Stability challenges in converter-dominated networks

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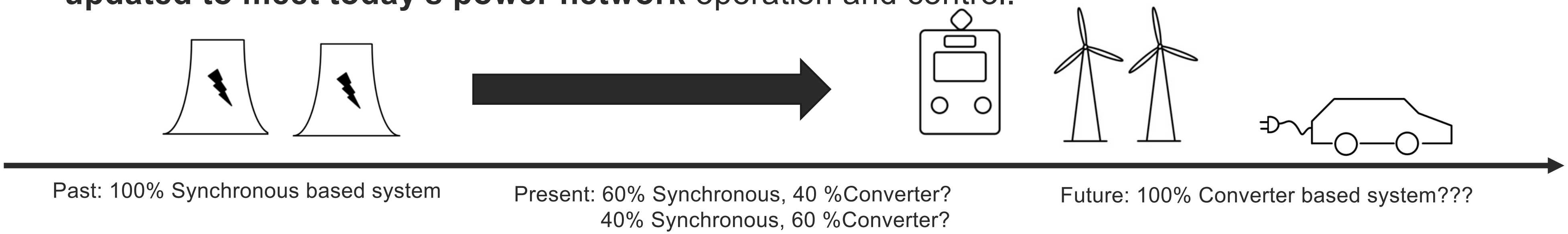
X THE PLACE OF USEFUL LEARNING

Contents

- Introduction and Social Impact of Electrical Instabilities
- GSIM: Changes in Assessing Stability in Converter Dominated Networks
- SIF BLADE: Restoration Using Offshore Wind

Changes in the electric network

- Power electronics converters (PECs) for renewable applications, and especially the control, are a legacy from the electrical drives – **converters are only required to cater for their own operation**.
- Grid codes try to address some issues, but the existing control requirements and rules are not fully **updated to meet today's power network** operation and control.



Power converters will soon be in charge of the operation and control of the network –controlling frequency, voltage, transient/protection etc

We need to transition from the old (passive) electric drive-based controllers (current or vector control) also known as **grid following,** to a new (active) approach **grid forming**

But also need to work alongside the legacy equipment (but this shouldn't be seen as a mortgage for the future power system)

Social impact of the grid issues

August 2019

Lightning strike 'partly to blame' for power cut

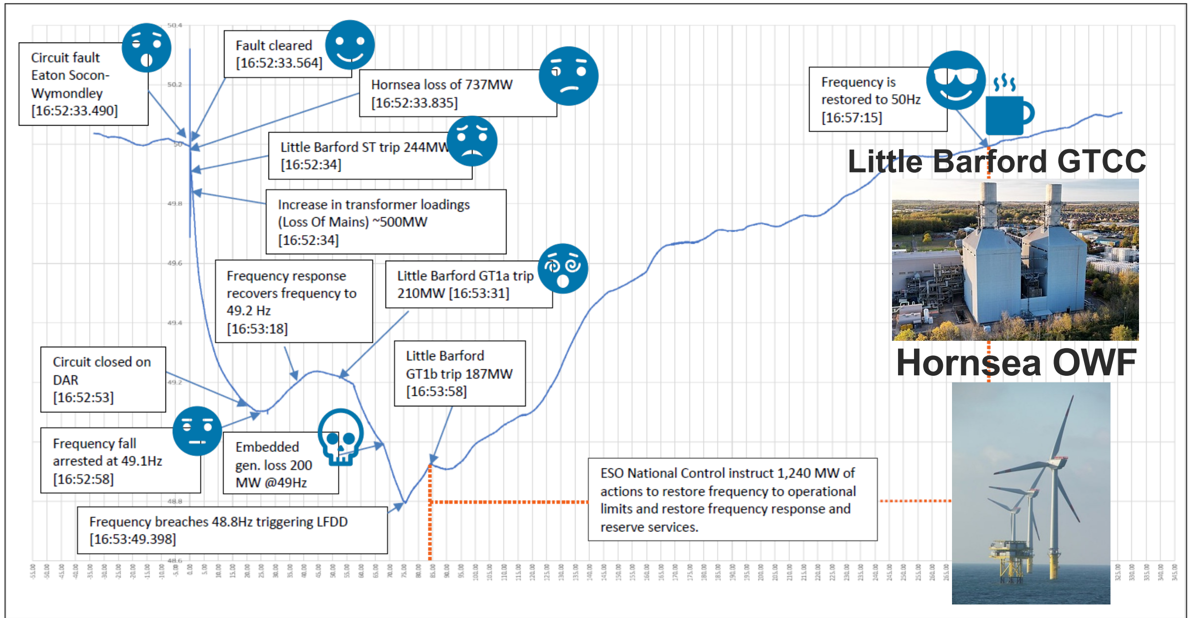
BBC NEWS

Blackout raises alarms on UK energy resilience

High-tech economy is more vulnerable even to short-term power cuts

FINANCIAL TIMES

Figure 2 – Annotated Frequency Trace of the Event



Full report published Jan 2020: 9 August 2019 power outage report

7 July 2023

STV News

Traffic lights across city go down following power surge

Traffic lights are out at around 20 sites across the city.

- Date: 07 July 2023
- Time: 00.27am and 01.10 am (UTC)
- Impact: traffic lights disruption in Glasgow and other? News Link (TBC)
- Device: SEL-451PMU (50 frames/s)
- Measurement point: 3-phase LV (110V nominal) connection, TIC
- Platform: LGMVP

Live Grid MVP

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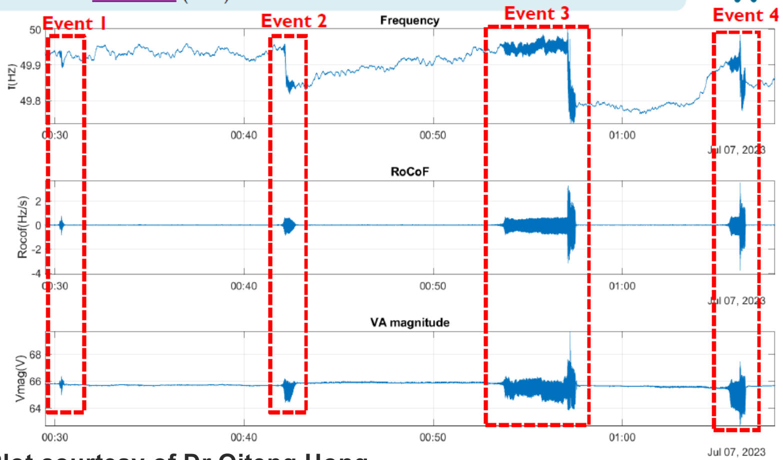
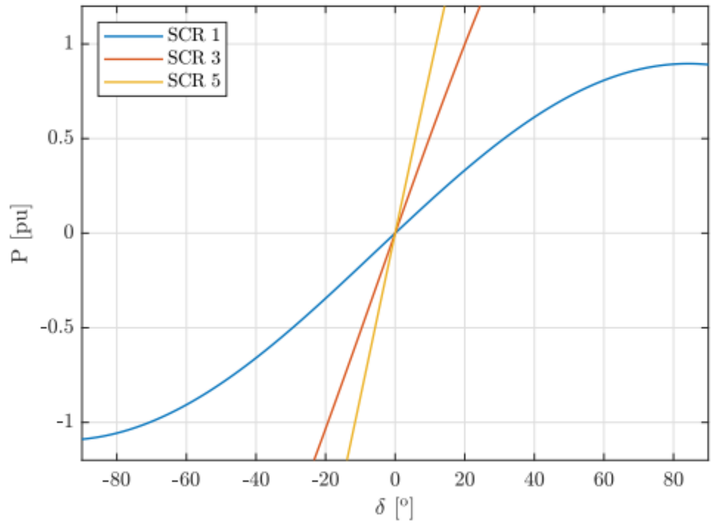


Plot courtesy of Dr Qiteng Hong

Full report published May 2024: Sub-synchronous oscillations in GB: Current state and plans for future management

Short Circuit Level and stability

- The Short Circuit Ratio (SCR) has been used to identify problematic scenarios in traditional networks, such as weak networks
- Fault current provision links to physical impedance and gave a good idea of possible interactions in classic systems
- A high SCR results in a low impedance (short electrical distance and improved voltage strength)
- Not capable of representing converter response, which is not governed by converter impedance
- No dissemination between grid forming and following



$$P = \frac{3U(EX_n sin(\delta) + R_n(Ecos(\delta) - U))}{X_n^2 + R_n^2}$$

$$SCR = \frac{SCL_{MVA}}{S_{rated}}$$

Alternatives to SCR

CSCR

Initially proposed by GE, Composite Short Circuit Ratio (CSCR) calculates the grid strength considering all electrically close converters

$$CSCR = \frac{CSC_{MVA}}{MW_{VER}}$$

ESCR

The Equivalent Circuit Short Circuit Ratio (ESCR) is very similar to the traditional SCR, but now considers all physical impedances on the network

$$ESCR = \frac{1}{Z_{sys,PU}} = Y_{sys,PU}$$

SCRIF

The short circuit ratio with interaction factors (SCRIF) looks to augment previous definitions of SCR with a component that captures voltage deviations

$$SCRIF_i = \frac{S_i}{P_i + \Sigma_j (IF_{ij} \times P_j)}$$

$$IF_{ij} = \frac{\Delta V_i}{\Delta V_j}$$

Can we define a new SCR measure for stability to consider the converter impedance?

Henderson C, Egea-Alvarez A, Papadopoulos P, Li R, Xu L, Da Silva R, Kinsella A, Gutierrez I, Pabat-Stroe R. Exploring an impedance-based SCR for accurate representation of grid-forming converters. In2022 IEEE Power & Energy Society General Meeting (PESGM) 2022 Jul 17 (pp. 1-5). IEEE.

Grid Strength Impedance Metric (GSIM)

- $Y_{sys}(s)$ is the full system admittance to be compared to the base network impedance $Y_b(s)$
- Eigenvalues for 2x2 matrices similar to impedance-based stability
- Multiply eigenvalues of system admittance by base impedance
- Combine 2 eigenvalues into one rating with the same scale and meaning as SCR
- It offers a black-box approach to identifying stability issues
- The GSIM frequency response might provide a clue of stability issues

$$\boldsymbol{Z}_b(s) = \begin{bmatrix} Z_{qq}(s) & Z_{qd}(s) \\ Z_{dq}(s) & Z_{dd}(s) \end{bmatrix} \qquad \boldsymbol{Y}_{sys}(s) = \begin{bmatrix} Y_{qq}(s) & Y_{qd}(s) \\ Y_{dq}(s) & Y_{dd}(s) \end{bmatrix}$$

$$\lambda(\boldsymbol{Z}_b(s)) = \begin{bmatrix} |\lambda_{Z_{b,q}}(s)| \\ |\lambda_{Z_{b,d}}(s)| \end{bmatrix} \qquad \lambda\left(\boldsymbol{Y}_{sys}(s)\right) = \begin{bmatrix} |\lambda_{Y_{sys,q}}(s)| \\ |\lambda_{Y_{sys,d(s)}}| \end{bmatrix}$$

$$\begin{bmatrix} GSIM_q(s) \\ GSIM_d(s) \end{bmatrix} = \lambda(\boldsymbol{Y}_{sys}(s) \odot \lambda(\boldsymbol{Z}_b(s))$$

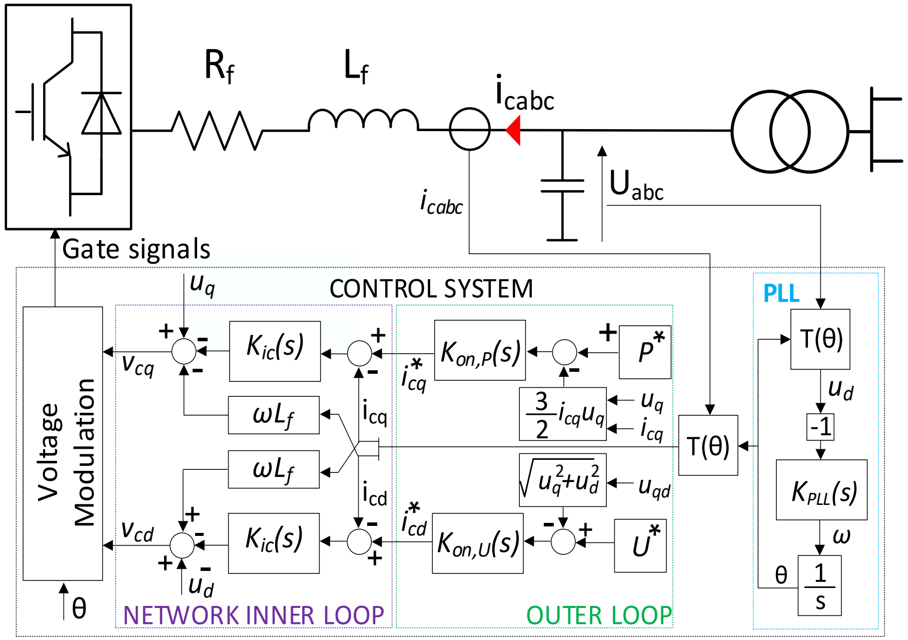
$$GSIM(s) = \sqrt{\frac{GSIM_q(s)^2 + GSIM_d(s)^2}{2}}$$

GSIM and SCR are equivalent for conventional networks

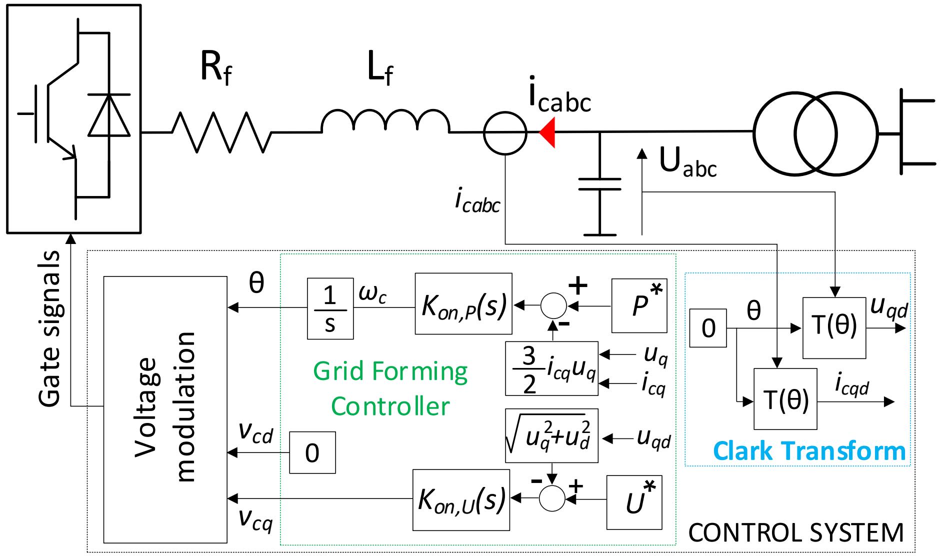
$$SCR = \frac{Z_b}{Z_{sys}} \equiv GSIM(0Hz)$$

Henderson C, Egea-Alvarez A, Kneuppel T, Yang G, [7]Xu L. Grid strength impedance metric: An alternative to SCR for evaluating system strength in converter dominated systems. IEEE Transactions on Power Delivery. 2023 Jan 9;39(1):386-96.

Analysed controllers

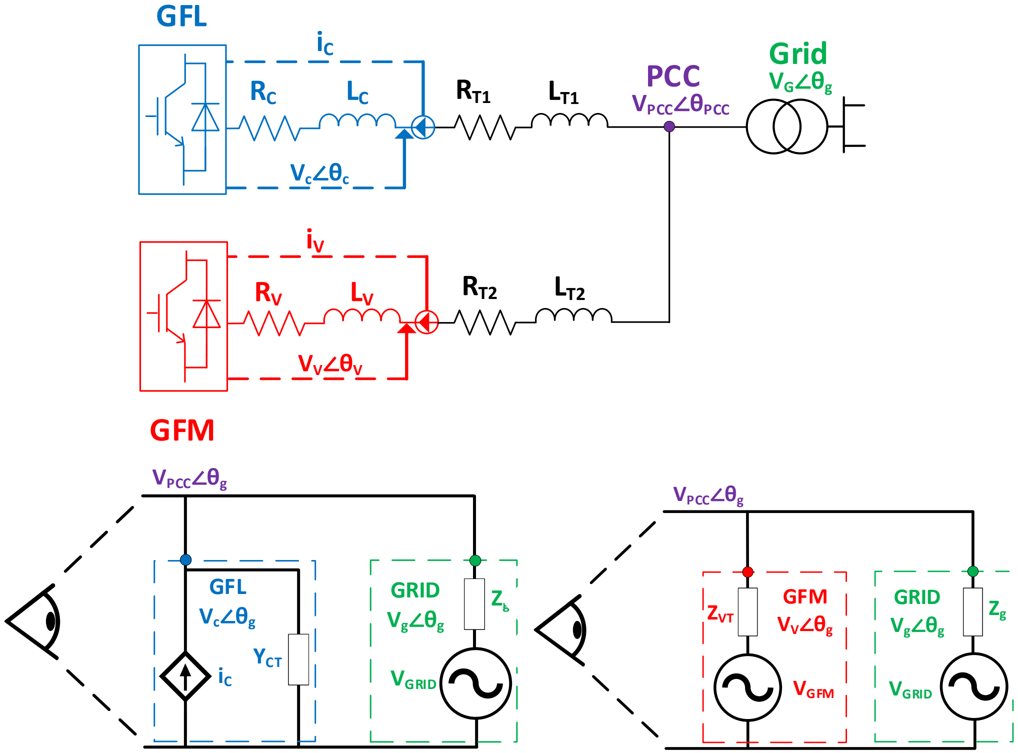


Grid-Following Control



Grid-Forming Control

Grid Strength Impedance Metric (GSIM)



$$Y_{sys1} = Y_{CT} + Y_G \qquad Y_{sys2} = Y_{VT} + Y_G$$

$$Y_{sys3} = Y_G + Y_{CT} + Y_{VT}$$

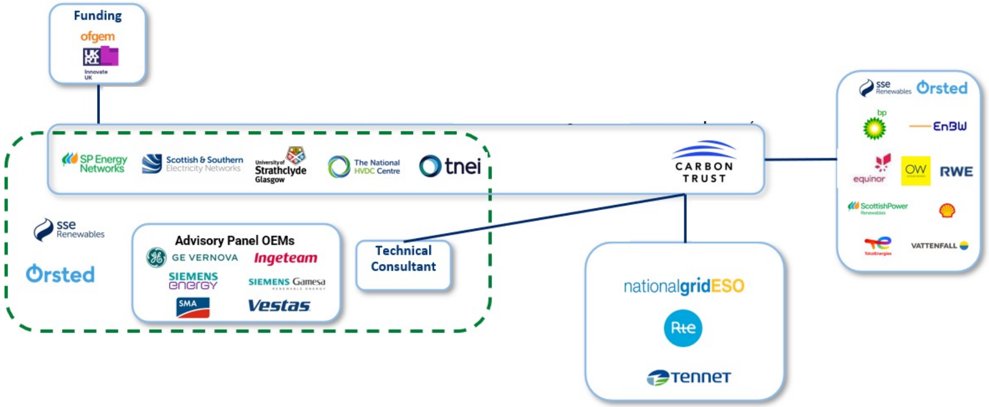
System	SCR	CSCR	ESCR	GSIM
Network	1	1	1	1
($\boldsymbol{Y}_{sys}$)	3	3	3	3
GFL	2	1.93	1.93	1.65
($\boldsymbol{Y}_{sys1}$)	6	5.42	5.42	5.61
GFM	2	1.93	1.93	4.42
($\boldsymbol{Y}_{sys2}$)	6	5.42	5.42	7.17
Full	1	0.95	0.97	1.98
($\boldsymbol{Y}_{sys3}$)	3	2.85	2.78	3.5

- Comparison for equivalent calculation for different SCR (1 and 3) and different converter technologies.
- Note that for Y_{sys2} and Y_{sys1} as there is only one converter the SCR is double

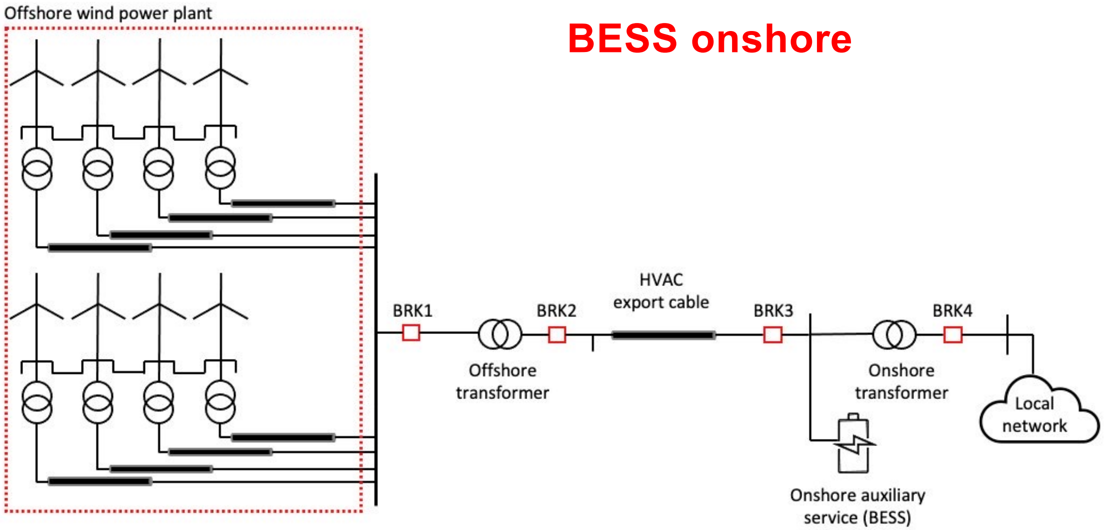
SIF BLADE Beta (2024-27)

Research project to develop hardware in the loop demonstration of a black start from offshore wind for two Scottish locations

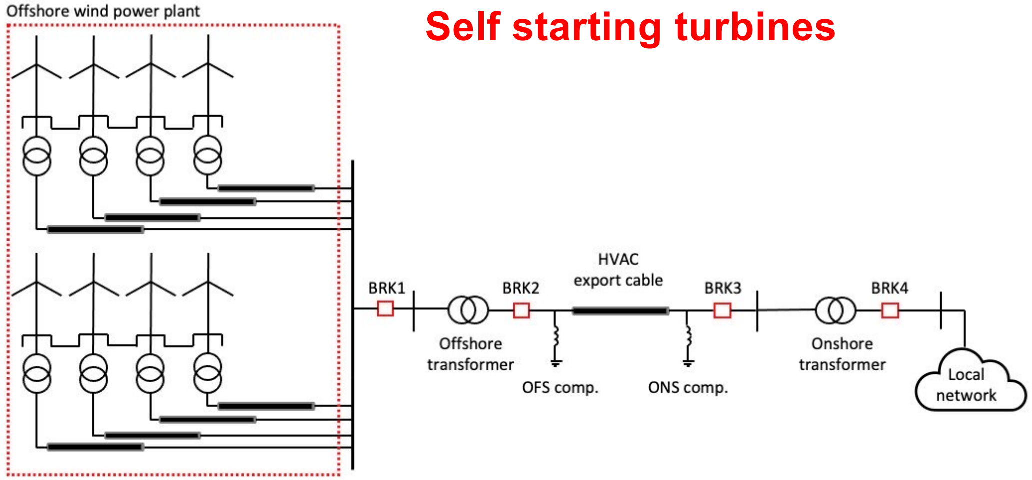
Derisk the future development of restoration from wind



BESS onshore



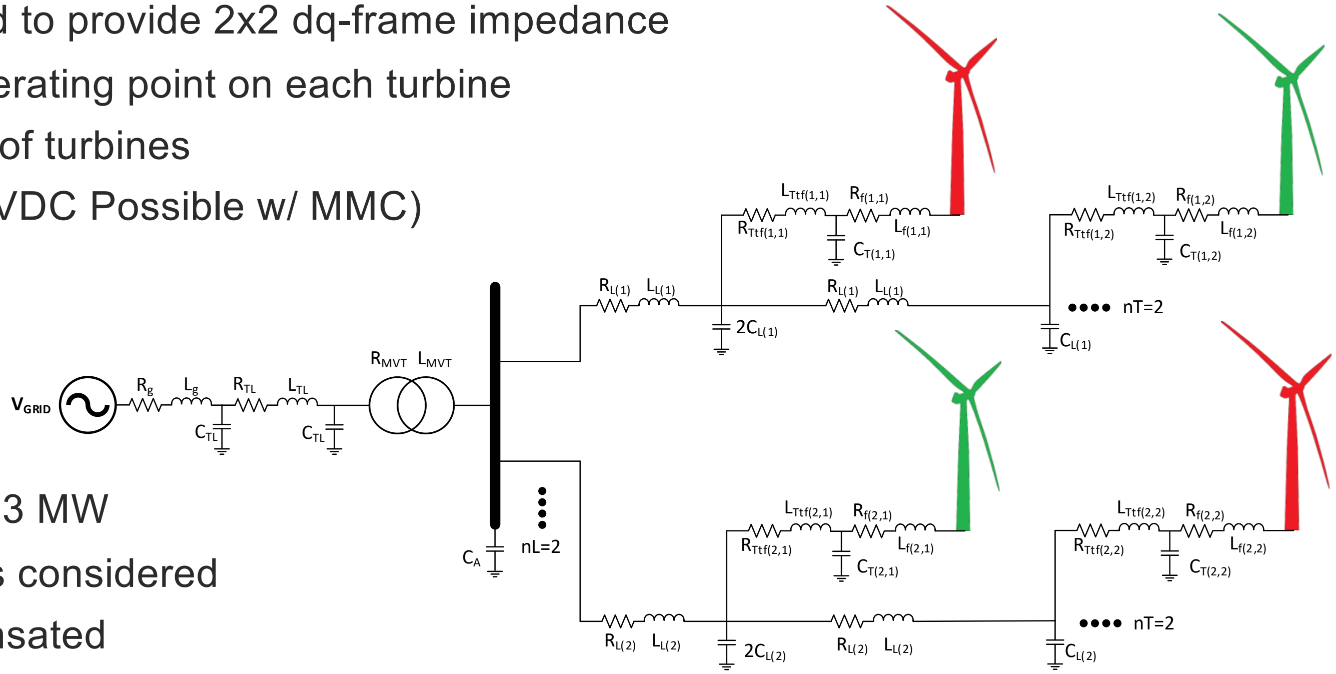
Self starting turbines



AC connected offshore wind farm analysis

Is there any optimal relationship between GFM and GFL for AC connected offshore wind farms?

- Modular approach fully vectorised to provide 2x2 dq-frame impedance
- Unique control structures and operating point on each turbine
- nL number of lines of nT number of turbines
- HVAC export cable as PI Line (HVDC Possible w/ MMC)

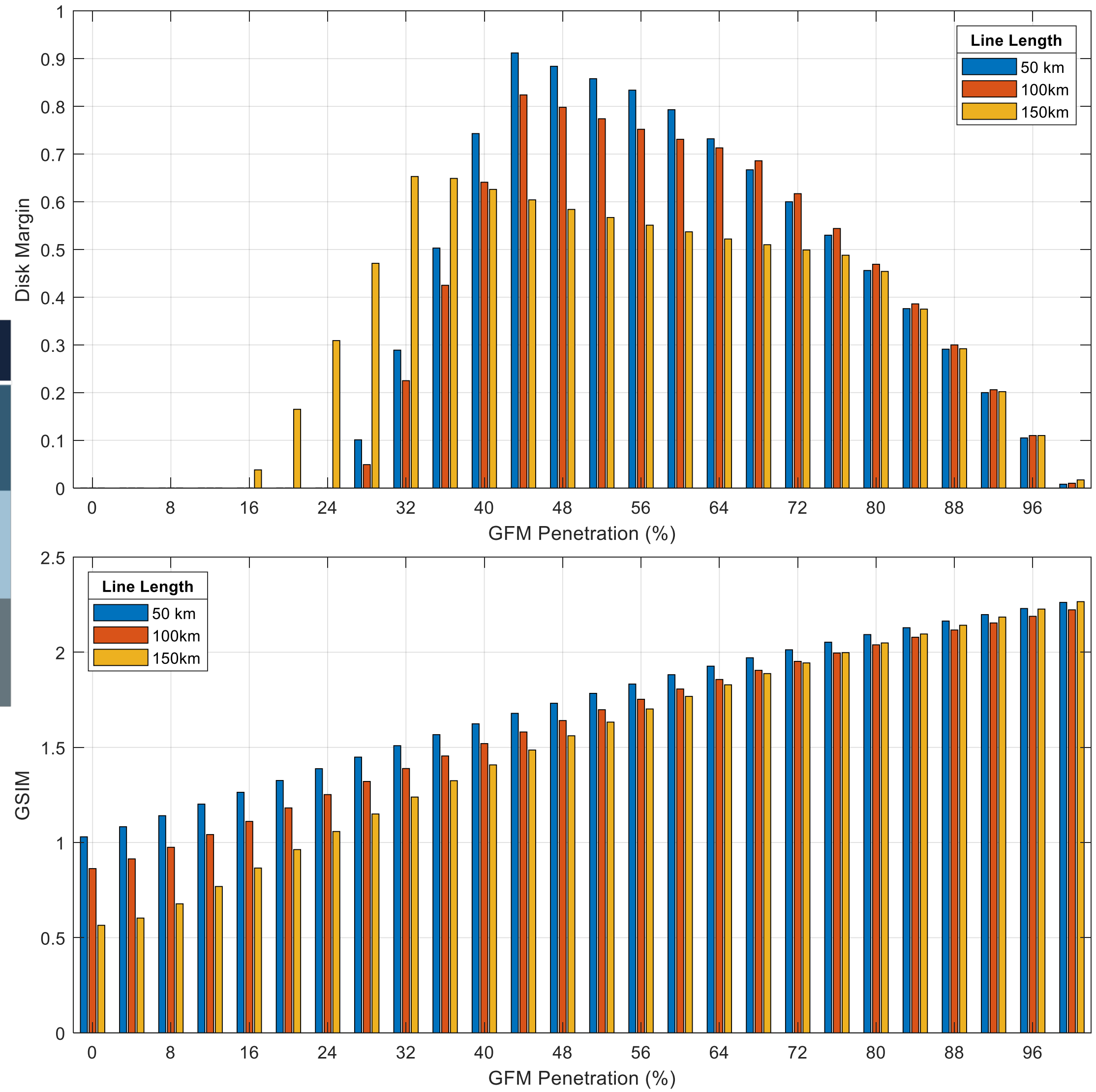


- 5 Lines of 5 Turbines rated at 3 MW
- 50, 100, 150 km HVAC cables considered
- Start, middle and end compensated
- Onshore SCR of 2 (before HVAC cable)

AC-connected offshore wind farm stability analysis

Key Points	50 km	100 km	150 km
Critical Penetration	28 % (1.45)	28 % (1.35)	16 % (0.8)
Optimal Penetration	44 % (1.65)	44 % (1.55)	32 % (1.25)
Maximum Penetration	64 % (1.95)	72 % (1.95)	80 % (2.05)

- **Critical penetration** which the system is first stable
- **Optimal penetration** which the system has maximum stability and GSIM
- **Maximum penetration,** which is the point after which the stability of the system begins to decay rapidly



Henderson C, Egea-Alvarez A, Xu L. Analysis of optimal grid-forming converter penetration in AC connected offshore wind farms. International Journal of Electrical Power & Energy Systems. 2024 Jun 1;157:109851.

Questions?

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