System Black Start from Wind Farm Sources

Ørsted

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About Ørsted

Ørsted overview and business units

Ørsted develops energy systems that are green, independent and economically viable

Ørsted

- Revenue (2018): DKK 76.9 bn (USD 11.6 bn)
- EBITDA (2018): DKK 30.0 bn (USD 4.5 bn)
- Credit Rating: Moody's Baa1 (stable), S&P BBB+ (stable)
- 6,080 employees
- Active in Scandinavia, United Kingdom, Germany, The Netherlands, USA, Taiwan and Japan

Major Shareholders (voting share %)

• Danish State	50%
• Seas NVE	10%
• Capital Group	5-10%

Offshore

- Global market leader in offshore wind
- Develops, constructs, owns and operates offshore wind farms
- Provides 100% wind backed Corporate PPA's & enabling products to large business customers
- 5.6 GW operational capacity
- 4.3 GW build-out plan towards 2022
- Ambition of 15 GW installed offshore wind capacity by 2025

Onshore

- Develops, constructs, owns and operate onshore wind, solar and energy storage projects
- 1,017 MW onshore wind operational capacity in the US
- 441 MW under construction and pipeline of 1.5 GW
- Energy storage solutions with a first 20MW battery storage project in operation
- 400MW Permian Solar PV plus 85MW of projects under development with PPAs secured

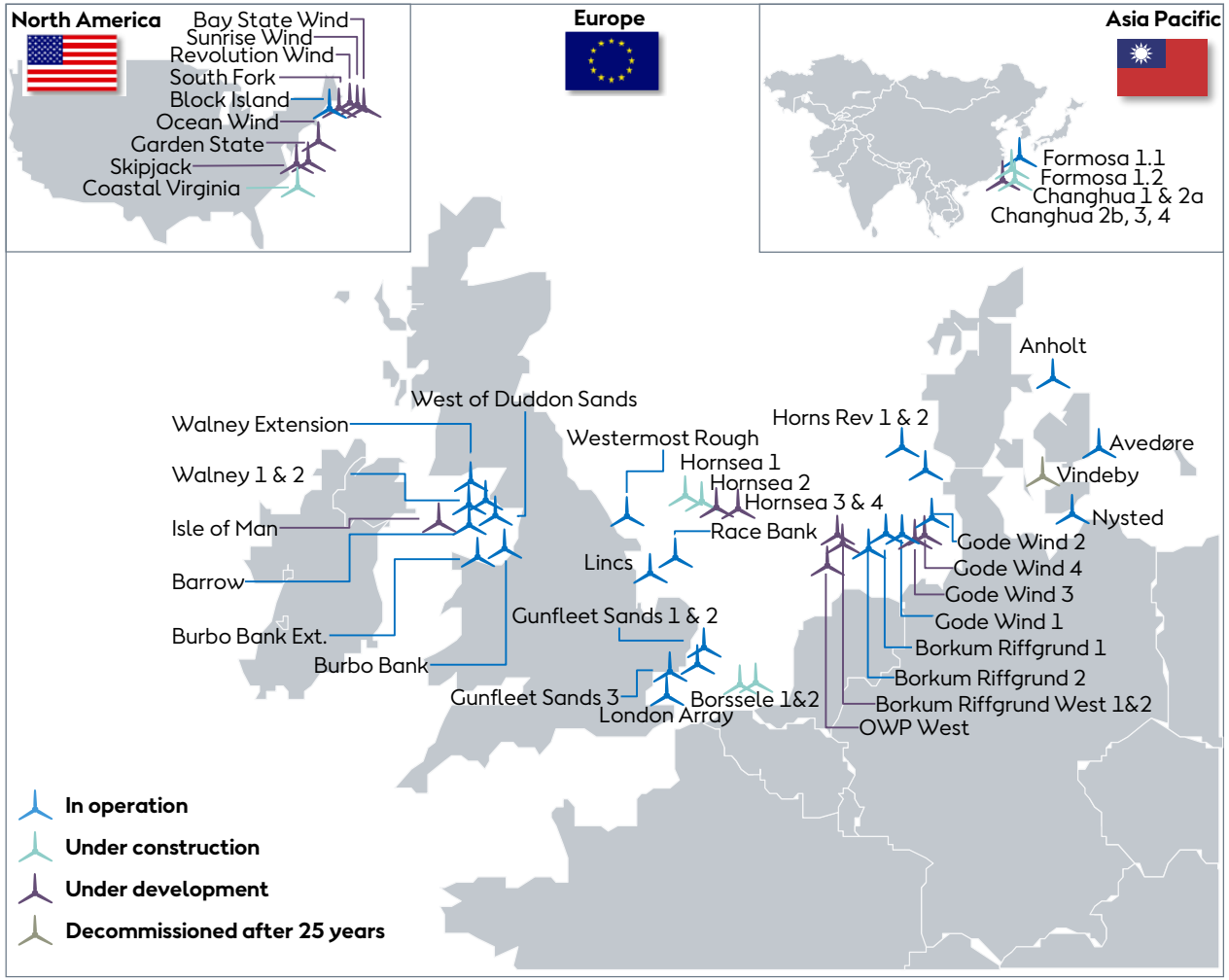
Markets & Bioenergy

- Heat and power plants converted from coal and gas to biomass and waste-to-energy
- #1 in Danish heat and power generation with 25% of market
- Energy supply solutions for B2B customers
- Provides route-to-market for own and customers' generation portfolio
- Market trading operations to optimize hedging contracts

Ørsted Offshore overview

Global market leader in offshore wind with 25+ years of experience

Ørsted offshore wind global footprint



Unparalleled experience and track record

1991 — 25+ years of experience and track record in the offshore wind power sector — 2019

25 offshore wind farms in operation

4 offshore wind farms under construction [1]

5.6 GW Constructed capacity

4.3 GW under construction

~ 2,450 Dedicated employees

13 million people with clean electricity

~ 1,150 turbines World's leading operator

23 Partnerships

Note 1: In addition to these wind farms, Ørsted is constructing the 12MW Coastal Virginia demonstration project in the US on behalf of Dominion Energy. Further Ørsted has a 35% share in Formosa 1 in Taiwan

About black start

Blackout

Largest outages in history

1

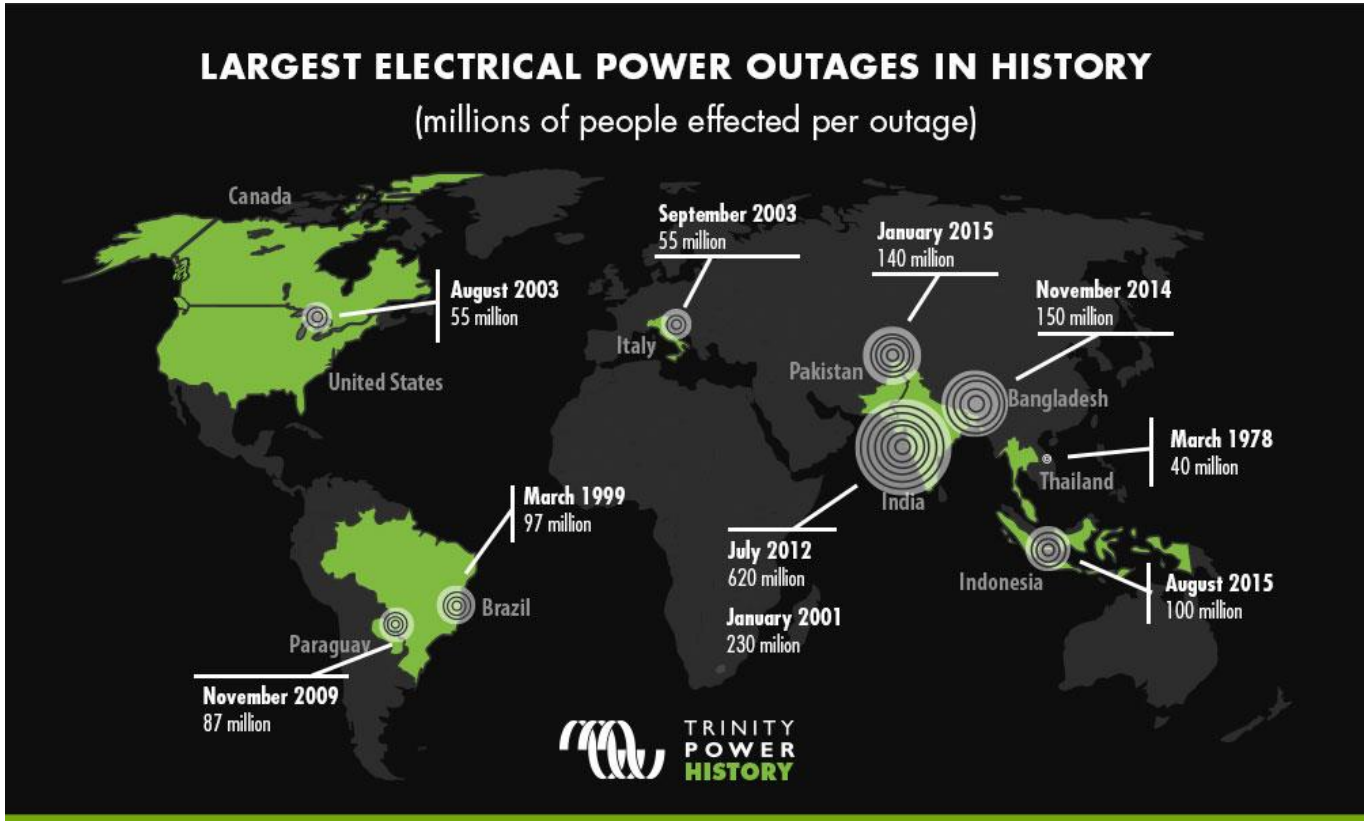
- July 2012, **India**: The biggest power outage in India to date, and potentially the biggest power failure in the world, ever, left half of India-upwards of 620 million people-without power.

2

- January 2001, **India**: 230 million people lost power due to a fault in the transmission system in one state, causing cascading failure throughout the northern Indian region.

3

- November 2014, **Bangladesh**: A nationwide power outage affected 150 million people for half a day, traced to the failure of a power transmission line from India into Bangladesh.



Source: https://www.trinitypower.com/ten-biggest-electrical-power-outages-of-all-time/

Black Start

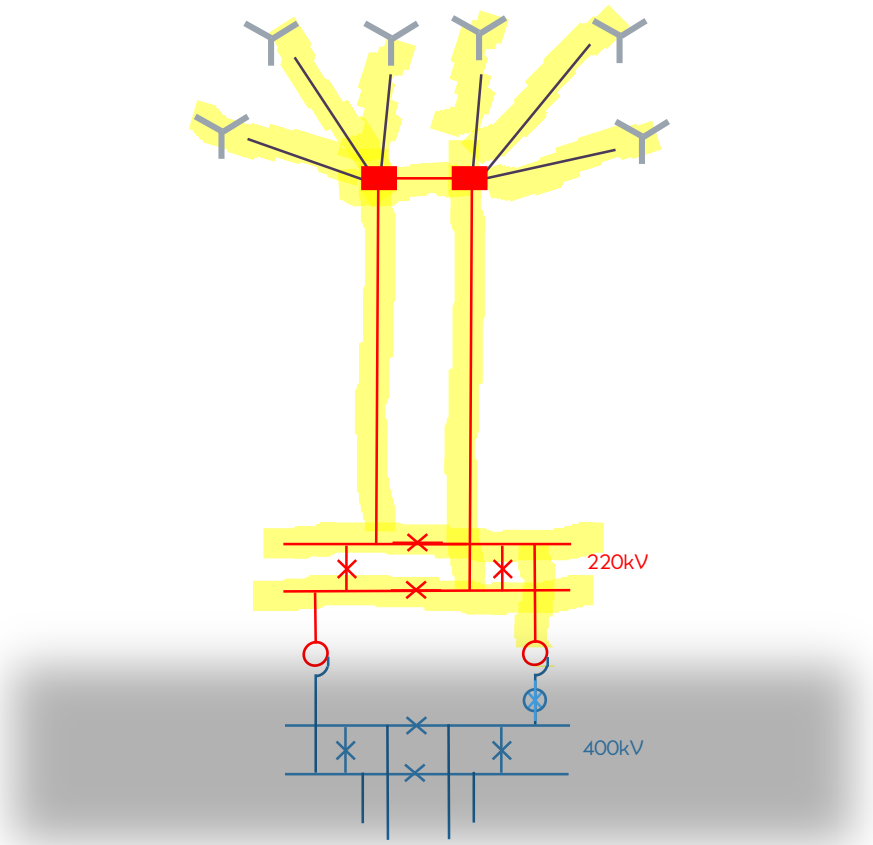
Can large offshore wind farms technically and economically provide black start?

Still within R&D area

- Renewables need to black start, if conventional generation to be closed
- Key challenges will be to incorporate design changes required to energize the cables and create a power island
- Ørsted is developing design solutions to overcome these challenges

Market development need

- Key way for a wind farm to provide black start economically is to build in the capability from the start
- Contracts for black start service need to be agreed at the early stage
- Contracts for black start need to be of reasonable duration to spread the cost



Black Start and Green Start

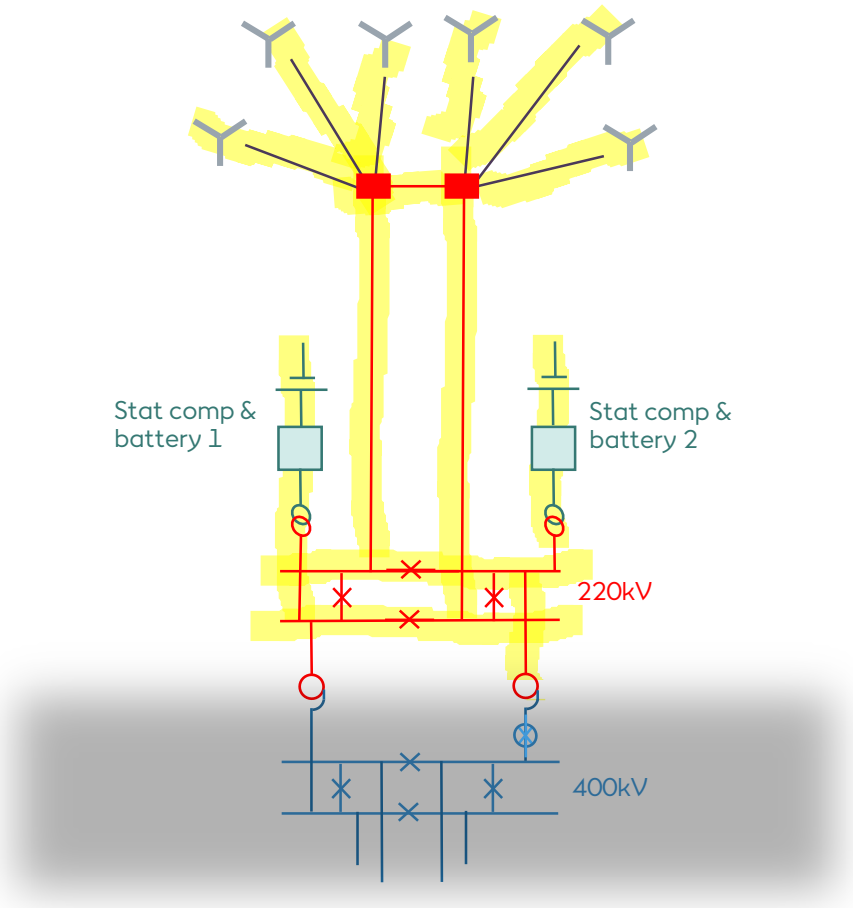
Can wind farms contribute to system restoration?

Green Start from wind farms

- The wind farm output power is dependent on wind conditions
- Grid restoration can be provided only when wind is blowing
- Does wind farm need to energize its own assets or also onshore transmission system?

Black start from wind farms

- Incorporating a BESS into the wind farm design may enable black start from wind farms
- STATCOM combined with BESS would provide uninterrupted grid forming capabilities

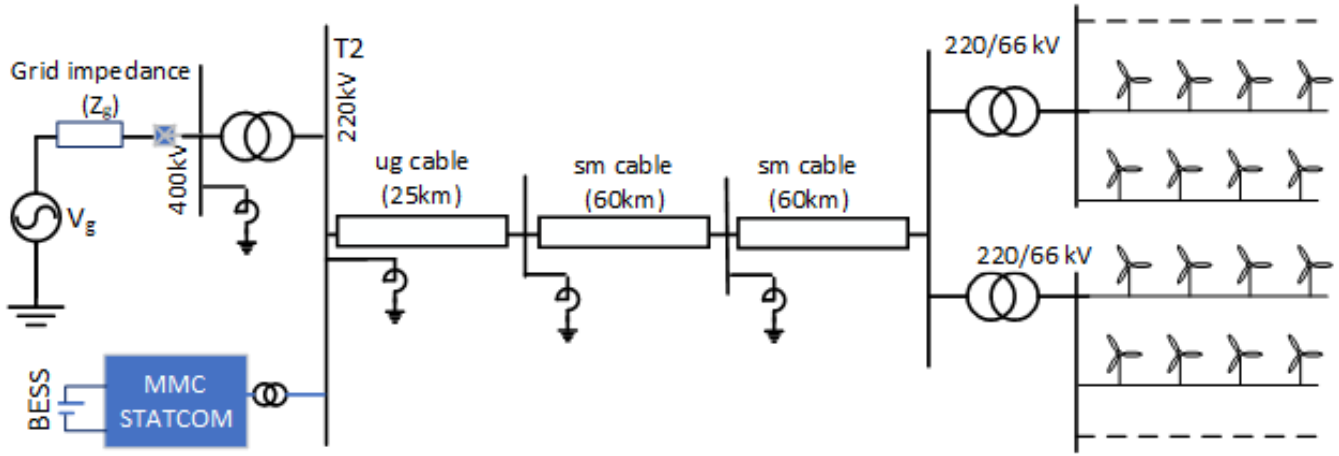


Grid Forming Converter

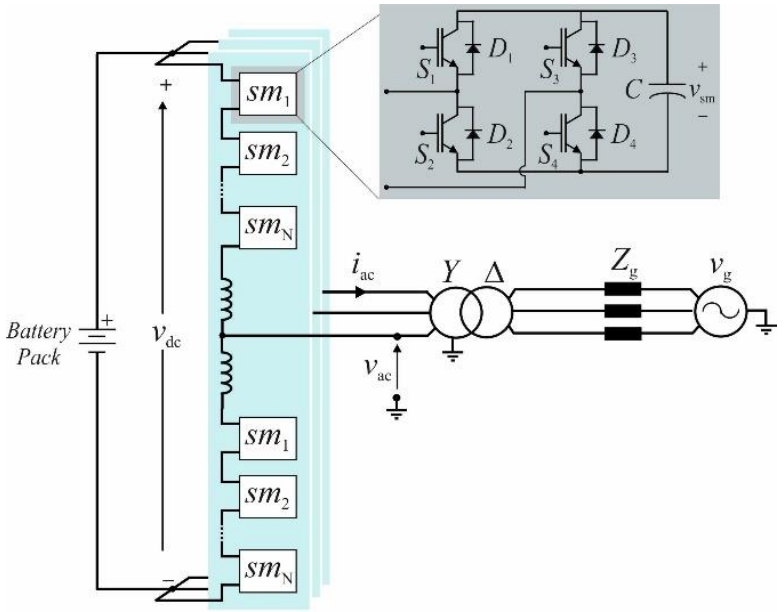
Integration of STATCOMs with BESSs

Black start in wind farms

- Option 1: service requirement adjustment to accommodate wind farm capabilities delivering green start. Wind is stochastic in nature. Service delivered when wind available.



- Option 2: expand wind farm functionality to deliver classical black start. Storage can increase the black start availability. Integration of storage at the transmission level is needed.



- R&D project on STATCOM and BESS integration:
  - Which STATCOM topology?
  - Which control solution (voltage control, current limitation, inertia response)?
  - What is the short-circuit current contribution?
  - How to assure power quality island mode (active filtering)?
  - What is the energization scheme?

Source: S. Chaudhary, R. Teodorescu, Ł. Kocewiak, P. Johnson, C. Y. Chen, B. Berggren, L. Harnefors, "Challenges in Integration of MMC STATCOM with Battery Energy Storage for Wind Power Plants," in Proc. The 18th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as Transmission Networks for Offshore Wind Farms, Energynautics GmbH, 16-18 October 2019, Dublin, Ireland.

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About modelling and simulations

Modelling and Simulations
In time domain

Desktop simulations

- Full wind power plant model for load flow (LF) studies.
- LF simulations: *active power flow, reactive power balance*.

- Full wind power plant model for short-circuit (SC) studies.
- SC simulations: *protection settings, components dimensioning*.

- Aggregated wind power plant model for electromagnetic transient (EMT) studies.
- EMT simulations: *grid forming, energization, switching operations*.

Real-time simulation

- Simplified wind power plant model for real-time (RT) simulations.

- Power converter control hardware in the loop (CHIL) studies..

- Converter operation: *grid-forming settings, controller tuning, stability*.

- System operation: *island mode operation, power quality, operational scenarios, stability*.

Onsite demonstration

- Commissioning of simulated and tested functionality.

- Disconnection from the power grid at the onshore substation.

- Adjustment of system protection settings to assure island mode operation.

- System energization by grid-forming converters.

- Island mode operation of wind power plant.

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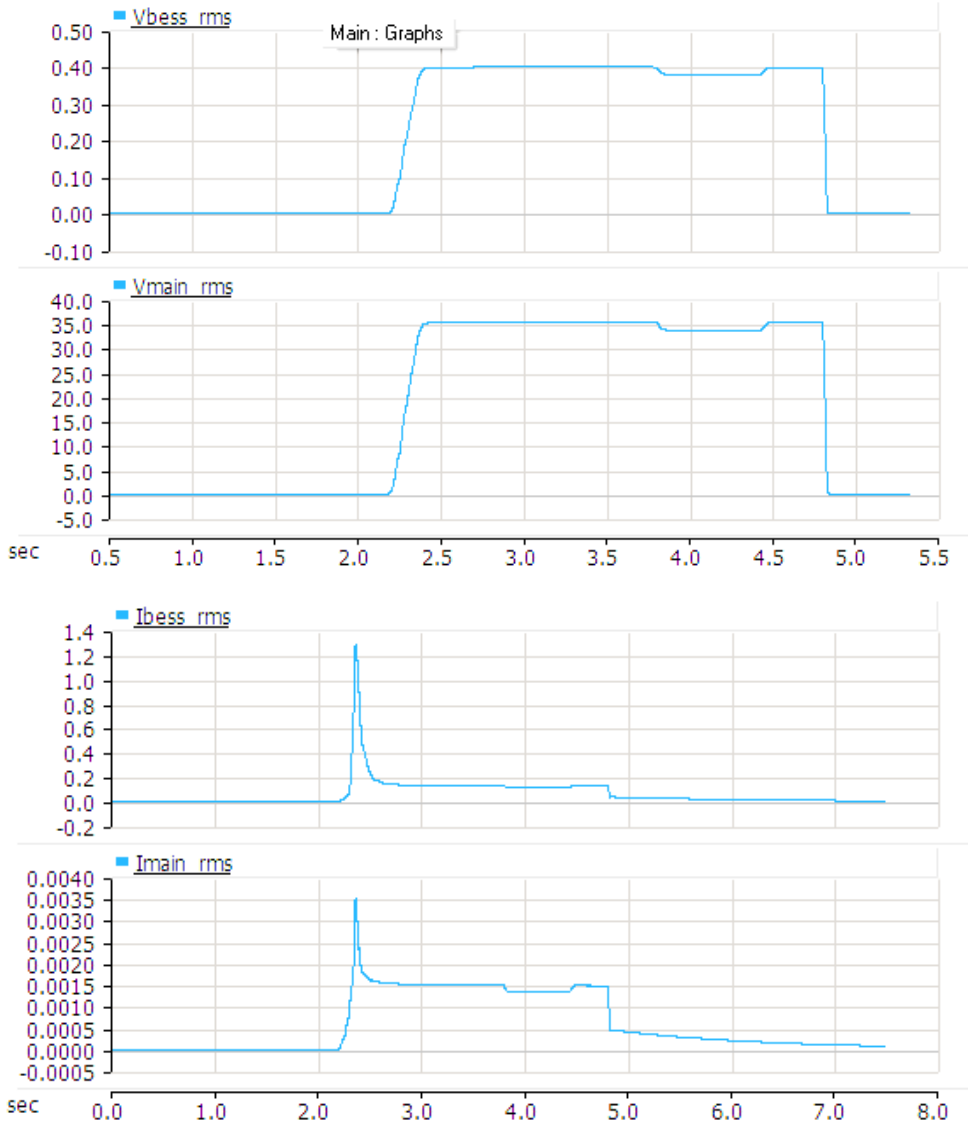
Black Start Concept Simulations

In an offshore wind power plant with BESS

Island operation

- Grid forming converter to provide voltage and frequency reference.
- Wind farm electrical infrastructure energization to provide island operation.
- Small- and large-signal stability need to be maintained during energization and normal operation.
- Accurate models need to be provided to perform complex black start complex simulations.

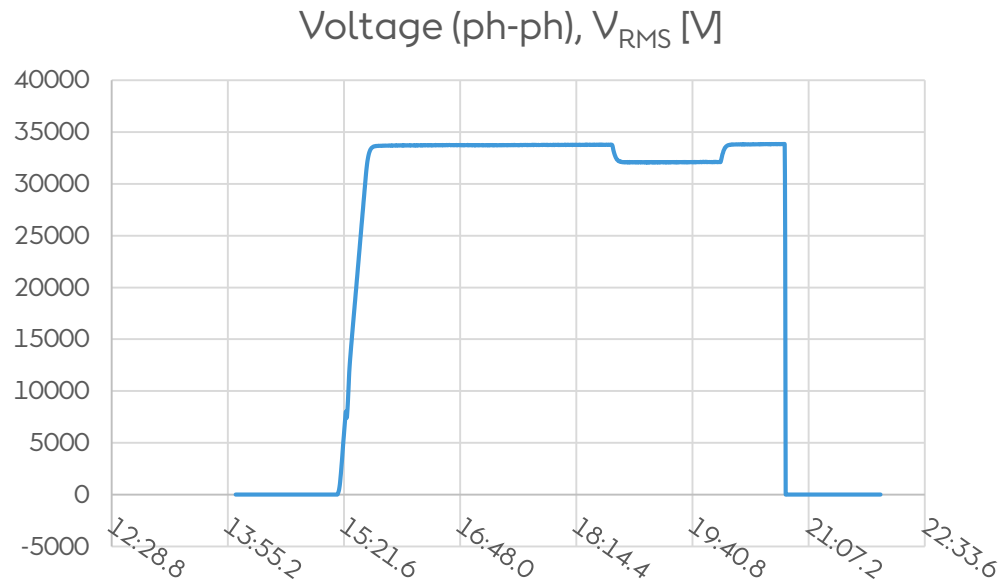


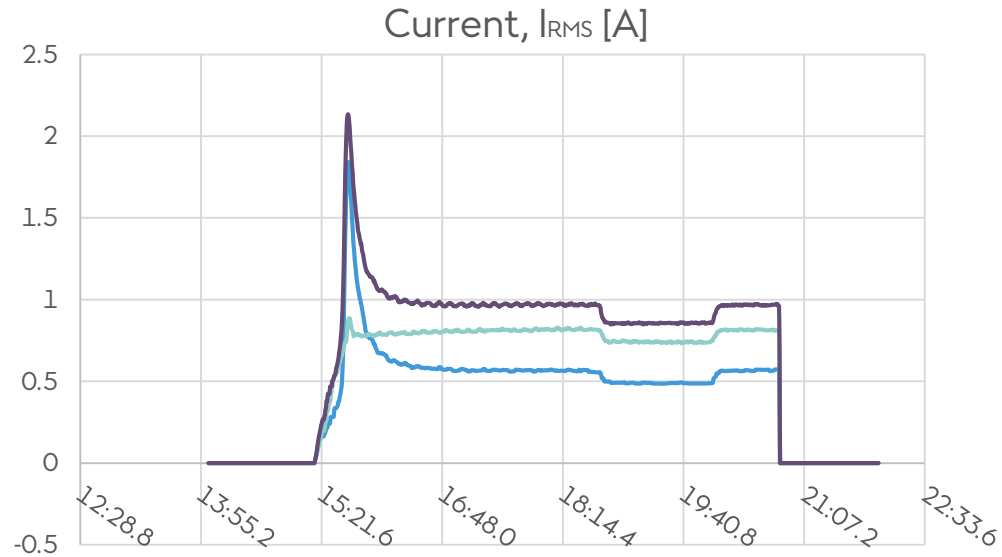
Black Start Concept Test

In an offshore wind power plant with BESS

Island operation

- Good agreement between simulations and real-life observations provides confidence in appropriate system operation.
- Robust grid forming converter design and control implementation is required for all possible operating conditions.
- Different grid-forming converter control scenarios are developed. Which is the best for black start?





Interoperability between converters

Stability analysis methods according to CIGRE C4.49

Transfer-function-based

- Classical approach used in control theory.
- Requires data from suppliers and TSOs.
- Black-box model approach.
- Indicates stability and quantifies robustness.
- Inconvenient for root cause analysis.

Impedance-based

- Previously used in DC grids.
- Requires data from suppliers and TSOs.
- Black-box model approach.
- Indicates stability but difficult to quantify robustness.
- Difficult to perform root cause analysis.

Passivity-based

- Commonly used in traction / railway systems.
- Requires data from suppliers and TSOs.
- Black-box model approach.
- Indicates stability but difficult quantify robustness.
- Difficult to perform root cause analysis.

Eigenvalue-based

- Commonly used in power system studies.
- Requires data from suppliers and TSOs.
- Black-box model approach but more information revealed.
- Indicates stability and quantifies robustness.
- Convenient to perform root cause analysis.

Time domain

- Commonly used for dynamic simulations.
- Requires data from suppliers and TSOs.
- Black-box model approach but more information revealed.
- Indicates stability but difficult to quantify robustness.
- Convenient to confirm stability.

Source 1: CIGRE C4.49, "Multi-frequency stability of converter-based modern power systems"
Source 2: . Ł. Kocewiak, Ch. Buchhagen, Y. Sun, X. Wang, G. Lietz, M. Larsson, "Overview, Status and Outline of the New CIGRE Working Group C4.49 on Converter Stability in Power Systems," in Proc. The 18th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as Transmission Networks for Offshore Wind Farms, Energynautics GmbH, 16-18 October 2019, Dublin, Ireland.

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Converter Model Quality to Perform Studies

Wind turbine model validation according to IEC TR 61400-21-3:2019

CLASS 1. SIMULATED/CALCULATED BASED ON WT DESIGN

- Harmonic model development based on simulations/calculations or software in the loop (SIL) studies incorporating actual design of a WT taking into account precise product specification, e.g. harmonic model developed based on WT design documentation and detailed models (e.g. EMTP-based, C-code from the control software, etc.).

CLASS 2. VERIFIED BY LAB

- Harmonic model development based on control hardware in the loop (CHIL) and/or power hardware in the loop (PHIL) studies in a controlled environment. The test will incorporate the actual WT components such as the control or/and converter systems.

CLASS 3. VERIFIED BY FIELD MEASUREMENTS

- Harmonic model is verified by measurements and model outputs are verified by measurement of the WT. The measurements can be done either at the test rig/bench or in the field, e.g. harmonic model verified by measurements or an prototype WT or at the test stand.

Source 1: IEC TR 61400-21-3:2019, "*Wind Energy Generation Systems – Part 21-3: Wind turbine harmonic model and its applications*"

Source 2: . B. Andresen, F. Martin, T. Dreyer, K. Ntovolos, F. Brinch Nielsen, P. Sørensen, Ł. Kocewiak, "IEC TC 88 Wind Power Generation Standards in Relation to Grid Connection Requirements," in Proc. The 18th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as Transmission Networks for Offshore Wind Farms, Energynautics GmbH, 16-18 October 2019, Dublin, Ireland.

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What next?

Summary

What is needed to provide black start from wind farms?

Simulations

- Suitable and validated models to perform complex black start simulations
- Time- and frequency-domain simulations to cover wide range of operational scenarios
- Grid-connected converter (e.g. wind turbine, STATCOM) interoperability to assure high performance and robustness

Technology

- Reliable and robust power electronic solutions to provide adequate grid forming solutions for black start
- Capability to provide grid-forming converter connection to the transmission system
- Integration of large-scale wind farms with battery energy storage systems

Market

- Adjustment of regulations to integrate renewables into the black start market
- Market conditions adjustment to allocate green start as well as black start from wind farms

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Thank you