Question	Answer
Are Type III wind turbines considered IBR? Can you comment on physical inertia of Type III wind turbine and other differences between pure IBR?	Yes, because the inverter on the rotor side can control the final output. Both Type III and Type IV wind do have quite a bit of inertia, however under present control paradigms, in both these resources, the inverter effectively decouples the machine from the grid. However, if one wants to extract inertial energy from wind turbines, it could potentially be easier to extract from Type III as the stator is directly connected to the grid.
Can you discuss tradeoff in providing fast active power injection vs fast reactive injection- need to worry about not just frequency but also voltage stability?	Absolutely. Unfortunately there is no single solution for every scenario. Fast reactive power injection could hold priority if recovering from a deep voltage sag (fault) because if there is no voltage, once cannot push power. On the other hand, for events where the voltage does not leave the continuous operation region (0.9pu to 1.1pu) fast active power injection would take priority.
How to control system inertia for this system type	Since we were looking at 100% IBRs, and all IBRs were assumed to be static devices (PV or BESS), there is no system inertia. The only inertia component would be from motor loads. If the question was regarding inertial response, then we don't explicitly consider inertial response as the objective. Instead, the aim is to inject fast active current.
VSM mode for inverters has already been tested in the UK. How will this technology change the frequency stability considerations if applied in the US ?	The general concepts would still carry over irrespective of whether the tests are done on a 50 Hz system or a 60Hz system. However, other considerations related to operation of the system, allocation of reserves, location of reserves can change from one network to another.
To achieve 100%, is it necessary to adjust UFLS tripping thresholds? It's impractical to expect perfect frequency control - should we trip below 59.5, 59.3 Hz?	Present UFLS thresholds have been set based on transient stability of rotating machine. As the grid moves towards 100% IBRs, it become necessary to re-evaluate the UFLS settings as it is possible that the value of 59.5Hz which was relevant for rotating machines is no longer relevant for IBRs
What is Smart Transformer you mentioned? Is it Phase Shifter something like that?	A smart transformer is a power electronics based transformer that is a topic of research. https://ieeexplore.ieee.org/document/997934
Are the 100% IBR results for WECC positive sequence? How can we be certain those results are accurate for such a large network?	Yes, they are positive sequence results. The performance of each of the IBR models that were used in the study were first verified with comparison against detailed EMT simulations. Once the frequency response and voltage response characteristics were matched, the positive sequence model was deemed to be acceptable in representing the behavior of the IBR. This was then used for the large network study.

what is preventing the electrical system operators and IBRs plant owner to start provinding these services in the US?	A lot of present day IBR plants operate at maximum power point. So although the plants may have the capability to provide under frequency response, they may not have the headroom to do so as they are operating at maximum. In order for these sevices to be provided, these plants would have to be dispatched down and then participate in anciliary and reserve service markets.
Are grid forming inverters required in a 100% IBR grid	It depends on how one defines grid forming. If grid forming inverter is defined as an inverter which can operate without synchronous machines and along with other inverters, then yes one would need such inverters. However if grid forming inverter is only defined as an inverter that is responsible for black start, then it may not be required as black start could be carried out specific rotating machines in the initial stages before handing off to inverters.
How does large RoCoF cause problem with UFLS?	With a large value of RoCoF, the frequency falls at a faster rate. This means that it will take shorter time to reach the UFLS threshold. Also, many UFLS relays themselves need to measure frequency in order to trip. If frequency falls at a very fast rate, the UFLS relays may not have time to accurately measure frequency and thus may fail to operate.
Generally the IBR output maximum power depending upon the wind or solar input. How much power reserve required for the IBRs to respond to the frequency fall.	Unfortunately there is no fixed answer for this question. The amount of power reserve required will depend on the largest contingency being studied, and also the UFLS thresholds. In North America, for each of the four interconnections, there are yearly metrics known as Interconnection Frequency Response Obligation (IFRO) that denotes how minimum MW of reserve is needed in each of the interconnections.
Is the ramp rate equivalent to the virtual inertia that modern IBR control techniques propose?	No. Ramp rate limits relate to the physical limits imposed by the source behind the inverter to restrict how fast the MW output can change. For example, in a wind turbine, due to mechanical and torsional constraints, the turbine can only increase its power output at a maximum rate. Any increase at a speed greater than this can cause increased wear and tear. These limits vary from one type of source to another.
What inverter model was used to simulations?	In most of EMT simulations, a switching level three phase IGBT based inverter model was used. For few of the EMT simulations, an average three phase inverter model was used. For the positive sequence simulations, an equivalent single phase positive sequence model was used.
Similar to the question on power mismatch - in a 100% IBR grid, how can generation detect a power imbalance in the system without that electromechanical link?	A combination of factors will have to be used. In the transmission network, since there is decoupling between angle and reactive power, and since most faults tend to be reactive, a change in angle at the terminal of the inverter can be indicative of power imbalance.

If we assume we have a good source and DC link behind the inverter, how are we going to tackle limited di/dt of semiconductor switches of the inverters?	The limit of di/dt of the semiconductor switches would become the limiting ramp rate if the power ramp rate limit is large. Here, in order to ensure that the actual current output conforms to the di/dt limit, some form of current control may always be required within the inverter controls. Whether this current control will always remain active or will get activated only if the current output increases at a rate greater than the di/dt limit is a control design problem.
Faster response times and interacion of controllers can lead to stability issues. What is a better solution: faster response times vs larger energy reserve?	Indeed faster response time can lead to stability issues. If there is a stability issue due to this, it takes precedence and top priority over all other factors. So which means definitely a slower response time will have to be imposed to keep stability. If this means larger energy reserves then that would have to be designed and accomodated. However, it could mean larger number of resources will have to respond simultaneously. So once speed of response due to stability constraint becomes the limiting factor, other solutions will have to be designed based upon this factor.
On slide 22, can you please explain what is implied by IBR being a STATCOM? Thanks.	in that scenario, the IBR only provides reactive power support to the grid and all its active power output is only to serve its own auxiliary load. Thus from the perspective of the grid, the IBR has a zero active power output and a non-zero reactive power output.
Very nice presentation! I was curious about the power-frequency oscillations from GFM inverters in PSLF that do not appear in PSCAD. Where do these come from?	Thank you. The structure of the IBR controller in PSLF was not a one-to-one representation of the structure of the IBR controller in PSCAD. The reason for this is that in PSLF, the present WECC generic models (specifically the REGC_C and REEC_C models) were being used whereas in PSCAD, newer forms of IBR control were being evaluated. The objective for using an 'older' version of control in PSLF was to verify whether one really needs a new model to be developed in PSLF or can one make do with existing models. Due to the difference in the control structure, there were additional control gains that were required in PSLF which resulted in an additional oscillatory mode appearing. It may be possible to reduce or even remove this oscillatory mode with adequate tuning of the controls in PSLF, however that task has not yet been carried out.
Typical PV plants are designed to support 0.95 leading/lagging PF grid support. Is this sufficient for most grid support concerns?	As the number of inverter based resources increase, the reactive power limit based on power factor may be sufficient for regular continuous operation but would likely not be sufficient during a fault and during recovery after fault clearing.

What do you mean by angle droop	We implemented a control loop that looks at how much the terminal voltage angle deviates during a transient, from its own pre-contingency steady state value of angle. Based upon this deviation in angle, the power reference is changed proportionally. So in some aspects, its operation is similar to voltage magnitude droop that is used in reactive control loops.
What kind of digital systems are required to maintain stability and manage such events in a 100% IBR systems?	Increased observability of the network will be required as the number of devices on the network will drastically increase. Further, there can be a need for wide area control systems which would require centralized controllers and measurement devices. Further, since there would be a need for IBRs to be dispatchable, communication elements, telemetry, and security protocols would be required.
It seems that the distributed slack bus approach would require mass deployment rather than incremental conversion. How do you manage the transition to 100% IBR?	For an incremental transition, one can give priority to the frequency droop portion of the control system rather than distributed slack bus portion. So with this difference in priority, the distributed slack bus can be a much slower acting controller similar to today's secondary frequency control. As the number of newer IBRs increase, the priority of distributed slack can be raised throughout the fleet.
How much energy reserve are you assuming to respond to the frequency events? No additional energy reserve has been considered?	In our simulations, we considered 10% of the rating of the devices to be the headroom available. No additional energy reserve was considered. Although 10% of the rating was available, not all of the 10% is used for the frequency events that were studied.
For IBRs to provide frequency response, must they operated at some level below their maximum?	Yes, if they have to provide under frequency response. Alternatively, if the IBR plant is a hybrid plant with say PV + storage, then the PV portion of the plant could operate at maximum power point while the storage portion could provide the frequency response service.
Are high frequency events even more serious in IBR systems? If UFLS is triggered in a low frequency event, it helps to stabilize frequency.	Yes, high frequency events can be serious. However, many IBRs have easier capability to respond to such events. But that being said, these events should be equally studied and planned for as suppose there is a system split condition, then the IBRs in the area that exported a large amount of power should have mechanisms available to either immediately trip or reduce there power output. This can be achieved through implementation of Special Protection Schemes (SPS) or Remedial Action Schemes (RAS)

There are diverse IBR resources that can provide primary frequency response, but all are energy limited. What is appropriate reservation of power vs energy?	Unfortunately there is no fixed answer for this question. The amount of power reserve required will depend on the largest contingency being studied, and also the UFLS thresholds. However the amount of energy reserve required will depend on for how long is that additional response to be provided. This will have to go into the design and build of the IBR resource. Further, it will also depend on what are additional services that the IBR provides to the network. For example, if the IBR aims to provide only frequency response services, then the energy reserve can be smaller as a larger amount of power can be delivered for a short duration of time. However, if the IBR also wants to provide regulation services, then the stacked amount of services will have to be ascertaing through a multi-objective optimization. This will subsequently decide the power vs energy balance and also play a role in the rate at which power is delivered to the network.
Do these studies consider how / if PWM saturation affects performance of high IBR systems?	We did not consider that in this particular study. The PWM of the switching models used did not saturate for the load imbalance events. However, for the faults, there could have been some amount of saturation that occurred during the fault, and upon
What is Pref	The reference active power that can also be construed as the active power command that comes from the control center as a dispatch signal.
How about the locational importance of the frequency support in a smaller network?	If the network is inherently electrically close, then the location importance can be much lower as the disturbance would propagate faster over the network allowing for the response to also propagate faster.
Grid Forming inverter with battery component will solve all the network issues?	Not necessarily. A grid forming inverter should not be construed as a silver bullet that can fix all issues. It can equally cause stability related issues. Further, it cannot override fundamental electrical properties of how much power can be transferred over a corridor. Here one assumes that the rating of the grid forming inverter is finite and reasonable. Thus, for the future network, grid forming inverters could only be one part of the solution set.