Virtual Resistor for Sequential Greenstart of Wind turbine and Offshore network

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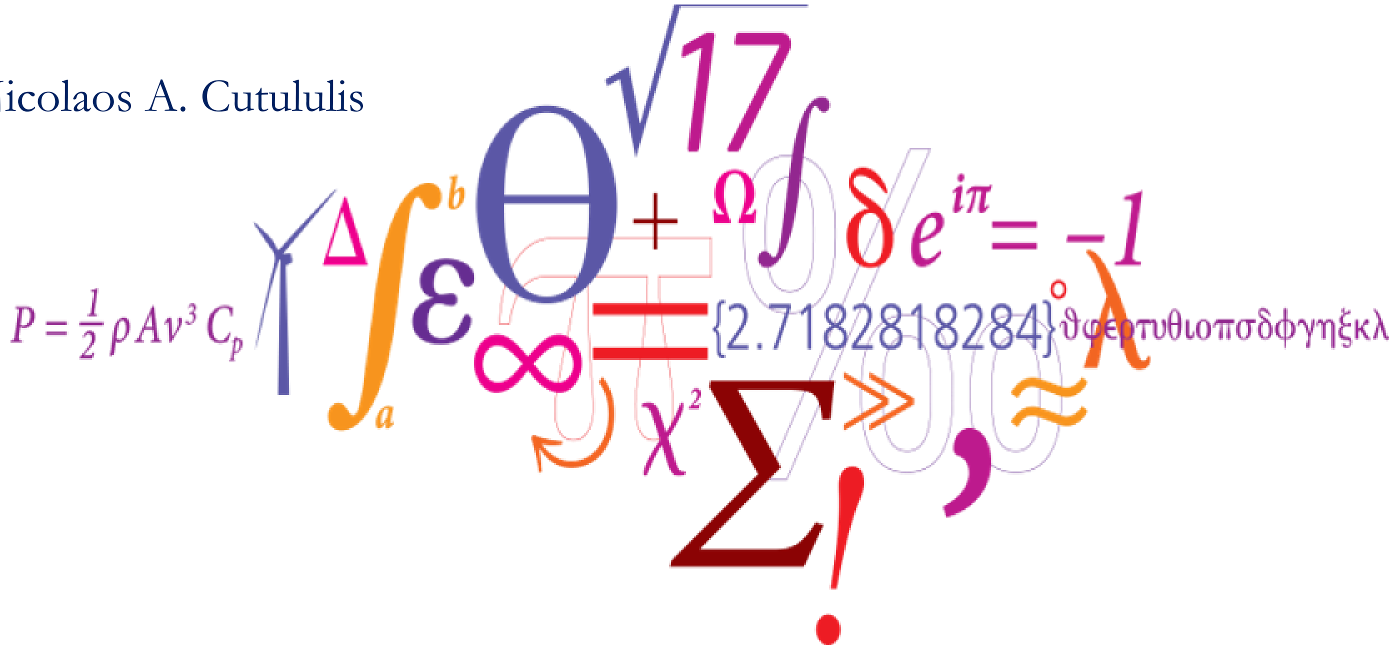


DTU Wind Energy
Department of Wind Energy

Motivation

High volume integration of RES far from loads
Increased trans-national power exchanges
Decreased Var reserve due to SG replacement
Power electronics EMT, Inertial decoupling
Uncontrolled Islanding, Protection settings re-design
Complicated grid operation: stability, reliability

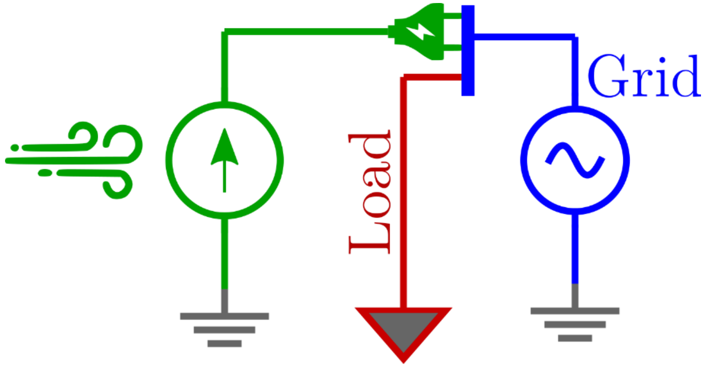
Increased risk of wide-area blackouts
eg: South Australia 2017, UK 2019

TSO

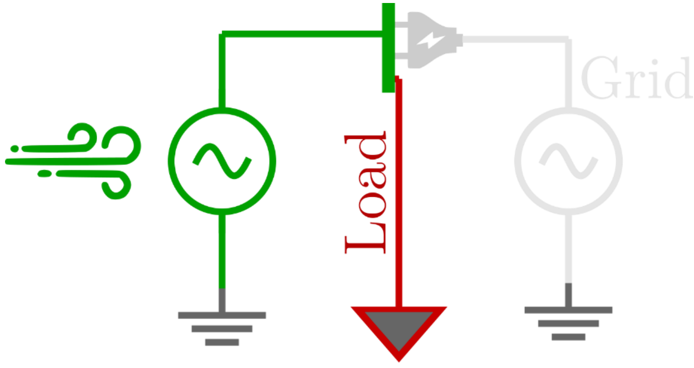
Large OWPPs with modern WTs can address Blackstart requirements targeted conventionally to large thermal plants (ENTSO-E codes)
Steady winds far-from-shore, thus *lesser availability-uncertainty*
Fast, fully-controlled, high-power, green blackstart capability of VSC-HVDC OWPP
Advanced V,f control functionalities from state-of-art PE interface of modern WTs

Gap…

➢ Grid Following



→ Grid Forming



Grid forming / Blackstart-able WTs

Voltage source
rather than traditional current source

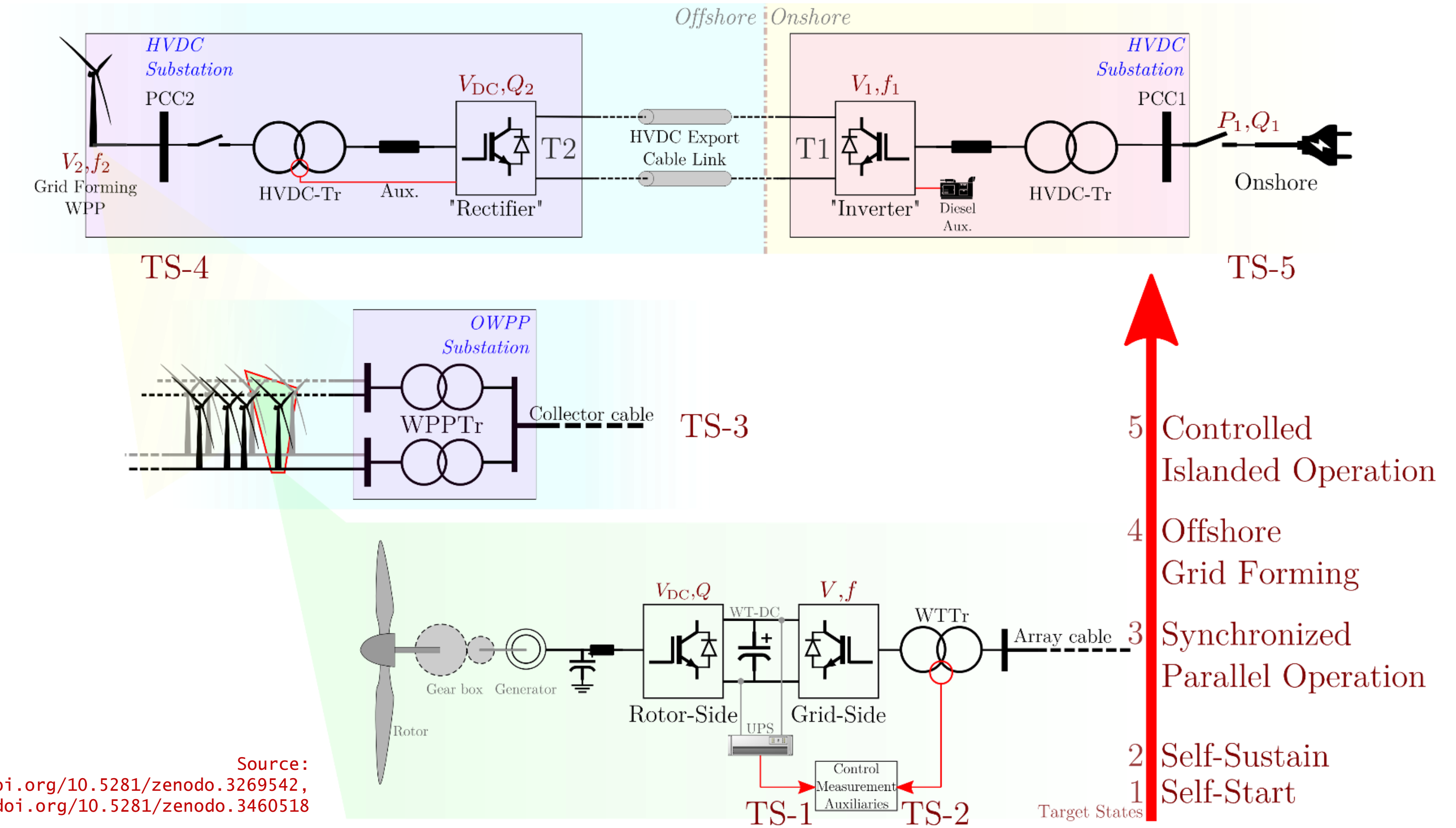
WFO

No waiting for end of network reconstruction; *controlled islanding* to ensure continuity of power supply
Reduce the overall impact of a blackout event: *reduced restoration time & unserved load*
Replace *backup offshore diesel generator* for auxiliary power & energization
Cost benefits, reduced shipping downtime, increased reliability & CO2 displacement.

Greenstart

Challenges…

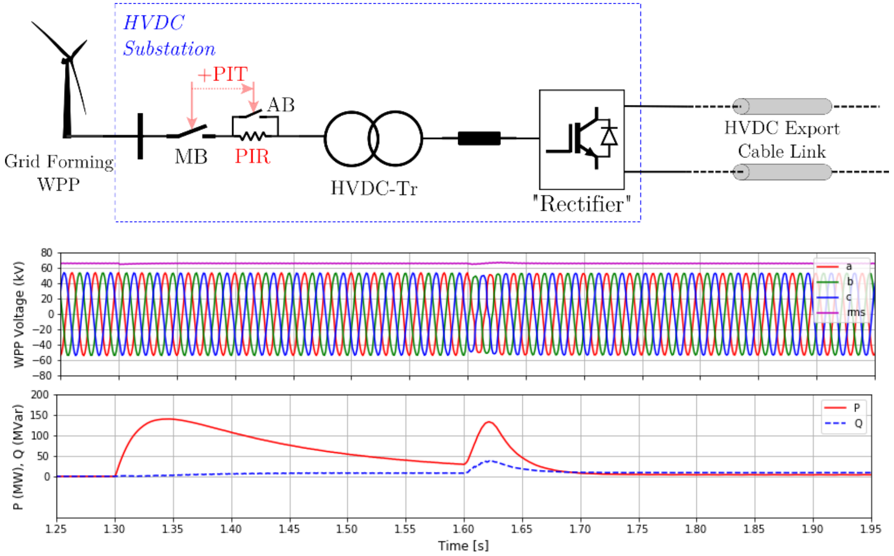
- Cable charging var
- Transformer inrush
- Synchronization transients
- Offshore grid: weak, power electronics rich
- Market

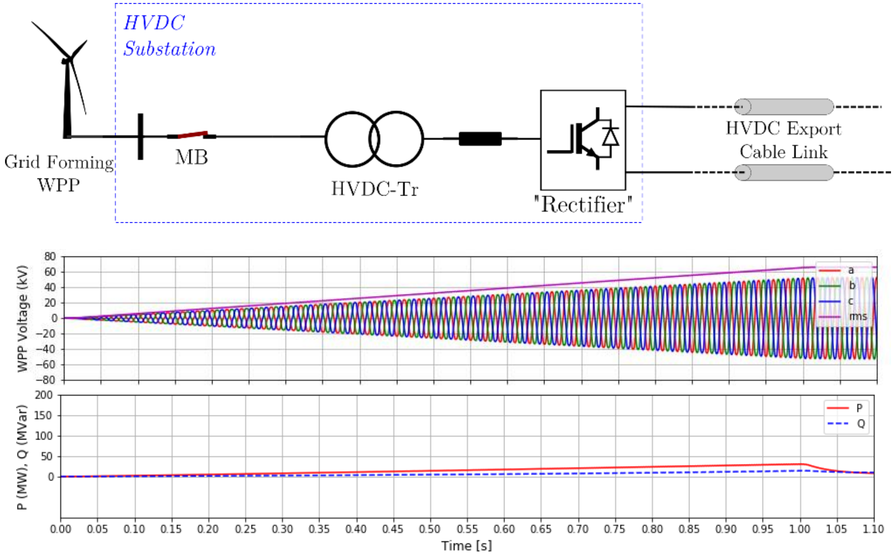


Source:
https://doi.org/10.5281/zenodo.3269542,
https://doi.org/10.5281/zenodo.3460518

Hard v Soft

Source: https://doi.org/10.36227/techrxiv.12948737.v1 (pre-print)





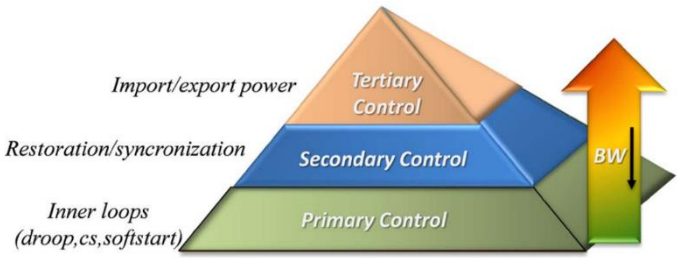
- Higher peak
- Enhanced robustness after initial transient
- Easier detection of failed component

- Lower peak
- Longer upstream exposure to 0<V<0.9pu
- Increased aux power
- Lesser fault current for protection

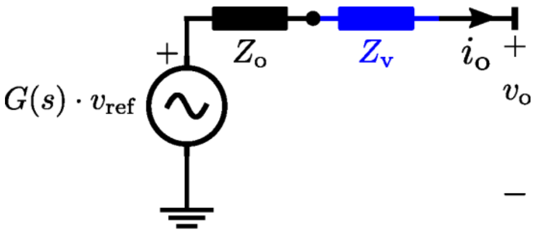
Virtual soft-starter

- Microgrids & converters
  - ➢ Hierarchical multi-level control
- Virtual impedance loop in converter control
  - ➢ Emulate SG inductive behaviour
  - ➢ Reactive current sharing
  - ➢ Harmonic load compensation
  - ➢ Hot-swap operation
  - ➢ No loss in efficiency
- Reduce overcurrent spikes at start-up
  - ➢ Like PIR but smooth variation for 'softer' transient
  - ➢ Mimic soft-starter in FSWT

Source: https://doi.org/10.1109/TIE.2010.2066534



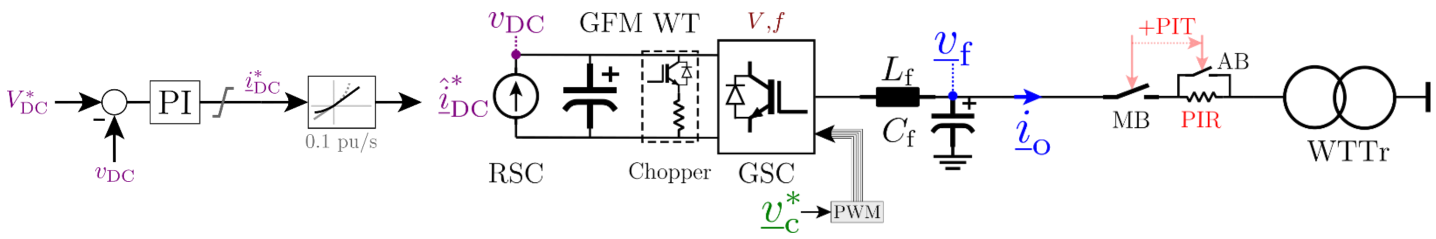
$$v_o = v_{ref} - i_o Z_v$$



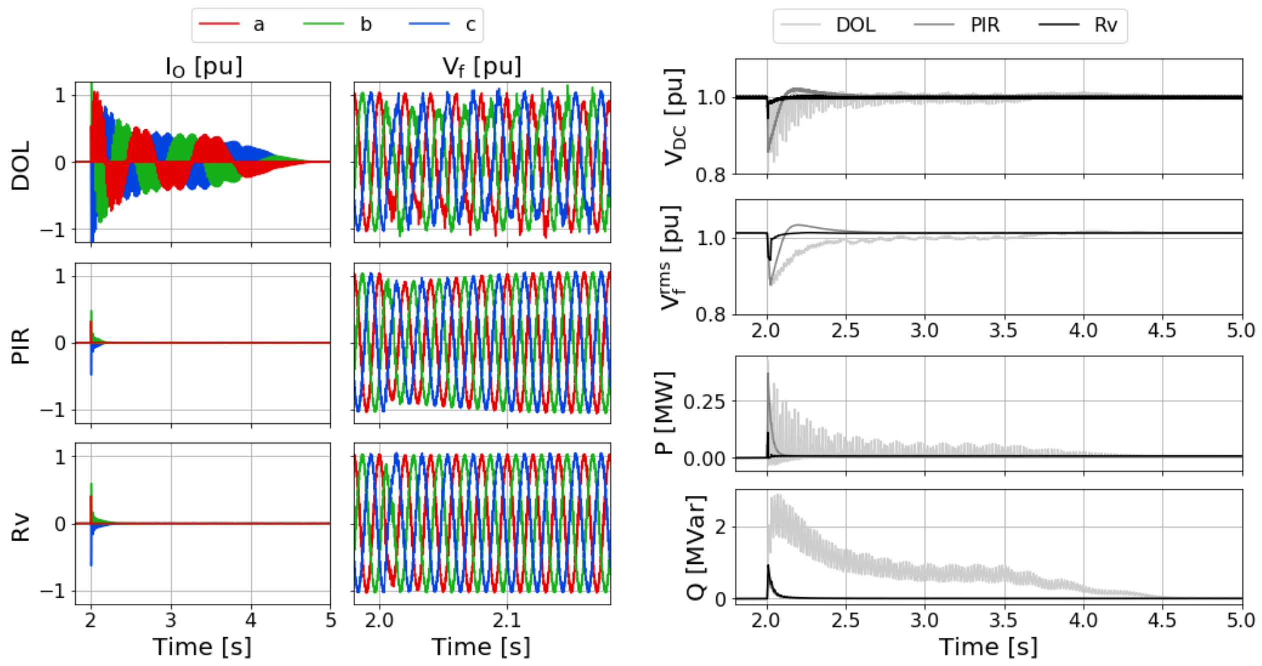
$$r_v(t) = \begin{cases} 0, & t < t_o \\ R_i e^{-\frac{t-t_o}{T}}, & t \geq t_o \end{cases}$$

Proof of Concept

- DOL vs PIR vs Rv
  - PIR = Ri = 0.8 pu
  - PIT = 5T = 0.2 s

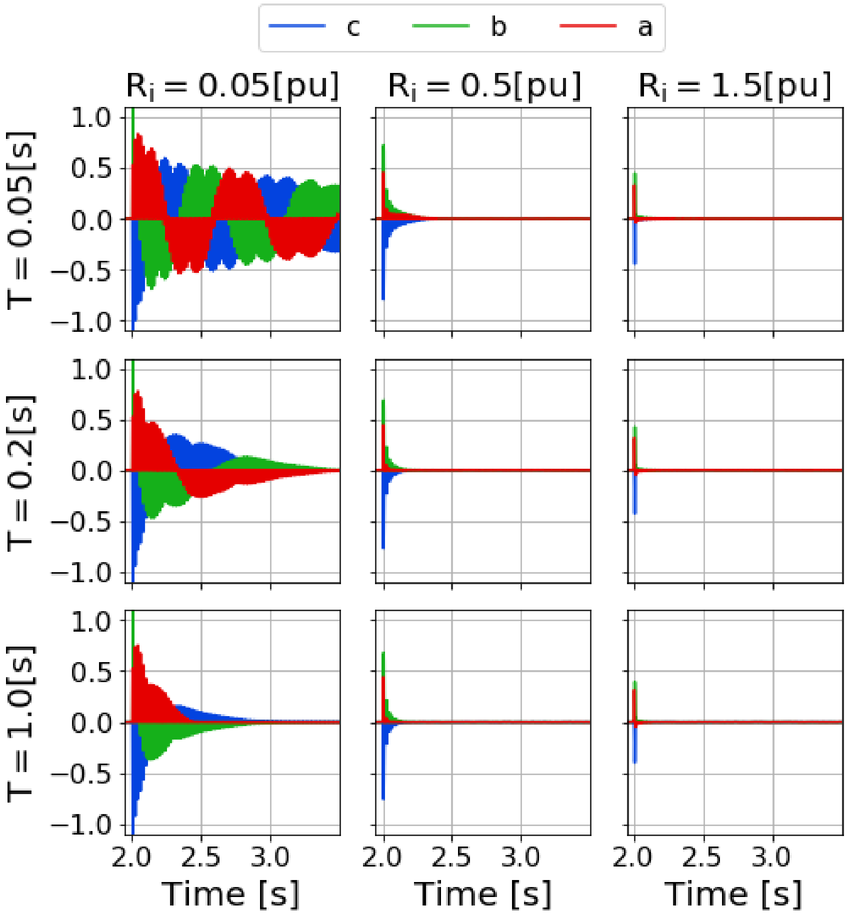


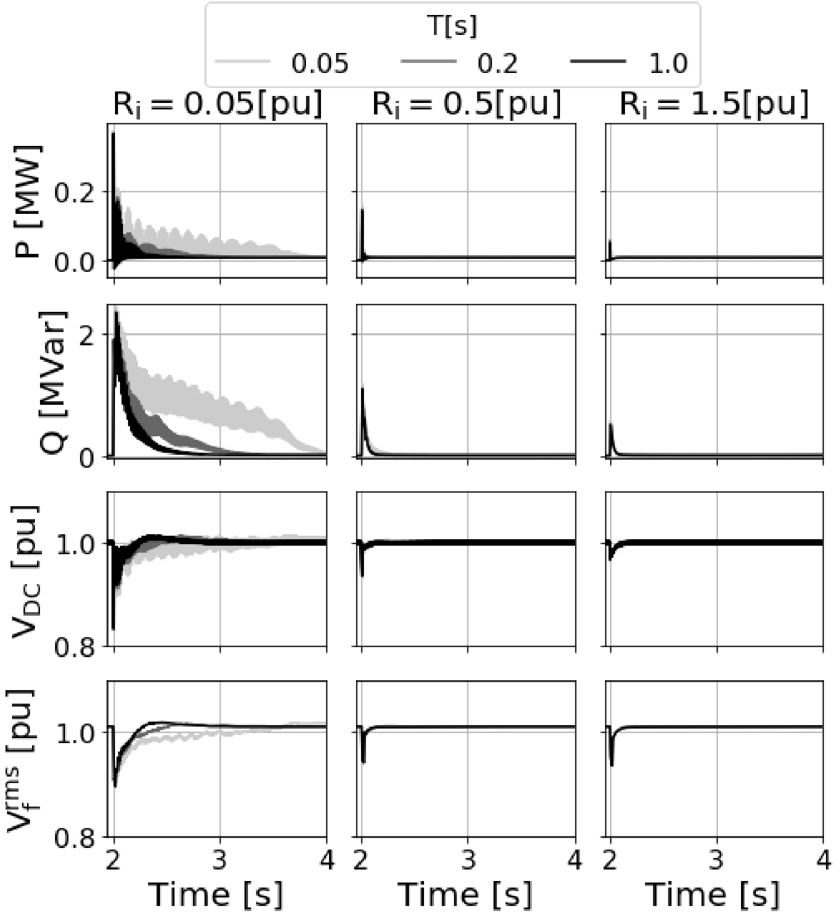
- Reduction in transient inrush current peak amp & settling time.
- Lesser transient distortion in 3ph volt & recovers faster for Rv.
- Smaller volt drops & power peaks for Rv.



Sensitivity analysis

- Ri, T varied
- Inrush current peak reduced for larger Ri.
- Transient damps faster for larger T, effect is more visible at lower Ri.

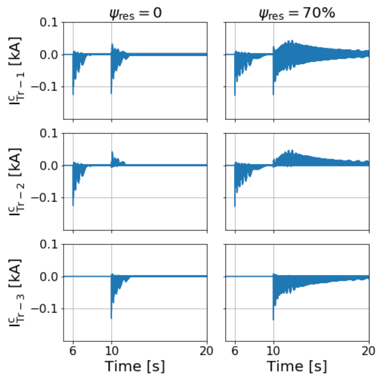


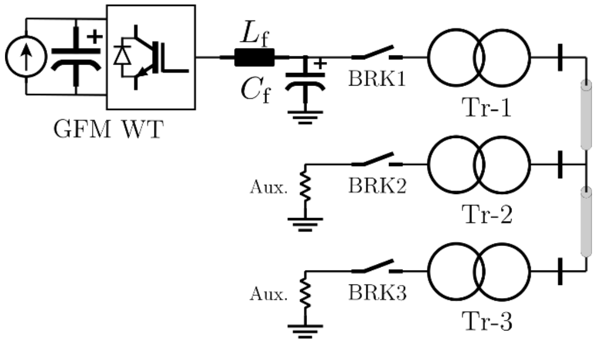


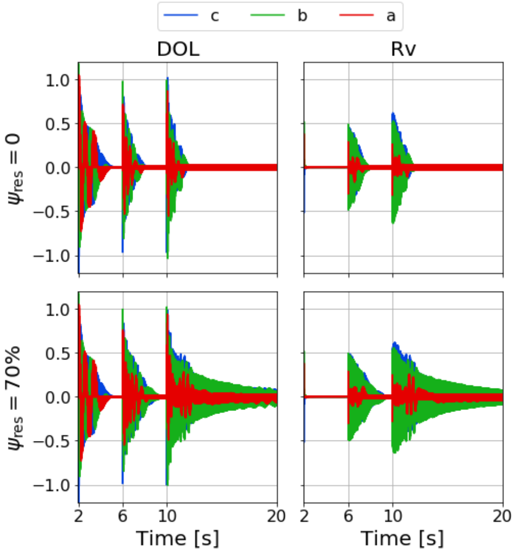
String energization

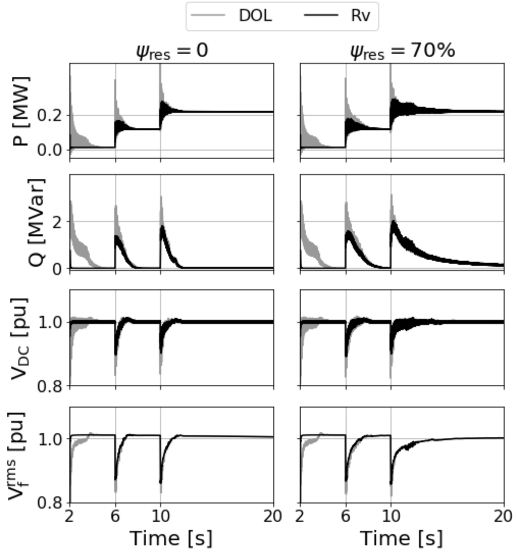
- Inrush, Sympathetic interaction
- Ri = 1 pu, T = 0.06 s
  - ➢ Residual flux = 0 (best), 70% (worst)

- Tr-1 inrush significantly reduced (as shown before) but for subsequent downstream trafos Tr-2,3 only reduction in peak with no impact on duration of decay, esp worst case flux.
- Transient power peaks and voltage dips are reduced in both cases.



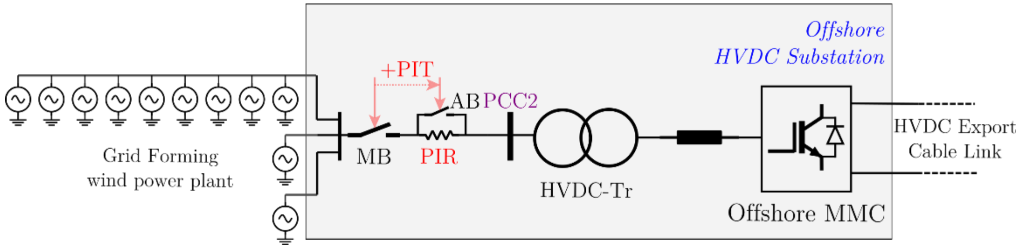




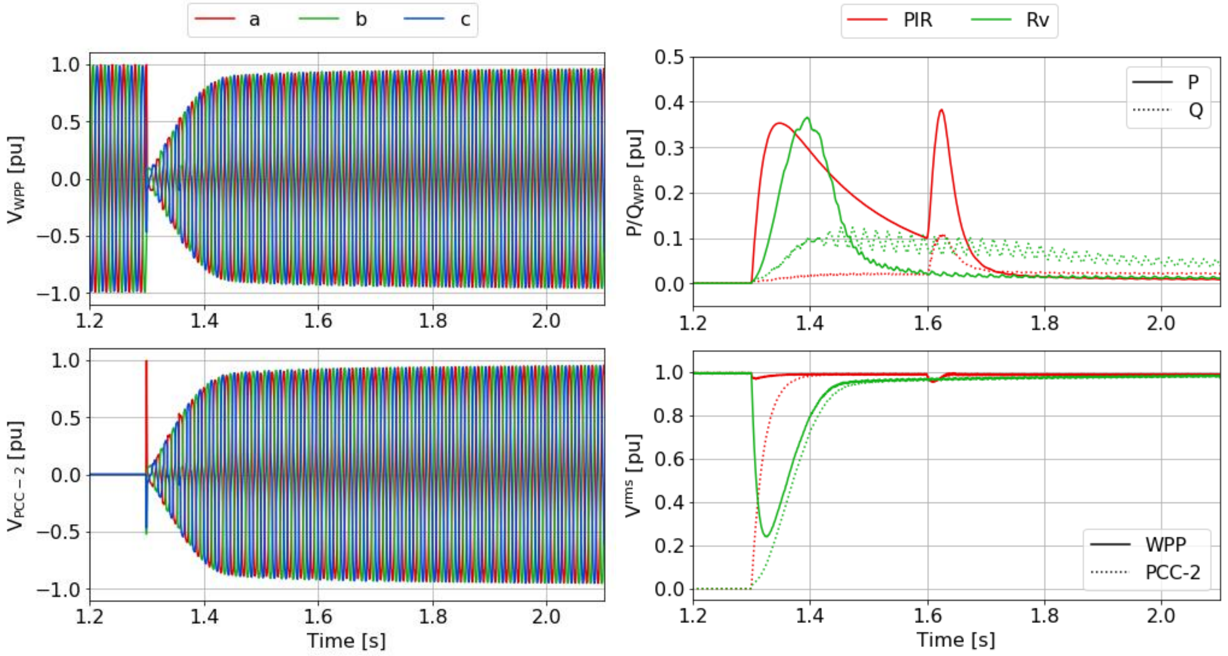


At WPP level

- PROMOTiON D3.7 (400 MW WPP)
  - ➢ PIR = 120 Ohm, PIT = 0.3 s
  - ➢ Ri = 1.5 pu, T = 0.06 s



- Mimics soft-start
- Transient peak reduced & no second peak as in PIR.
- Higher volt dip as internal resistance.
  - ➢ Volt drop ~ fault; Protection settings to be changed (as in conventional soft-start)



Conclusions

- Virtual soft-starter can reduce the inrush transients during transformer energization by grid-forming wind turbine, similar to a pre-insertion resistor.
  - ➢ Can eliminate PIR in hard-switching, without any loss of fault selectivity as in soft-start case.
  - ➢ Brunt of the transient born by WT-DC link, thus rotor-side control is essential in governing the dynamics.
- Sensitivity analysis results give insight into how the virtual resistance value can be chosen.

- Virtual resistance can reduce transient current peak during energization of downstream transformers in a string by grid forming wind turbine.
  - ➢ Worst case 70% residual flux leads to significant sympathetic inrush that lasts for sustained period of time, with virtual resistance effective only in reducing the peak amplitude.
- Virtual resistance method can also be used to minimize the inrush transient during the large offshore transformer energization, when implemented at the WPP level.
  - ➢ However, due to the nature of the method being similar to conventional soft-start, protection settings need to be changed to avoid the voltage dip triggering under-voltage trip relays.

Thank You

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