Minimum Grid-Forming Turbines needed for Greenstart of Offshore Wind Power Plants: a case study

Anubhav Jain*, Jayachandra N. Sakamuri* and Nicolaos A. Cutululis†
*Vattenfall Vindkraft A/S, Kolding, Denmark
†Department of Wind & Energy Systems, Technical University of Denmark, Roskilde, Denmark

***Abstract*—High penetration of power-electronics interfaced renewable energy sources are expected to play a key role in acting as the cornerstone of the electric grid by participating in services such as blackstart and controlled islanding. Large offshore wind power plants cannot connect during early stages of system energization as the grid is weak so grid-forming wind turbine control is a viable option as it not only allows local power islands to help reduce warm-up time and facilitate restoration but also makes them more self-reliant with significant cost savings especially in areas where auxiliary power is costly. However for participation of conventional grid-following wind turbines in the offshore network energization sequence, transient stability of the inertia-less, reactive power demanding weak collector network must be ensured. First a rule-of-thumb estimate is proposed then by EMT simulations with detailed plant model and converter control we verify the minimum number of grid-forming wind turbines that makes greenstart feasible without loss-of-synchronism during any stage. Additionally key insights regarding the potential instabilities due to PLL tunings and Var injections in weak-grids have been highlighted, and the proposed solution in careful tuning of the grid-forming control parameters has been verified.**

***Index Terms*—Grid forming, Energization, Islanded Operation, Transient, Stability, Synchronization**

I. Introduction

GREEN energy transitions aiming for carbon neutrality and energy security have accelerated rapidly in recent years across the world. Driven by progressive electrification of energy demand shaped primarily by government policies, significant growth in wind and solar energy has made renewables cost-viable compared to fossil-fuel powered technologies across various sectors [1]. Renewable energy sources have already surpassed coal as the largest electricity source in 2025 and are projected to account for over 42 % of the global electricity generation by 2028 [2].

Today's grid codes are more demanding than for first generation power-electronics interfaced resources especially in regions of high penetration of non-synchronous renewables due to increased risk of transient voltage, frequency and harmonic instability [3]. Grid-forming (GFM) capabilities — such as standalone voltage creation, inertial and phase-jump frequency response, synchronization stability in weak grids and system survival support — are being increasingly requested from inverter-based resources like offshore wind power plants (WPP) [4] so that they can support the grid more pro-actively not only under normal and emergency states but also post blackout without having to rely on services from synchronous generators [5].

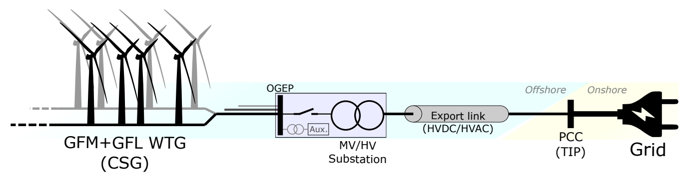


Fig. 1: Schematic of an offshore WPP consisting of Collector String Groups (CSG) all connected at Offshore Grid Entry Point (OGEP) via a step-up transformer to HVDC/HVAC cable that exports the power to the main grid at the Transmission Interface Point (TIP).

For an offshore WPP as shown in Fig. 1 to provide the grid with the most challenging grid-forming service of an aggregated blackstart unit in power system restoration, various target states for its own energization must first be passed [6]. This *greenstart* sequence up to the OGEP terminal begins with self-start of wind turbine generator (WTG) by a backup supply leading to houseload operation when rotor is oriented to the wind followed by magnetization of transformers and charging of array cables that demand early-stage voltage/frequency stability during associated transients [7]. Once multiple WTGs are synchronized to emulate a relatively strong voltage source the upstream network including offshore transformer, export link and onshore terminal can be energized while ensuring stable and robust islanded operation before finally synchronizing to the onshore grid for block load pickup. Due to high reactiver power requirements of long-distance HVAC that limits power transmission capability for large offshore WPPs, HVDC provides a more economic alternative for efficient long-range bulk power transmission with slightly more complex energization sequence [8].

A. Contribution

This study focuses on the energization of the offshore collector network which is of utmost concern to the plant operator to ensure controlled islanded operation of the aggregated asset before providing any onshore blackstart or grid-forming service. Moreover keeping the WTGs ready for *hot-start* power ramp-up can decrease the impact of a blackout by reducing restoration time and unserved load [9]. GFM

WTGs offshore can also help eliminate or minimize dependence on auxiliary diesel generators essential for maintaining temperature and humidity for safe and reliable operation of all components. Apart from reducing fuel consumption and related maintenance costs, this can help save costly space and personnel-safety volume constraints on the substation thus increasing power/energy density. Lastly and more importantly emissions during plant downtime when the diesel gensets are run fulltime shall be offset improving carbon footprint and also potentially increasing reliability.

The best case is to have all WTGs as GFM as that clearly allows for successfull energization of an offshore WPP by soft-start to mitigate distortions and reduce risk of protection trips, whether HVDC [8] or HVAC [10] connected. However an open question remains as to after grid re-connection is it better to keep using GFM or rather transition smoothly to GFL mode. This is especially relevant for the turbine controller due to contrasting objectives i.e. extract power as per demand of the island system for keeping rotor speed within limits during block load pickups as opposed to satisfy maximum power production in normal grid connected operation for optimizing revenue. Thus the principal question tackled in this study is how many minimum GFM WTGs are necessary and sufficient for the energization and islanded houseload operation of the offshore WPP. It is essential for CAPEX optimization since GFM WTGs have an additional development and reliability cost compared to the state-of-art grid-following (GFL) WTGs.

The system model and control for this study is explained in Section III, followed by a rule-of-thumb estimate in Section IV of the minimum number of WTGs required to sustain offshore network greenstart and islanding based on the dynamic loading. Then EMT studies have been performed in Section V as Non-Lyapunov method for transient stability analysis [11] to verify and optimize the calculated estimate of the GFM share.

B. State-of-art and Gap identification

Firstly it has been proven that only GFM converters can provide true voltage source behavior for enhancing grid strength, that is well maintained regardless of the direction of the current vector perturbation. Additionally a GFM/GFL capacity ratio of around $18\,\%$ already increases the stability margin significantly enough to allow WPPs to work stably at LV-terminal SCR $= 1$ although only small-signal stability in grid-connected scenario with infinite-bus has been demonstrated. Notably slightly more GFM converters are needed to achieve similar damping performance if the infinite-bus is replaced by an equivalent synchronous generator [12].

A GFL inverter is more precisely *voltage-following current-forming* meaning it can form a current-island with a stable frequency but widely fluctuating grid voltage depending on setpoint and load impedance. It is interesting to note that two GFL inverters can synchronize with each other without an external voltage sources (GFM) and maintain transient stability when the system impedance is resistance-dominated [13]. However this does not apply for offshore collector networks due to long network of high cross-section cables resulting in a large capacitance Var demand during the initial stages of energization before power-production begins.

A recent study of fully converter-based Ireland grid identifies a minimum of approximately $40\,\%$ GFM capacity for the future system based on balanced three-phase fault response requirements at all busbar nodes [14]. However all converters were assumed to be of large size and replacing existing conventional generation close to major load centres and the HV-transmission network. This is equivalent to having GFM behaviour at the HV terminal of the OGEP in case of an offshore WPP — a rarity since transmission grid scope enforces converter manufacturers to provide LV-side control that limits GFMness — touched upon in Section V-A.

Moreover as suggested in [14] the capacity of most converter buses tends to be smaller than existing fossil-fired generation buses and distributed somewhat unevenly around the network, distant from load centres and the HV network that can reduce the *system wide average* GFM share to $30\,\%$. Since individual regions may experience a minimum GFM requirement noticeably higher or lower than the mean value, the transient stability for a single node — here the OGEP — is the main motivational focus for this study.

Some recent simulation studies and field demonstrations for onshore wind farms show that specifically designed parameterization can result in a ratio as high as 20 GFL WTGs per GFM WTG, although it is noted that the combination is robust only when subjected to small load steps and standard configurations indicate a ratio of 3:1 as safer, albeit depending on the exact layout and size of the wind farm [15]. Since offshore WPPs tend to be significantly larger in capacity with a larger cable network and reduced stability margins, it is expected that for a transient-wise challenging use-case such as blackstart/energization, a lower ratio would be more robust, as proven later in Section V. This is already hinted at by Section IV that shows the need for at least 3 WTGs to energize only 1 CSG or $25\,\%$ of the offshore network for the plant considered in this specific case study, while only 1 was needed for the entire onshore wind farm in [15].

The already foreseen system-wide stability challenges in a power-electronics rich grid are relevant more so for the offshore collector network especially with low loading and less generation connected in the start of a blackstart or post-blackout islanding scenario [3]. For the aggregated offshore plant to have GFM behaviour at OGEP it is essential that the constituent mix of GFM and GFL demonstrate synchronization stability not only during steady-state but also in transients associated with energization sequence. Similar to a microgrid the GFM voltage control imposes a strong or slow-changing (internal) voltage phasor but its outer power-control loops must be slower to avoid control interactions with nearby converters. This can be especially challenging at higher power levels which restrict switching frequency and thus limit inner-most current-control loop bandwidth [16]. Thus careful tuning is essential as demonstrated in Sections V-B & V-C. Since maintaining synchronism is key for having plant-level stiff GFM behaviour, Loss-of-Synchronism (LoS) is selected as the KPI for transient stability studies performed here. This is explained briefly in the next Section II.

II. Synchronization Stability

A significant amount of research has been done to understand small and large signal transient stability of converters for maintaining synchronization with the grid during loading dynamics and faults.

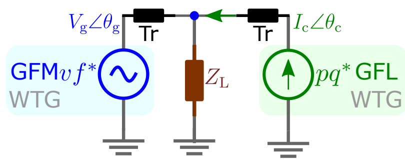


Fig. 2: Simplified conceptual single-line circuit of a single GFM and GFL WTG island with local load.

For GFL inverters synchronization is almost always exclusively *voltage-based* done by a Phase-Locked-Loop (PLL) that works well for traditionally strong grids but faces instability issues in weak grids with high impedance, large reactive power loads, less generation or heavy loading [17], [18]. The basic PLL structure must be enhanced to avoid the well known problems that occur in weak grid operation viz. [19]:

- Higher injection current with bigger reactive components and larger grid impedance increase the self-synchronization effect which is a positive feedback disturbance that pushes the PLL output away from its steady-state grid input phase.
- Instabilities can also arise due to interactions between PLL and grid impedance with larger gains leading to a negative resistance at the inverter output and decreasing passivity-based stability.

To avoid LoS in GFL inverters, the power network should be strong enough, or the point-of-connection should be close enough to an ideal/stiff voltage source (infinite bus) such that the GFL control can effectively follow the established frequency and voltage. Changing the converter control scheme from GFL to GFM is equivalent to increasing the power grid strength thanks to the latter's voltage source behaviour [12], [13].

GFM converters on the contrary rely on *power-based* synchronization mimicing synchronous generators and are able to avoid instability issues of PLL in weak grids [18]. A large droop gain creates a small inertia and damping in the GFM inverter making it likely to transient instability due to less stiff voltage source behaviour [13]. However parameters for a single unit system may not guarantee stability for multiple units and it is to be noted that low effective frequency and voltage droops with high inertia signifying stiffer sources are required to damp the inter oscillations [20]. It must be noted that GFM inverter is vulnerable to instability in strong grids with low grid impedance [13] and while stiffness helps in weak-grids some droop for power-sharing allows for flexibility between parallelled GFM sources reducing voltage/frequency swing transients as in conventional synchronous generator operation.

Transient stability of both GFM and GFL inverters in two and multi-unit systems can be assessed considering their virtual inertia (J) and damping (K_D), which depends on power-frequency filter time constant and droop for GFM while related to PLL gains for GFL [13]. For both smaller J and K_D increase the chance of transient instability like a synchronous generator and GFM-GFL inverters synchronize to each other depending on their inertia ratio. Moreover duality of GFM and GFL control suggests that the swing-equation based power-synchronization has a similar structure to PLL [13], [21] and cross-synchronization can make PLLs interact with each other through system impedance leading to cross-coupling related instabilities [19]. Thus in general large synchronization controller gains (droop in GFM and PLL bandwidth in GFL) increase the likelihood of interaction and synchronization instability [13].

A single voltage-source emulating GFM WTG connected to a current-injecting GFL WTG in an island with local load (such as auxiliary, cables, transformers) and in absence of any external grid can be compared analogously to a PLL-synchronized converter in a weak-grid scenario as shown in Fig. 2. Thus the transient stability tuning insights mentioned above have been directly used to explain the results presented in this study in the upcoming Section V.

III. System Model and Control

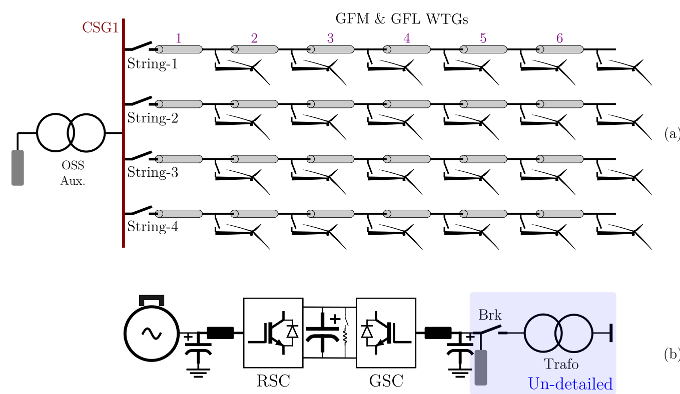


Fig. 3: (a) Schematic of offshore CSG consisting of 4 strings each with 6 cable sections and 6 WTGs, along with OSS auxiliary transformer and load. (b) Detailed model of GFL/GFM WTG with the highlighted (in blue) part being used as an undetailed version.

In scope of this study an EMT model of the $1.4\,\mathrm{MW}$ Norfolk Vanguard-East offshore wind zone [22] has been developed in PSCAD. For simplicity and due to the modular approach adopted in this work, only one (out of four) $66\,\mathrm{kV}$ Collector String Group (CSG) is modelled in detail as shown in Fig. 3(a). PI-section model has been used for the two types of cables with reactive power requirements of 0.33 and $0.63\,\mathrm{MVar/km}$ resulting in total string-wise demand as summarized in Table I. A high-frequency model with saturation is used for the $0.69/66\,\mathrm{kV}$ WTG transformers rated $16\,\mathrm{MV\,A}$ and Offshore Sub-Station (OSS) auxiliary $0.44/66\,\mathrm{kV}$ $2.5\,\mathrm{MV\,A}$ transformer. An auxiliary load of $1\,\%$ for WTG and $0.1\,\%$ for OSS has been considered.

Fig. 3(b) shows the model used for $15\,\mathrm{MW}$ WTG developed in scope of this study, consisting of $2\,\mathrm{kHz}$ switching model

String	1	2	3	4	CSG-1
MVar	10.79	6.47	7.49	9.29	34

TABLE I: Reactive power requirements of each string and total in CSG-1.

for grid-side converter (GSC) and average model for rotor-side (RSC) converter since machine-side dynamics are much slower than electrical transients. The permanent magnet synchronous generator receives torque setpoint from a simplified turbine controller consisting of a closed-loop power feedback to create the speed reference [23]. A pitch controller is used to regulate the rotor speed at power levels above rated. Additionally a protection module for over/under voltage/frequency and over-current trips along with a synchronizer for speeding up synchronization are also implemented.

For sake of simulation speed the undetailed version as highlighed in Fig. 3(b) is used at nodes where WTGs are not subject to GFL/GFM control but remain essential to represent the distributed loading needs such as auxiliary and transformer, correctly capturing any inrush transient related stability impacts at low loads during early stages of the CSG energization.

A. GFL

The WTG is controlled conventionally with RSC extracting power from the machine based on setpoint from turbine controller and GSC regulating the DC link voltage along with any reactive-power injection requirements of the grid. The startup sequence is initiated by main breaker closing to energize the WTG transformer when grid voltage is available, followed by deblocking GSC to precharge the DC link and then finally deblocking RSC for machine control to ramp-up power production. It is important for energization studies that the DC control bandwidth and ramp-rate limits of the machine are set to best represent the generator capability.

B. GFM

The WTG is controlled such that GSC regulates the magnitude and frequency of the AC voltage while RSC maintains the DC link voltage by extracting power from the machine to feed the electrical load. Droop based GFM control with cascaded voltage-current inner control loops as implemented in [10] has been used for the purpose of this study, shown in Fig. 4. The $\frac{\Delta V}{\Delta Q} = K_{\mathrm{QV}}$ droop is used to adjust the voltage reference based on reactive-power flow while $\frac{\Delta f}{\Delta P} = K_{\mathrm{Pf}}$ droop with a low-pass filter T_{f} is used to provide power-based synchronization mimicking a virtual synchronous machine [24]. An additional proportional feed-forward gain $\frac{\Delta \theta}{\Delta P} = K_{\mathrm{P}\theta}$ is present to provide active damping and ensure stable parallel operation of multiple GFM WTGs.

The startup sequence for GFM is different than for GFL, in that first RSC is deblocked to control the DC link then GSC is deblocked to start forming the MV AC grid point, finally followed by main breaker closure to energize the string cable sections and WTG transformer. Here transformer is energized with the AC voltage ramp-up using soft-start to reduce inrush transients [8].

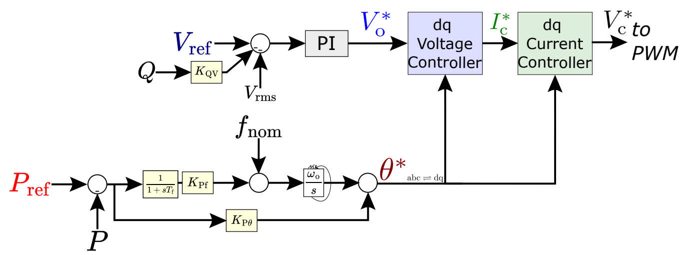


Fig. 4: Droop based GFM control implemented, reproduced from [10]

IV. Rule-of-thumb

A first estimate of the minimum number of WTGs needed to power the energization of CSG can be made based on the static load demand viz. reactive power requirements of the cables and real power auxiliary demand of the offshore plant. Based on the total auxiliary load in the offshore network that includes WTGs and OSS, a single WTG would be enough for the entire offshore zone consisting of four CSGs and for redundancy two WTGs would safely allow supplying auxiliary loads.

However to supply all the distributed auxiliary load the entire inter-array cable network must be energised. Thus sufficient WTG capacity is needed to absorb the reactive power generated by the long cumulative length of cables (order of $100\,\mathrm{km/CSG}$) for controlling the voltage of the offshore island. Based on the plant layout data the average reactive power requirement is about $8.75\,\mathrm{MVar}$ per string, $35\,\mathrm{MVar}$ per CSG, and in total $140\,\mathrm{MVar}$ for the entire offshore network zone. Simple arithmetic provides an estimate of $15\,\mathrm{MW}$ WTGs needed to at least *1 per string* or *3 per CSG*. A more optimal choice results in 5 for 2 CSGs thus, a minimum of 10 and maximum of 16 WTGs to meet the entire offshore zone's static power demands during energization. It must be noted that the "greenstart" WTGs must supply not only the cable Var but also the network losses and auxiliary load for successfully starting up the offshore WPP.

Since WTGs can be GFM or GFL the next logical question to answer is what is the optimal minimum number of GFM WTGs required to control the offshore island voltage and frequency while maintaining stability for GFL WTGs to share the majority of real and reactive power demand. This is essential to create a valid business case for self-startup of offshore WPPs using GFM WTGs justifying their extra cost as today they are still in development and are not yet proven to be reliable or cost-effective for offgrid systems with variable generation.

Keeping aside the economic optimization as it is not the focus of this work, offshore zone self-energization without a strong external grid connection is technically challenging especially during the start of the sequence when loading and generation is low, making the network extremely prone to instabilities. This follows directly from the offshore network's similarity to a converter-rich weak-grid with lack of inertial reserves and voltage control capability, high impedance related cross-couplings and potential new interactions between converter controls and filters [3], [5].

Thus the startup sequence with rule-of-thumb estimate of number of WTGs must be simulated to ensure that the minimum number of GFM WTGs is valid not only for steady-state operation but also during transients throughout the energization sequence.

V. Simulation Study Results

To verify the transient stability of the self-energization of the offshore CSG EMT simulations have been performed aiming at successful step-wise sequence with minimum number of total and GFM WTGs viz. 1 per string to 3 per CSG. GFL WTGs are connected to share the reactive power demands and loss-of-synchronism (LoS) is used as success criteria for the sequence, giving insights into stability limits for large load steps and robustness obtained from delicate tuning of specific control parameters.

A. String energization by GFM WTG

The first step in the sequence is energization of a string by a GFM WTG. The first "blackstart" WTG must be GFM to create network voltage for energising cables and other WTG transformers so that they can be synchronized. Clearly sufficient reactive power capability is needed in the first WTG to connect the string and soft-start methodology or virtual-resistance loop can be adopted for reducing transformer inrush effect [7].

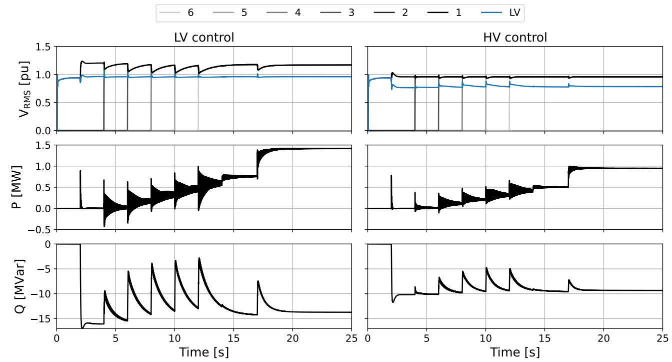
Fig. 5 shows transients during energization of the entire string-1 followed by sequential connection of WTG transformers, with GFM WTG controlling LV-side or HV-side terminal voltage to $0.94\,\mathrm{pu}$. It is clear that the WTG is able to deal with the transients safely as converter currents are within limits and the reactive loading is within the WTG capability. Moreover transformers do not cause any severe transient issues with the farthest one being most demanding due to sympathetic inrush.

While the HV-side rises to an over-voltage of $1.2\,\mathrm{pu}$ in case of LV-control due to the large Var being absorbed single-handedly by WTG-1, the LV-side voltage drops to about $0.8\,\mathrm{pu}$ in case of HV-control both of which may trigger over/under-voltage protection. Thus protection settings during startup must be adjusted although it is generally preferred to connect more WTGs first before switching in the long cables and share the total reactive power demand, since it also allows a higher fault current contribution due to more sources being online.

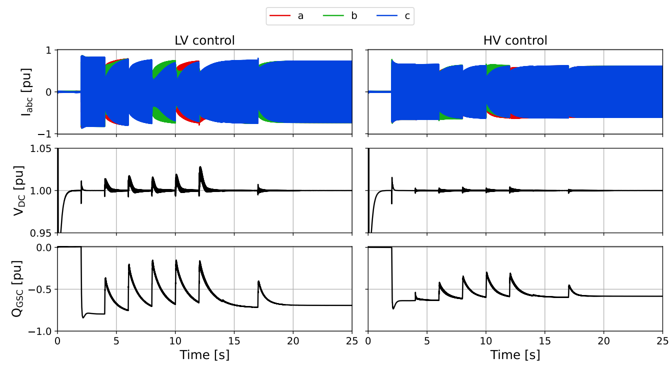
Overall the HV-side control allows for a stiffer voltage source behaviour of the GFM WTG resulting in lower steady-state power flows and peaks associated with transformer inrush, and reduced transients in the DC link voltage.

B. Next WTG synchronization and parallel operation

The next step in the sequence is connection of GFL WTGs to help offset the Var demand allowing for better voltage regulation and relieving the GFM WTG's capability for picking up subsequent strings and supplying OSS auxiliary load for CSG



(a) AC RMS voltage at transformer HV-side for each WTG and at LV-side also for WTG-1, along with the real and reactive power output at HV-side of WTG-1.



(b) 3-phase instantaneous currents and reactive power output of GSC, along with DC link voltage of WTG-1.

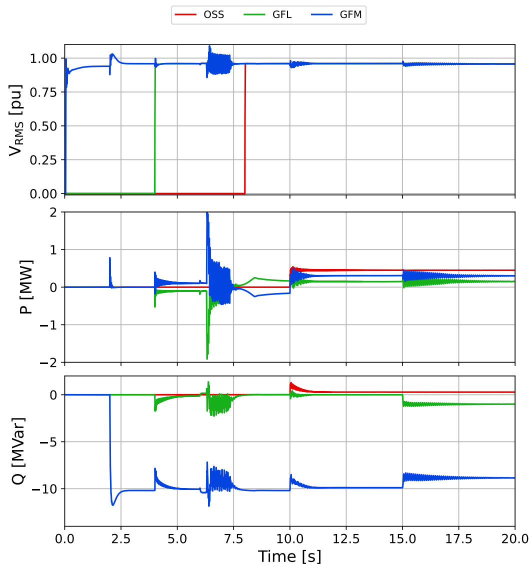
Fig. 5: Transients during energization of complete string-1 by GFM WTG-1 in LV-side and HV-side control at $0.94\,\mathrm{pu}$ reference voltage, followed by sequential transformer switchings.

energization. However the offshore network with a single GFM WTG represents an extremely weak grid making the transient stability of GFL WTGs challenging due to limitations of PLL, as described in Section II.

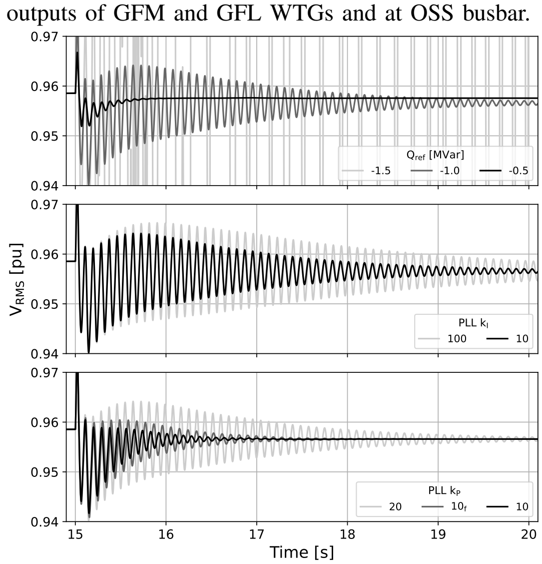
Fig. 6a shows successful synchronization of GFL WTG to GFM WTG and the oscillations observed when the GFL GSC is deblocked to control the DC link voltage around $6\,\mathrm{s}$ disappear when it starts producing power to share the OSS auxiliary transformer and load energization with the GFM WTG at $10\,\mathrm{s}$. Lastly, increasing the GFL WTG's reactive power setpoint Q_{ref} at $15\,\mathrm{s}$ unlocks capacity of the GFM WTG to be ready for the next string's energization.

However the Var share of GFL WTG seems to have a relatively low limit as $|Q_{\mathrm{ref}}| > 1\,\mathrm{MVar}$ step reduces stability margin causing instability for GFL WTG consuming $1.5\,\mathrm{MVar}$ out-of-total $10\,\mathrm{MVar}$ demand, as shown in Fig. 6b (top subplot). Guided by conclusions from Section II, tuning of the PLL is also essential in such weak-grid operational scenario to ensure safe stability limits [25]. Mid and bottom subplots in Fig. 6b show:

- increasing the PLL integral gain worsens the oscillatory response due to a decrease in damping and effectively the phase margin.
- decreasing the proportional gain leads to a lower band-

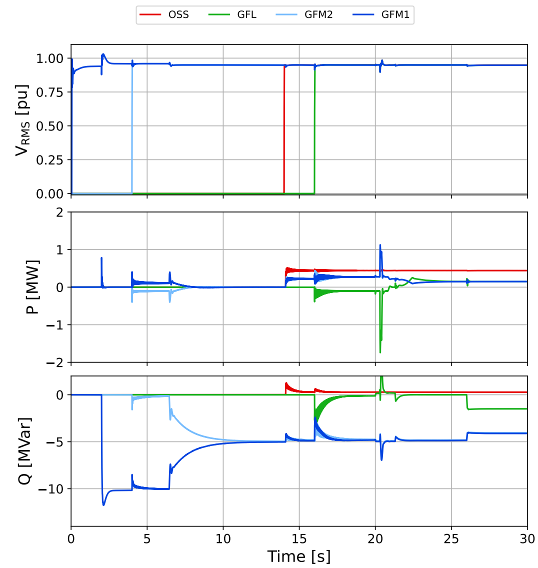


(a) AC RMS voltage at 66 kV level along with the real and reactive power outputs of GFM and GFL WTGs and at OSS busbar.

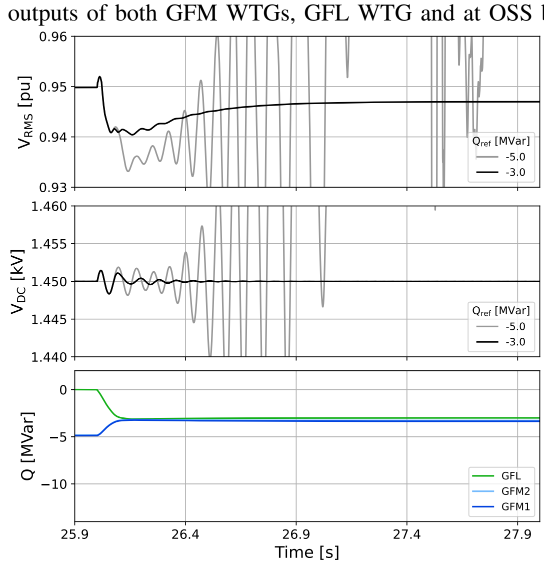


(b) Sensitivity of the transient instability to GFL WTG PLL gains and reactive power absorbed by GFL WTG when its $Q_{\rm ref}$ is changed.

Fig. 6: Transients during full string energization by GFM WTG at 2 s followed by synchronization of GFL WTG from 4 s and connection of OSS auxiliary transformer and load at 10 s, after which the $Q_{\rm ref}$ of GFL WTG is changed at 15 s.



(a) AC RMS voltage at 66 kV level along with the real and reactive power outputs of both GFM WTGs, GFL WTG and at OSS busbar.



(b) Sensitivity of the transient instability to reactive power absorbed by GFL WTG when its $Q_{\rm ref}$ is changed.

Fig. 7: Transients during full string energization by a GFM WTG at 2 s followed by synchronization of another GFM WTG around 6 s resulting in sharing of the load, after which OSS auxiliary transformer and load are connected at 14 s, ending with synchronization of GFL WTG at 16 s and change of its $Q_{\rm ref}$ at 26 s.

width thus increasing the settling time but improving steady-state filtering.

- enhancing the PLL loop filter of the PLL while keeping same gain also impacts the transient stability, as indicated by the curve corresponding to 10_2 in the lowest plot.

The stability limit can be increased, as shown in Fig. 7 by using two GFM WTGs as this naturally provides a stiffer voltage source behaviour with lower effective grid-impendance (due to paralleling) improving the PLL's synchronization. Additionally the maximum Var share of GFL WTG now doubles to 3 MVar due to higher transient stability margin. However $Q_{\rm ref} = -5\,\mathrm{MVar}$ step still triggers instability and hinders proceeding further with the energization sequence.

While adding an extra GFM WTG is a straightforward solution to increase the stability limits, it has an extra cost and reliability risk as mentioned before, besides that the aim of this study is to prove transient stability of energization with the minimum number of GFM WTGs. Fig. 8 shows that reducing the $P \to \theta$ droop from 10 to 5 helps the GFM WTG keep stable for GFL Var step of $-2\,\mathrm{MVar}$ that already doubles the previous limit in Fig. 6b. Further reduction of $K_{\rm P\theta} \to 0$ allows the GFM WTG to tolerate even a step of $-5\,\mathrm{MVar}$ in the GFL

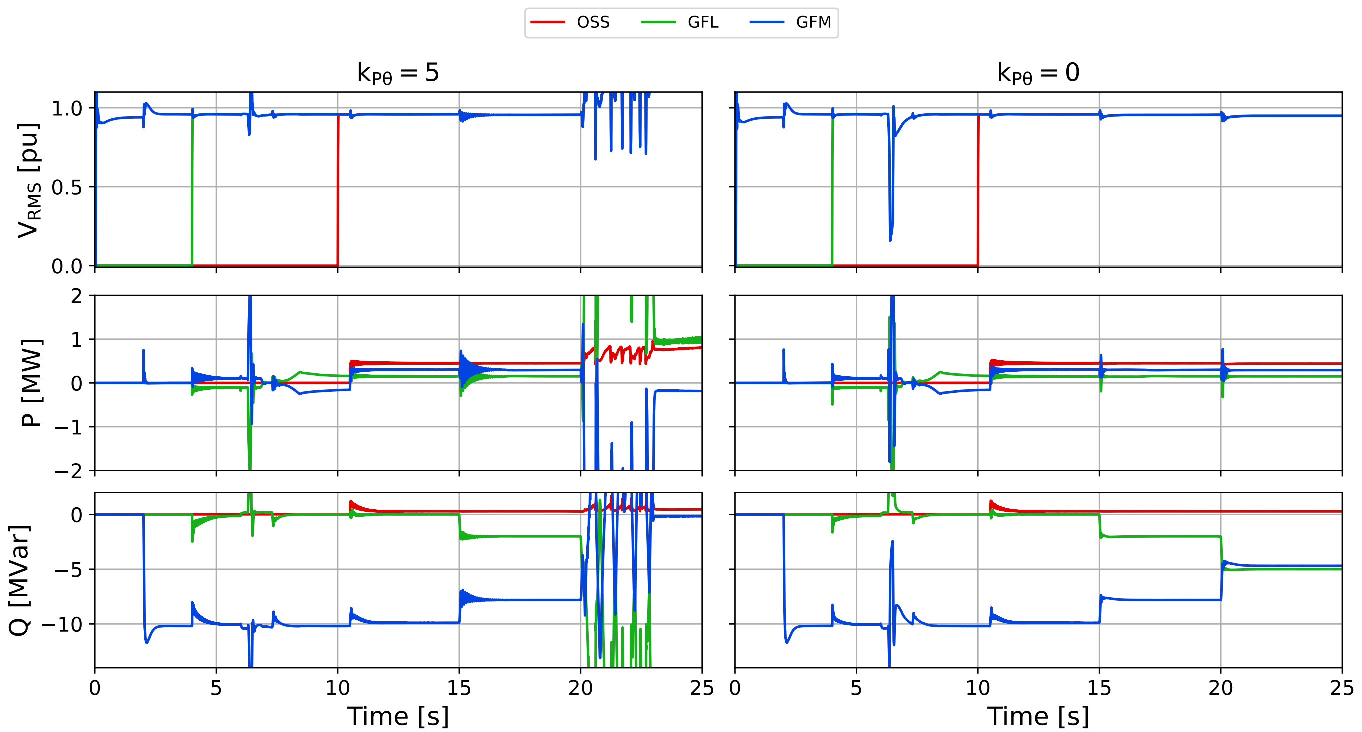


Fig. 8: Impact of $k_{\mathrm{P}\theta}$ on transient stability during synchronization (around 6 s) and Q_{ref} change ($-1.5\,\mathrm{MVar}$ at $15\,\mathrm{s}$ and $-5\,\mathrm{MVar}$ $20\,\mathrm{s}$) of GFL WTG, in full string energization sequence by a GFM WTG. AC RMS voltage at $66\,\mathrm{kV}$ level along with real and reactive power outputs of GFM and GFL WTGs, and at OSS busbar are shown here. Clearly, the configuration on the right is favourable.

WTG share. This can be explained since a power-exchange based droop on the voltage phase-angle results in a less stiff voltage source behaviour of the GFM WTG making it more sensitive to the PLL gains and reactive power currents of the GFL WTG. Such mere software tuning is extremely valuable as it allows to offset the cost of extra hardware required for stability enhancement.

Sections V-A and V-B verify that 1 GFM WTG as estimated in Section IV, is able to successfully deal with transients during all steps of energization of a single string and with proper parameter tuning it also maintains stability for the next GFL WTG to connect making it ready for subsequent string pickups.

C. Full CSG network energization

The final steps and complete energization of the CSG is verified now starting with the initial estimate per Section IV of 3 WTGs as all GFM and then subsequently replacing them one-by-one with GFL to find the absolute minimum number of GFM WTGs that can allow a successful complete sequence. For sake of transient stability the sequence begins with WTG-1 energizing String-2 (shortest first) followed by connection of WTGs-2/3 for load sharing before finally picking up remaining strings in order of increasing length viz. $3 \rightarrow 4 \rightarrow 1$, since higher reactive power jumps are more likely to trigger instabilities.

Fig. 9 shows results for CSG-1 energization by *3 GFM WTGs* tuned with different values of $K_{\mathrm{P}\theta}$. Contrary to a *stiff* power phase-angle characteristic for stable connection of a GFL WTG as demonstrated previously in Fig. 8, it can be inferred that allowing for some droop $K_{\mathrm{P}\theta} = 2$ is most optimal as $K_{\mathrm{P}\theta} = 0$ causes the power oscillations between the WTGs like parallel connected synchronous generators without any droop causing LoS, indicated by trip flag.

Alternatively a high droop of $K_{\mathrm{P}\theta} = 10$ allows for well-damped synchronization transients and ensuring stable parallel operation during pickup of string-3 but failing when string-4 is connected. Reducing the droop to mid-range $K_{\mathrm{P}\theta} = 5$ increases the stability margin that ensures successful connection of string-4 but failing when the longest string-1 is picked-up.

Finally a value of $K_{\mathrm{P}\theta} = 2$ ensures that the GFM WTGs remain in-synchronism for the entire energization sequence with stable load sharing and no observed WTG trips, including when the final string-1 is connected. However the synchronization transients are lesser damped that may negatively impact the mechanical drive-train due to load exceedances, cycling wear-tear or risk of exciting a critical eigen mode.

Thus a tradeoff exists and the proportional feed-forward gain must be tuned carefully as noted in [10] due to the sensitivity of second-order power-based synchronization GFM controls in a multi-unit system [18], [20].

Proceeding further to reduce the number of GFM WTGs by using WTG-3 as GFL instead of GFM, Fig. 10 shows that $K_{\mathrm{P}\theta} = 2$ ensures stability throughout the entire energization sequence. Here the GFL WTG's reactive load share is increased in steps from $0 \rightarrow -5 \rightarrow -12\,\mathrm{MVar}$ at $21-23\,\mathrm{s}$,

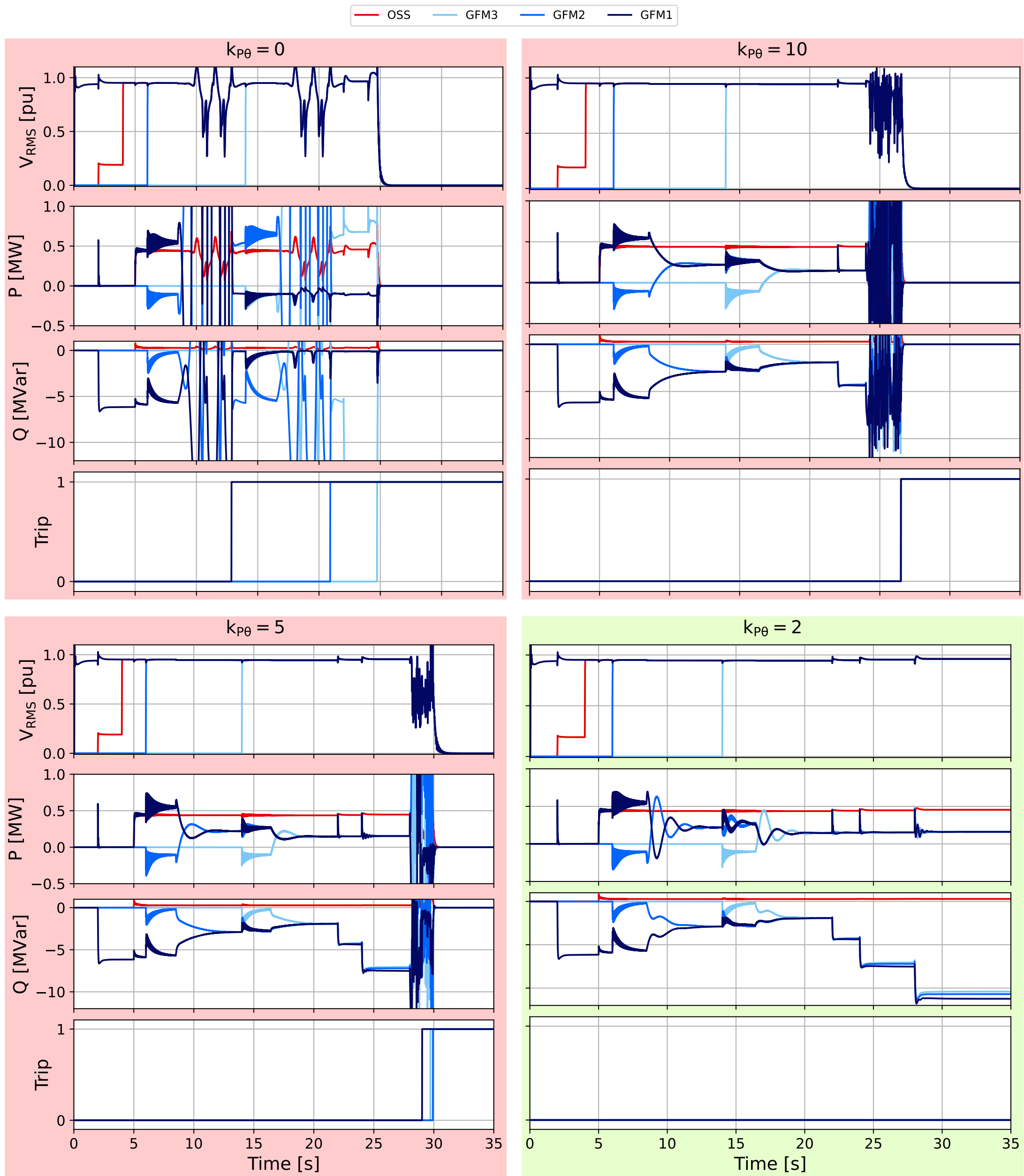


Fig. 9: Impact of $k_{P\theta}$ on transient stability during energization sequence of CSG-1 by 3 GFM WTGs on string-2: startup and energization of string-2 by WTG-1 at 2 s followed by synchronization of WTG-2 at 8 s and WTG-3 at 16 s, ending with energization of remaining strings 3, 4 and 1 at 22 s, 24 s and 28 s, respectively. AC RMS voltage at 66 kV level along with the real and reactive power outputs of GFM WTGs, and at OSS busbar are shown here in addition to the WTG Trip signals. The background colour indicates FAIL or PASS case.

respectively relieving the GFM WTG's capacity for next string energization (as shown by GFM WTG load going to $\tilde{0}$) and preventing instability by increasing stability margin. As a final verification step, *only 1 GFM WTG* (using $K_{P\theta} = 0$ for maximum stiffness) is not able to mainain stability with 2 GFL WTGs resulting in LoS and trip.

This proves that the combination of *2 GFM WTGs with 1 GFL WTG* is the absolute minimum that allows for the most robust greenstart of one CSG while ensuring stability in face of the challenging transients during the entire sequence.

VI. Conclusion

Recent studies have demonstrated that large offshore wind power plants with grid-forming control can provide power system restoration services and stability support in weak grid areas. However for the aggregated plant to have voltage-source behaviour at the offshore connection point it is essential that the constituent mix of grid-forming and grid-following wind turbines demonstrate synchronization stability during both small and large signal transients associated with the greenstart energization sequence. An estimate for the minimum number

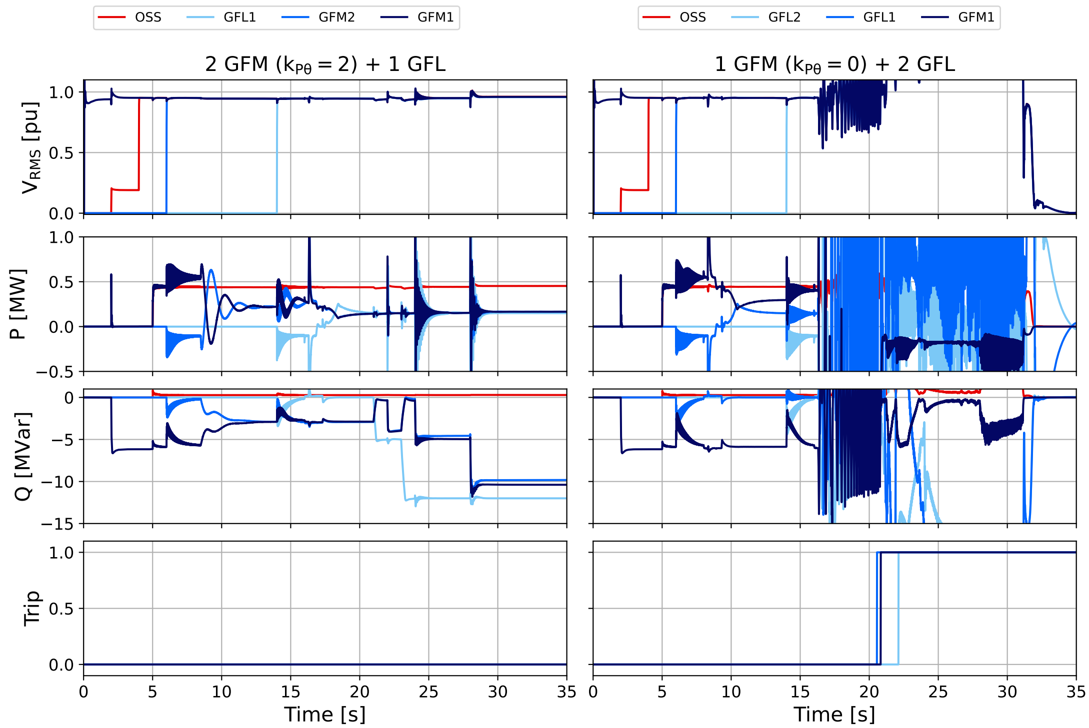


Fig. 10: Impact of $k_{P\theta}$ on transient stability during synchronization (around 6 s) and Q_{ref} change (at 21 s and 23 s) of GFL WTG, in full string energization sequence by a GFM WTG. AC RMS voltage at 66 kV level along with real and reactive power outputs of GFM and GFL WTGs, and at OSS busbar are shown here. Clearly the scenario on the left is favourable.

of wind turbines needed as per dynamic loading demands of the offshore collector network energization has been first proposed and then verified by means of EMT simulations using a detailed plant model and control. While more grid-forming turbines provides more stability it has been proven that the optimal share is two grid-forming and one grid-following turbine that allows for complete energization of the entire collector string group without sacrificing transient stability. It is noted that although early-stage greenstart by reduced number of grid-forming wind turbines is prone to PLL based instabilities due to weak-grid operation and large reactive current injections, but careful tuning of the synchronization control parameters in both grid-forming and grid-following controls can solve most issues without having to rely on costly stabilizing harware. This can provide significant CAPEX savings helping the business case for large offshore wind power plants.

Acknowledgment

Special thanks to Vattenfall Vindkraft A/S (6000 Kolding, Denmark) for supporting this work with resources, data, technical know-how and finance.

References

[1] IEA, "World Energy Outlook 2023," Paris, 2023. [Online]. Available: https://www.iea.org/reports/world-energy-outlook-2023

[2] International Energy Agency (IEA), "Renewables 2023," Paris, 2024. [Online]. Available: https://www.iea.org/reports/renewables-2023

[3] Massive Integration of power Electronic devices (MIGRATE), "D1.1 Report on Systemic Issues," Project Deliverable, dec 2016. [Online]. Available: https://www.h2020-migrate.eu/_Resources/Persistent/9bf78fc978e534f6393afb1f8510db86e56a1177/MIGRATE_D1.1_final_TenneT.pdf

[4] S. Ghimire, G. Guerreiro, K. Vatta Kkuni, E. Guest, K. Jensen, G. Yang, and X. Wang, "Functional specifications and testing requirements of grid-forming offshore wind power plants," *Wind Energy Science*, 2024.

[5] ENTSO-E, "High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters," 2019. [Online]. Available: https://euagenda.eu/publications/high-penetration-of-power-electronic-interfaced-power-sources-and-the-potential-contribution-of-grid-forming-converters

[6] A. Jain, K. Das, Ö. Göksu, and N. A. Cutululis, "Control Solutions for Blackstart Capability and Islanding Operation of Offshore Wind Power Plants," in *17th International Wind Integration workshop*. Stockholm: Energynautics GmbH, 2018. [Online]. Available: https://doi.org/10.5281/zenodo.3269542

[7] A. Jain, O. Saborío-Romano, J. N. Sakamuri, and N. A. Cutululis, "Virtual resistance control for sequential green-start of offshore wind power plants," *IEEE Transactions on Sustainable Energy*, vol. 13, no. 3, pp. 1420–1429, 2022.

[8] A. Jain, O. Saborío-romano, J. N. Sakamuri, and N. A. Cutululis, "Blackstart from HVDC-connected Offshore Wind : Hard vs Soft Energization," *IET Renewable Power Generation*, vol. 15, no. 1, pp. 127–138, 2021.

[9] A. Jain, J. N. Sakamuri, K. Das, Ö. Göksu, and N. A. Cutululis, "Functional Requirements for Blackstart and Power System Restoration from Wind Power Plants," in *2nd International Conference on Large-Scale Grid Integration of Renewable Energy in India*. New Delhi: Energynautics GmbH, 2019. [Online]. Available: https://doi.org/10.5281/zenodo.3460518

[10] M. Aten, R. Shanahan, F. Mosallat, and S. Wijesinghe, "Dynamic Simulations of a Black Starting Offshore Wind Farm Using Grid Forming Converters," in *18th Wind Integration Workshop*, nov 2019.

[11] Q.-H. Wu, Y. Lin, C. Hong, Y. Su, T. Wen, and Y. Liu, "Transient stability analysis of large-scale power systems: A survey," *CSEE Journal of Power and Energy Systems*, vol. 9, no. 4, pp. 1284–1300, 2023.

[12] H. Xin, C. Liu, X. Chen, Y. Wang, E. Prieto-Araujo, and L. Huang, "How many grid-forming converters do we need? a perspective from small signal stability and power grid strength," *IEEE Transactions on Power Systems*, vol. 40, no. 1, pp. 623–635, 2025.

[13] Y. Li, Y. Gu, and T. C. Green, "Revisiting grid-forming and grid-following inverters: A duality theory," *IEEE Transactions on Power Systems*, vol. 37, no. 6, pp. 4541–4554, 2022.

[14] X. Zhao, P. G. Thakurta, and D. Flynn, "Grid-forming requirements based on stability assessment for 100% converter-based irish power system," *IET Renewable Power Generation*, vol. 16, p. 447–458, 2022. [Online]. Available: https://doi.org/10.1049/rpg2.12340

[15] A. Roscoe, P. Brogan, D. Elliott, T. Knueppel, I. Gutierrez, P. Crolla, R. D. Silva, and Juan-Carlos Perez Campion, "Practical Experience of Providing Enhanced Grid Forming Services from an Onshore Wind Park," in *18th International Wind Integration Workshop*. Energynautics GmbH, 2019.

[16] A. Yazdani and R. Iravani, *Voltage-Sourced Converters in Power Systems*. John Wiley & Sons, Inc., Hoboken, New Jersey, 2010.

[17] I. Ray and L. M. Tolbert, "The case against phase-locked loops in weak AC grids," in *2019 IEEE Electrical Power and Energy Conference, EPEC 2019*, 2019, pp. 1–5.

[18] X. Wang, M. G. Taul, H. Wu, Y. Liao, F. Blaabjerg, and L. Harnefors, "Grid-synchronization stability of converter-based resources—an overview," *IEEE Open Journal of Industry Applications*, vol. 1, pp. 115–134, 2020.

[19] D. Dong, B. Wen, D. Boroyevich, P. Mattavelli, and Y. Xue, "Analysis of phase-locked loop low-frequency stability in three-phase grid-connected power converters considering impedance interactions," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 1, pp. 310–321, 2015.

[20] C. Sun, G. Joos, and F. Bouffard, "Identification of low-frequency oscillation mode and improved damping design for virtual synchronous machines in microgrid," *IET Generation, Transmission and Distribution*, vol. 13, no. 14, pp. 2993–3001, 2019.

[21] Q. C. Zhong and D. Boroyevich, "A droop controller is intrinsically a phase-locked loop," in *39th Annual Conference of the IEEE Industrial Electronics Society, IECON 2013*, nov 2013, pp. 5916–5921.

[22] "About the Norfolk Zone," accessed: 2025-03-15. [Online]. Available: https://norfolkzone.rwe.com/about-norfolk#facts-and-figures

[23] K. Clark, N. W. Miller, and J. J. Sanchez-Gasca, "Modeling of GE Wind Turbine-Generators for Grid Studies," General Electric International, Inc., Report, apr 2010.

[24] S. D'Arco and J. A. Suul, "Equivalence of virtual synchronous machines and frequency-droops for converter-based microgrids," *IEEE Transactions on Smart Grid*, vol. 5, no. 1, pp. 394–395, 2014.

[25] F. D. Freijedo, J. Doval-Gandoy, Ó. López, and E. Acha, "Tuning of Phase-Locked Loops for Power Converters Under Distorted Utility Conditions," *IEEE Transactions on Industry Applications*, vol. 45, no. 6, pp. 2039–2047, 2009.

Biographies

Anubhav Jain received his bachelor's degree from the Indian Institute of Technology (Delhi) in 2014 and master's degree from the Swiss Federal Institute of Technology (ETH Zurich) in 2017, both in Electrical Engineering. He completed his PhD in 2021 from the Department of Wind Energy at the Technical University of Denmark, focusing on blackstart and islanding capabilities of HVdc-connece offshore wind power plants. He has worked on offshore wind farm grid compliance and R&D in the grid studies team at Vattenfall Vindkraft A/S (Kolding, Denmark). He also has experience in offgrid plant design, stability analysis and integrated product performance verification from his time at Vestas Design Centre (Porto). Currently he is working at Hitachi Energy (Spain) on converter control. His research interests include grid-forming control, hybrid power plants design (incl. battery energy systems & P2X), grid integration of renewables, system stability, and EMT studies.

Jayachandra N. Sakamuri received the MTech degree in Electrical Engineering from the Indian Institute of Technology (Kanpur) in 2009, after spending a year as an exchange student at the Technical University of Berlin in 2008. He obtained his PhD degree in 2017 from the Department of Wind Energy at the Technical University of Denmark, where his work focused on coordinated control of wind farms in offshore HVdc grids. He has worked for Grid System R&D, ABB on HVdc System Design for three years, at Crompton Greaves Ltd. on HV switchgear design, and at Vattenfall Vindkraft A/S (Kolding, Denmark) as Lead Grid Study Engineer. Currently he is working at Hitachi Energy as Principal Project Engineer for HVDC system design. His research interests include HVdc, offshore wind farm integration and control, and HV switchgear design.

Nicolaos A. Cutululis (SM'18) received the MSc and PhD degrees, both in Automatic Control, in 1998 and 2005, respectively. Currently, he is a professor at the Department of Wind & Energy Systems, Technical University of Denmark. His main research interests are grid integration of wind power, with a special focus on offshore wind power, HVdc transmission, control and ancillary services, and electrical infrastructure design and optimization.