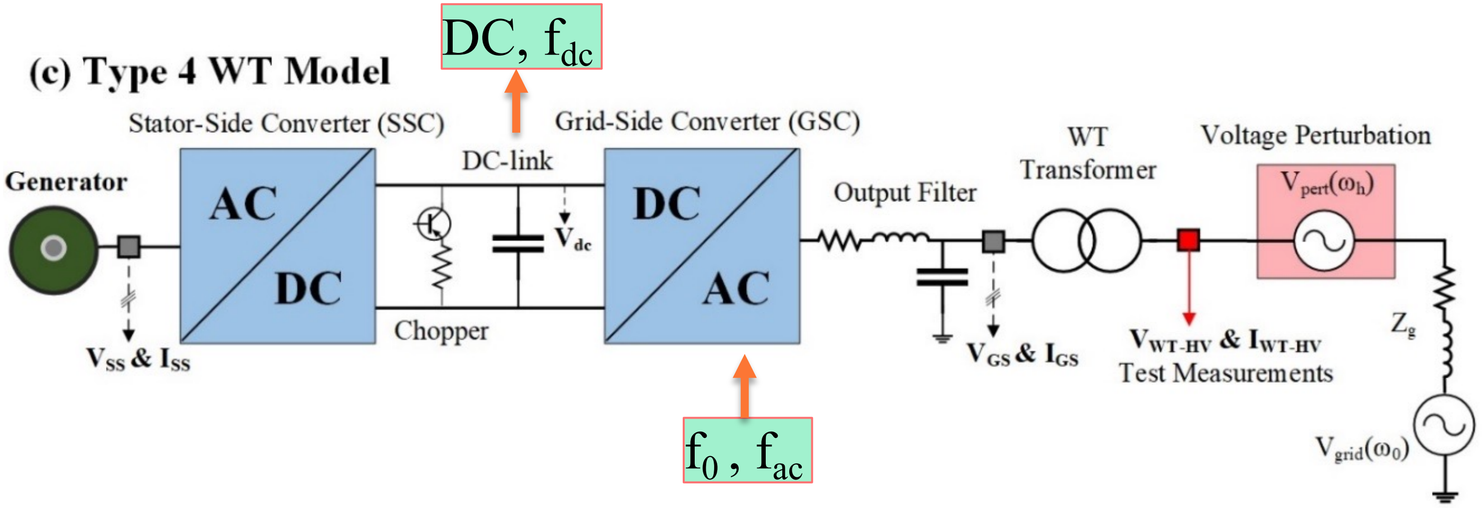
Frequency coupling from PWM (from literature)

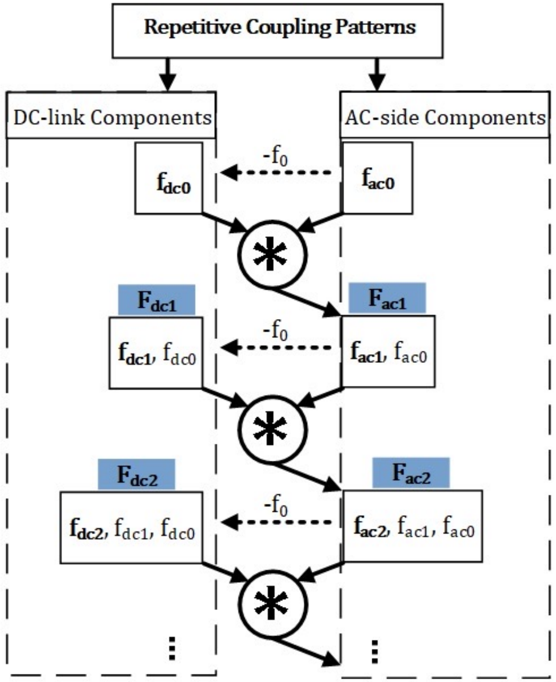


$$(DC, f_{dc}) \circledast (f_0, f_{ac}) = \{f_0, f_{dc}, f_{ac}, f_{ac} \pm f_{dc}, f_0 \pm f_{dc}\}$$

M. Bakhshizadeh, and et al., "Couplings in phase domain impedance modelling of grid-connected converters," IEEE Transactions on Power Electronics, vol. 31, no. 10, pp. 6792–6796, Oct. 2016.

Repetitive frequency coupling (PhD contribution)

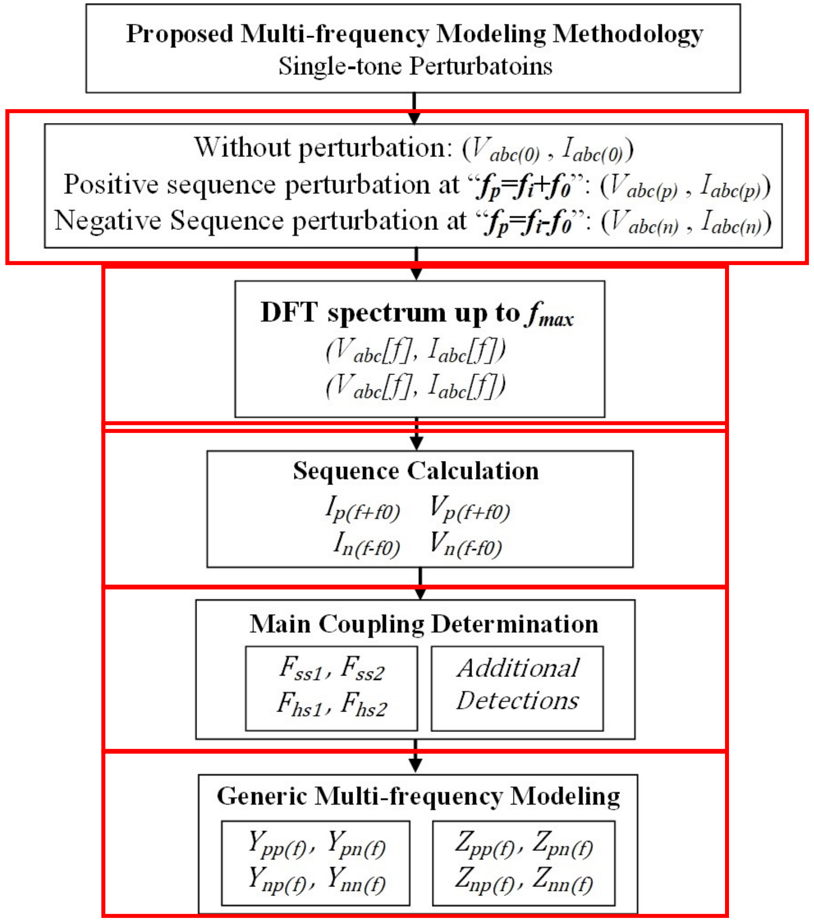




$Single\ coupling\ form\colon\ (f_i, f_i \pm \boldsymbol{k} f_0), k = 1,2,3, \ldots$

$Repetive\ couplings\ form\colon\ (f_i, \boldsymbol{m} f_i \pm \boldsymbol{k} f_0), k = 0,1,2,3, \ldots, m = 0,1,2,3, \ldots$

Generic empirical modelling – type 4



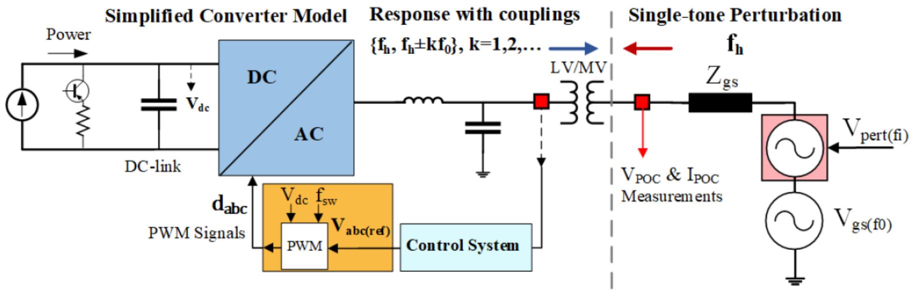


Figure 3.1: Typical example of a grid-connected converter and state-of-the-art form of couplings in response to a single perturbation.

Couplings form: $(f_i, \boldsymbol{m} f_i \pm \boldsymbol{k} f_0),\ k = 0,1,2,3,\ldots,\ m = 0,1,2,3,\ldots$

$$\begin{bmatrix} I_p^1 \\ I_p^2 \\ \vdots \\ I_p^k \end{bmatrix} = \begin{bmatrix} I_{p0}^1 \\ I_{p0}^2 \\ \vdots \\ I_{p0}^k \end{bmatrix} + \begin{bmatrix} Y_{pp}^1 & Y_{2p}^{1\,2} & \ldots & Y_{ip}^{1k} \\ Y_{1p}^{2\,1} & Y_{pp}^2 & \ldots & Y_{ip}^{2k} \\ \vdots & \vdots & \ldots & \vdots \\ Y_{kp}^{k\,1} & Y_{ip}^{k2} & \ldots & Y_{pp}^k \end{bmatrix} \begin{bmatrix} V_p^1 \\ V_p^2 \\ \vdots \\ V_p^k \end{bmatrix} + \begin{bmatrix} Y_{pn}^{1\,1} & Y_{pn}^{1\,2} & \ldots & Y_{pn}^{1\,k} \\ Y_{pn}^{2\,1} & Y_{pn}^{2\,2} & \ldots & Y_{pn}^{2\,k} \\ \vdots & \vdots & \ldots & \vdots \\ Y_{pn}^{k\,1} & Y_{pn}^{k\,2} & \ldots & Y_{pn}^{k\,k} \end{bmatrix} \begin{bmatrix} V_n^1 \\ V_n^2 \\ \vdots \\ V_n^k \end{bmatrix} \quad (3.1)$$

$$\begin{bmatrix} I_n^1 \\ I_n^2 \\ \vdots \\ I_n^k \end{bmatrix} = \begin{bmatrix} I_{n0}^1 \\ I_{n0}^2 \\ \vdots \\ I_{n0}^k \end{bmatrix} + \begin{bmatrix} Y_{nn}^1 & Y_{2n}^{1\,2} & \ldots & Y_{kn}^{1\,k} \\ Y_{1p}^{2\,1} & Y_{nn}^2 & \ldots & Y_{kn}^{2\,k} \\ \vdots & \vdots & \ldots & \vdots \\ Y_{kn}^{k\,1} & Y_{in}^{i\,2} & \ldots & Y_{nn}^k \end{bmatrix} \begin{bmatrix} V_n^1 \\ V_n^2 \\ \vdots \\ V_n^k \end{bmatrix} + \begin{bmatrix} Y_{np}^{1\,1} & Y_{np}^{1\,2} & \ldots & Y_{np}^{1\,k} \\ Y_{np}^{2\,1} & Y_{np}^{2\,2} & \ldots & Y_{np}^{2\,k} \\ \vdots & \vdots & \ldots & \vdots \\ Y_{np}^{k\,1} & Y_{np}^{k\,2} & \ldots & Y_{np}^{k\,k} \end{bmatrix} \begin{bmatrix} V_p^1 \\ V_p^2 \\ \vdots \\ V_p^k \end{bmatrix} \quad (3.2)$$

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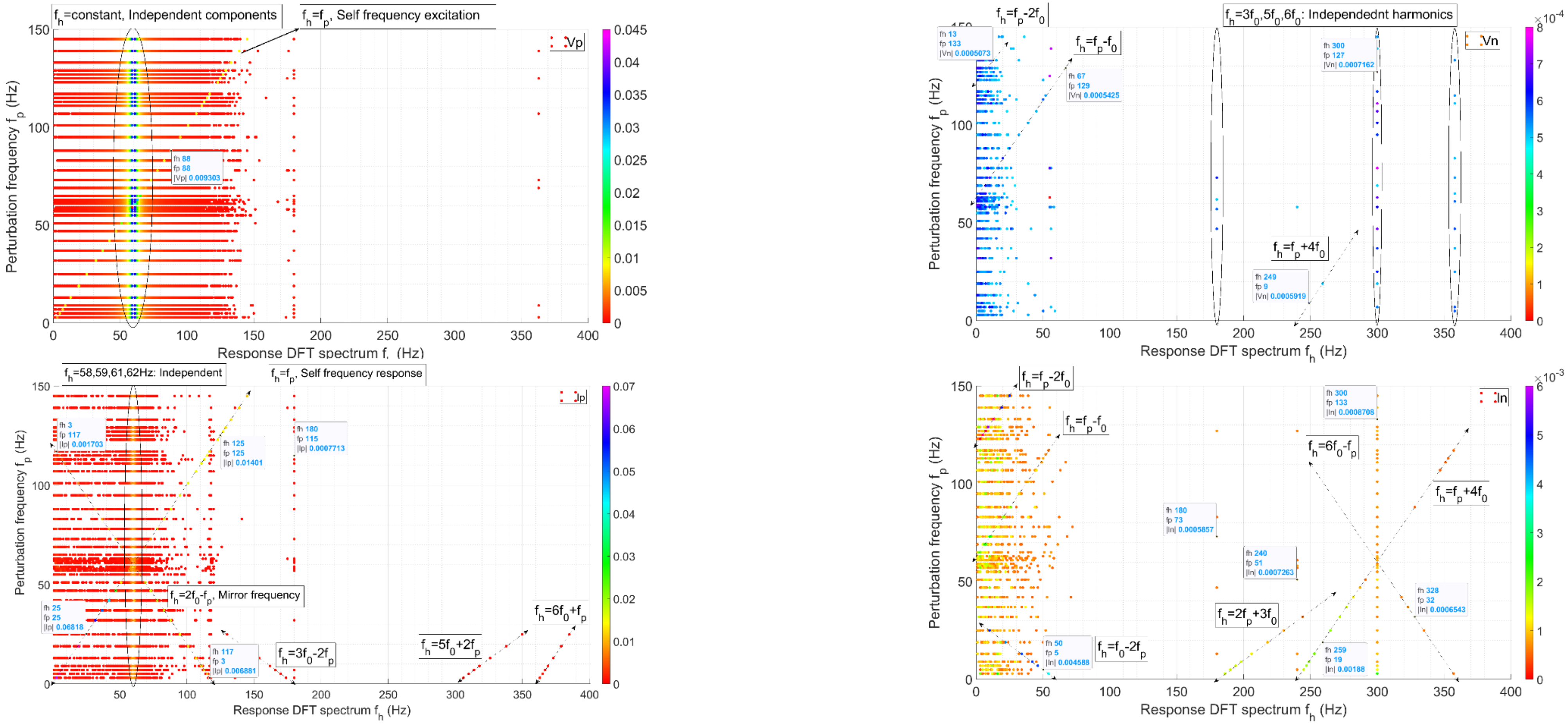
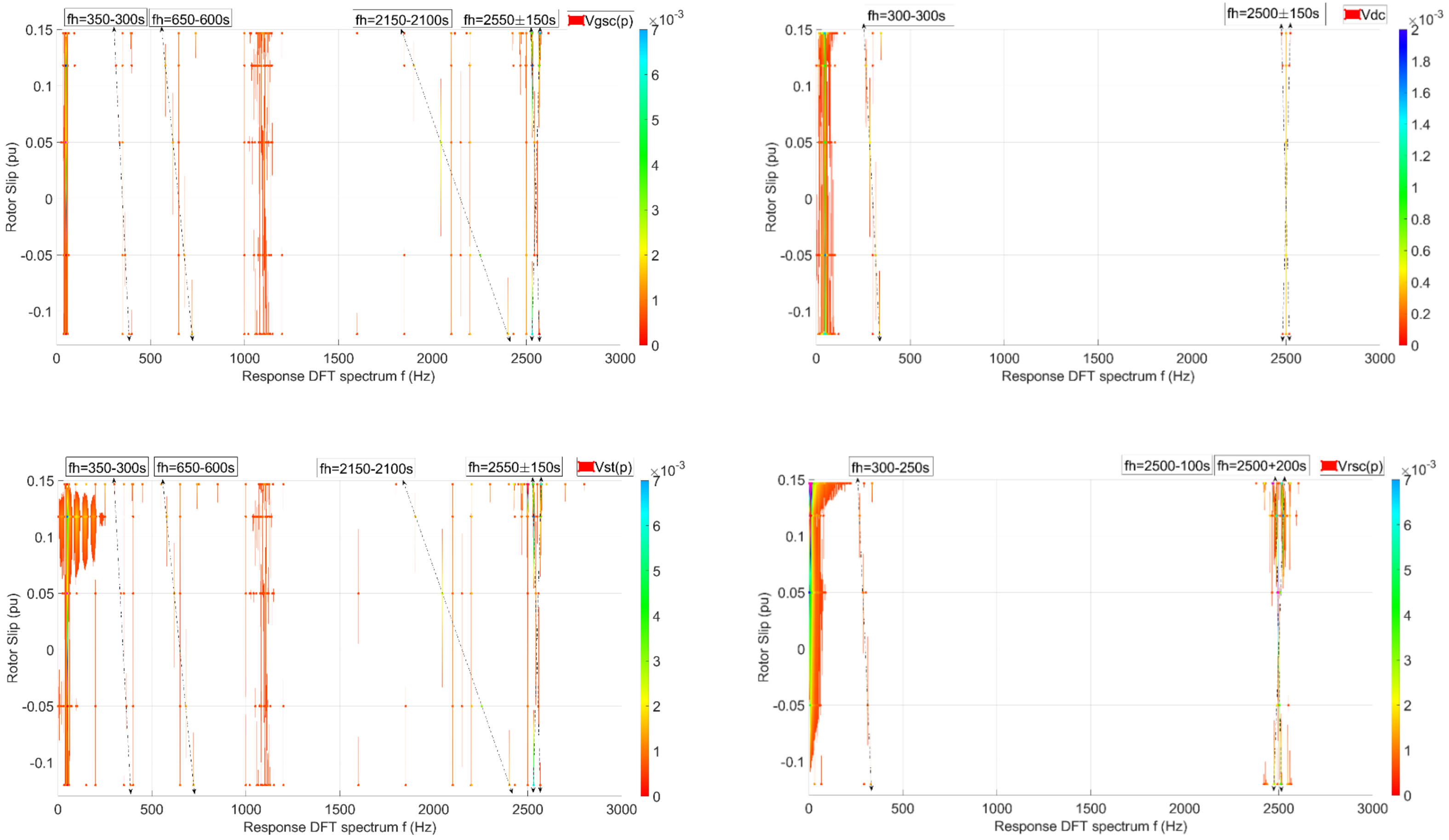
Perturbation on 2MVA PV inverter at NREL



B. Nouri, Ł. H. Kocewiak, S. Shah, P. Koralewicz, V. Gevorgian and P. Sørensen, "Generic Multi-Frequency Modelling of Converter Connected Renewable Energy Generators Considering Frequency and Sequence Couplings," in IEEE Transactions on Energy Conversion, 2021. https://doi org/10.1109/TEC.2021.3101041

Rotor speed dependent emissions
Tests on a 2.2 MVA Type 3 WT at Fraunhofer



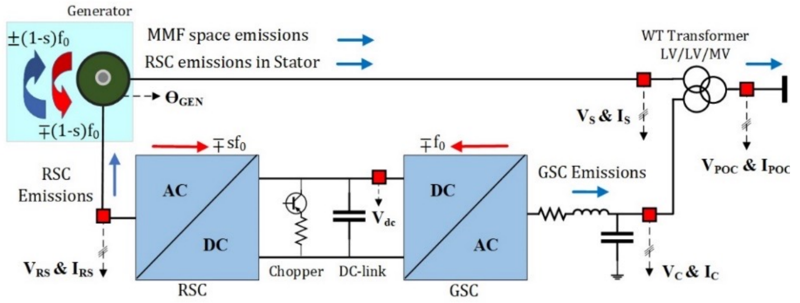
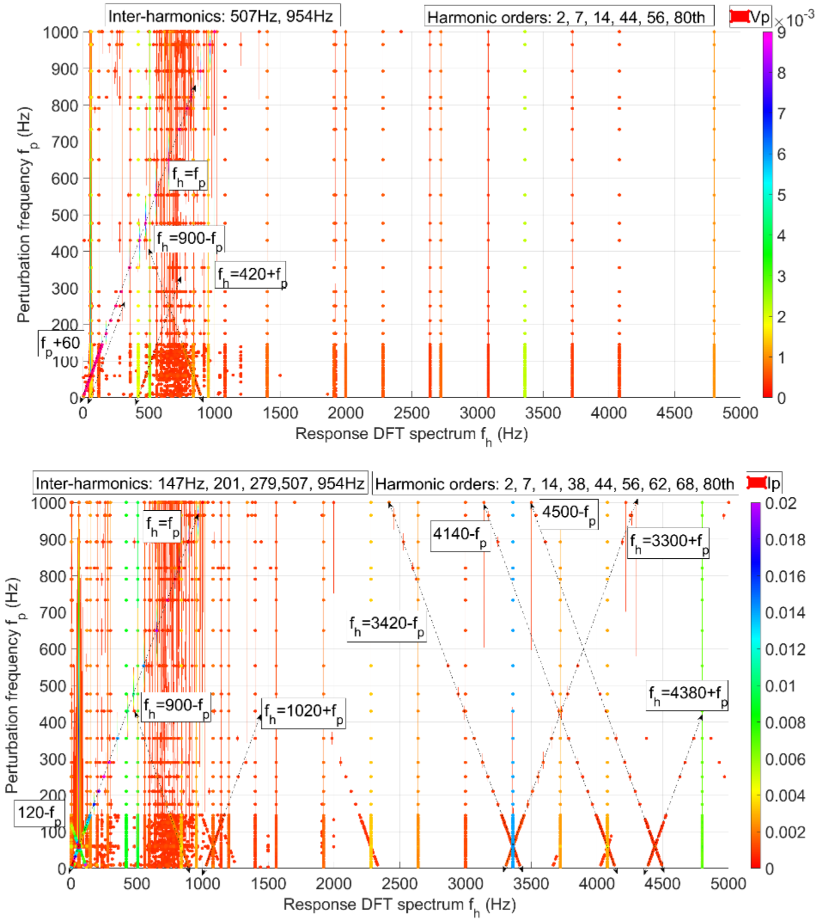


Table 2: Identified main emission patterns.

Measured Point	Patterns in Positive Sequence
POC	50+300s, 350-300s, 650-600s, 2150-2100s, 2550±150s
ST	50+300s, 350-300s, 650-600s, 2150-2100s, 2550±150s
GSC	350-300s, 650-600s, 2150-2100s, 2550±150s
RSC	300-250s, 2500-100s, 2500+200s
DC-link	300-300s, 2500±150s

Nouri, B., Kocewiak, L. H., Jersch, T., Quistorf, G., Fenselau, C., Prima, I., Lehmann, J., & Srensen, P. (2022). Experimental Analysis of Root Causes for Rotor-Speed-Dependent Emissions from Type 3 Wind Turbines. *IEEE Transactions on Power Delivery*, *37*(5), 3939-3946. https://doi.org/10.1109/TPWRD.2022.3141652

Perturbation tests on a 2MVA Type 3 WT at NREL



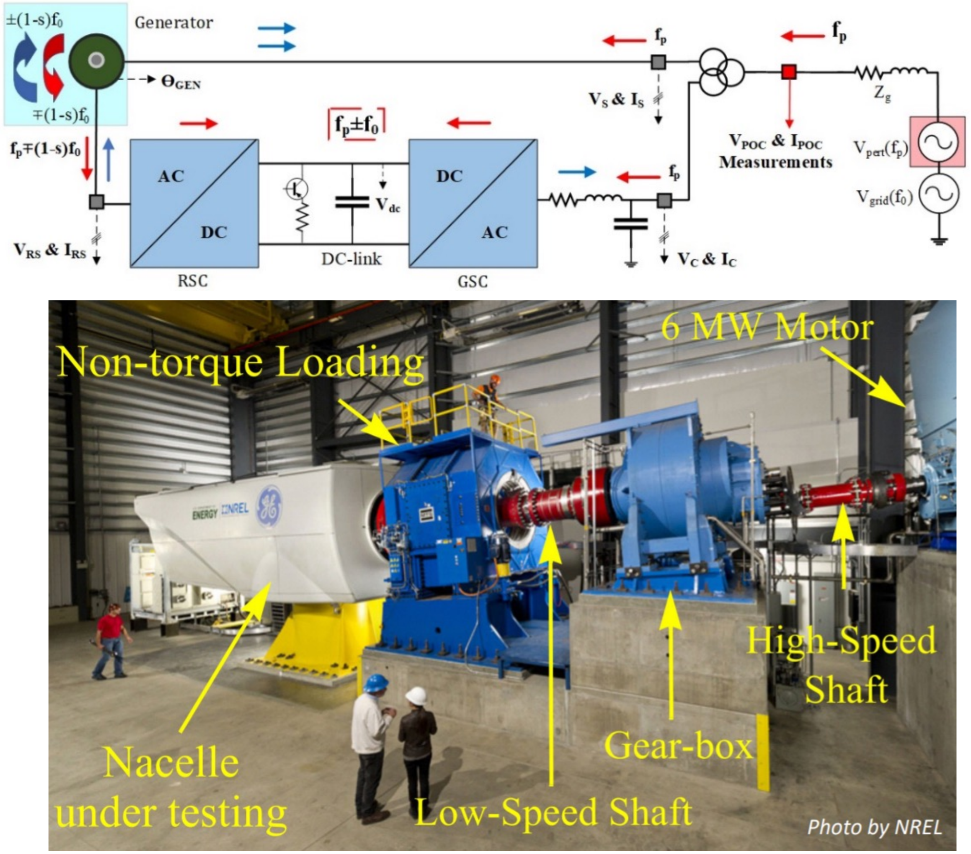


Figure 3.3: Grid and wind/torque emulators at NREL [12]

B. Nouri, Ł. Kocewiak, S. Shah, P. Koralewicz, V. Gevorgian and P. Sørensen, "Extension of the Generic Multi-Frequency Modelling Method for Type 3 Wind Turbines," in *IEEE Transactions on Energy Conversion*, vol. 37, no. 3, pp. 1875-1884, Sept. 2022, doi: 10.1109/TEC.2022.3166470.

Conclusions

- The proposed generic multi-frequency modelling method can be extended for Type 3 WTs by addressing the rotor speed dependent (RSD) emissions and couplings

$$I_{p(f+f_0)} = I_{p0(f+f_0)} + Y_{pp}V_{p(f+f_0)} + Y_{pn}V_{n(f-f_0)}$$
$$I_{n(f-f_0)} = I_{n0(f-f_0)} + Y_{np}V_{p(f+f_0)} + Y_{nn}V_{n(f-f_0)}$$
$$Couplings = \begin{cases} \pm m f_i \pm k f_0, & \text{if is not RSD} \\ \pm m f_i \pm (k f_0 \pm z s f_0), & \text{if is RSD} \end{cases}$$

- A limited number of rotor speed dependent couplings are observed in the practical application.

- The proposed modelling procedure: ***Empirical Modelling & Model Validation***

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