Question	Answer
@Nicholas: in the Grid Strength Impact study, is the fault current contribution of the synchronous generator not taken into account in the SCR calculation?	Correct. That is, the sending end generator is not included in the calculation. This was to allow an apples-to-apples comparison of the host system SCR.
@Nicholas: tech. perform. slide: severity of the event relates to 1) duration, 2) size. Have you done this study considering different sizes of fault/torque?	Actually we only looked at duration, using that as a proxy for a variety of severity attributes. This is admittedly limiting, but we expect that the characteristics would be directionally similar to the results we present: the key point being that synchronous machine stability are highly dependent on the energy acquired during the fault; IBRs much less so.
How much of the dynamic behaviors is the outcome of the controllers software rather than inherently grid following	The control behavior of inverters is strongly dominated by the software. For example, as we noted, GFLs common just a few years ago (and still widely in use), would almost certainly exhibit poorer behavior than we showed. Even better performance may be possible.
Is there an interaction between GFL and GFM with STATCOM.	This we have not explored yet. Given that all three have software-defined controls, the answer will be heavily dependent on how the controls are designed and tuned. If the controls design and tuning is done properly, there need not be interactions.
What tools have been used for studies below 2.2? (edited)	EMT (PSCAD) was used for all of the work so far.
@Matt. Synch. machines should be considered with their controllers AVR, PSS, etc. Imagine SG connected to the grid without control, can it behave as we expect?	The synchronous machines were also modeled with an excitation system, and for the synchronous generator, it was modeled with a governor and a PSS - albeit a PSS with relatively low gain. The impact of these secondary in the first 2 seconds after an event and nearly irrelevant in the first 200msec after an event.
@Nicholas: Is it all about "voltage weakness"? I think strength is more than voltage stability and sensitivities, such as damping, synchronisms, etc.	Quite honestly, we are still digesting. But, while "all" might be an overstatement, we see that the stability of the IBRs is dominated by the post-disturbance system topology, rather much less by the energy associated with the actual disturbance. This appears to be a fundamental difference, and we think it is likely to impact how we (the industry) looks at stability limits. Stay tuned, there's more work to be done here.

What type of models have been used? The power and voltages seems heavily filtered, is the models based on actual product performances?	EMT (PSCAD) was used for all of the work so far. RMS quantities were not heavily filtered. Models used are among the best the industry has to offer -- high-fidelity, firmware-derived EMT models.
There are many different GFM control strategies in development and testing. Is VSM model applied in this study? Can it represent general GFM performance?	You are correct that there are many GFM schemes. There is little consensus about exactly what constitutes VSM (vs other GFM schemes), so we're reluctant to call this one. Certainly, this control does NOT mimic the mechanical state variables of a synchronous machine, but it does (as we showed, particularly in the step tests) exhibit the "persistence" of the internal voltage that is prized from synchronous machines. The language of GFM is as unsettled as the details!
GFL interacting with SC , will GFL interacting with GFM also?	It is possible, depending on the controls and tuning used in each, but this was not explored in this analysis.
Can GFL controls be tuned to minimize the interaction with SCs? If yes, how would this change the conclusion between interactions of GFL/GFM with SCs?	It is possible, depending on the controls and tuning used in each, but this was not explored in this analysis. We *speculate* that the conclusion will continue to be directionally correct, but the degree to which they interact will almost certainly vary.
Can we not conclude that all new IBR should get on the GFM bandwagon right away?	While we believe that these results are significant and important, we make no claim as to the completeness, nor that we've uncovered all unintended consequences. So, we'd moderate "jumping" to mean: all should have GFM in their sights or basket of options. We (the industry) has a ways to go, but we will be well served by moving there with alacrity.
When all of this is not possible to model in PSSE, how will this be studied at the ISO/TSO moving forward?	Thank you for this critical question - it is on the top of our minds. Please reach out to discuss more!
Also posted in chat - It's well understood where the transient energy comes from in SM case. Where does it come from in GFM?	In this case -- a BESS GFM -- the transient energy comes from the battery. This is a part of what makes it most convenient to implement GFM controls on inverters with batteries -- the battery provides a substantial, stable reservoir for sinking or sourcing power. Other non-battery-backed inverters could be GFM as well, but they need a way to quickly and stably sink and source power for, say half a second.

Different GFM control scheme may have different performances/impacts on the results. What type of GFM control scheme was used in the study?	see #10
You mention it is too early for grid codes on GFM. Any thoughts on how to define grid codes for controls highly dependent on software?	Functional specification of desired performance coupled with a rigorous, repeatable validation process.
There is gap in the industry standard models used in PSCAD and concerns about accuracy. How has the model been verified?	This is not an industry standard model. It is a specific OEM's implementation, and reflects one of their implementations of the 2 control types.
What is the difference between top and bottom lines in each chart - volt vscurrent?	I think you are referring to the "eye chart" with the 9 cases early in the presentation. If so, the upper trace in each is the voltage at the POI of the IBR, and the lower trace is the active power of the IBR.
What type of SCR are you referring to, what standard is used?	Typical Z circuit, using subtransient reactance of sink synchronous machine; ignoring load at sink. See next answer.
How can GFM deliver rated power with an SCR < 1. Doesn't this violate the power-angle law of ac power flow?	The "limit" of SCR = 1 considers a very simple circuit of a voltage source behind a series impedance. While our test system modeled is simple, it is still far more complex with distributed-parameter transmission line models. These realistic complexities result in viable AC power transfers for conditions that appear to an SCR metric < 1.0. In short, at very low SCR values, the simplifications baked into the SCR screening method make the metric less reliable. Having said that, your point is well taken and important. See answer #8 above.
Technology Performance Comparison: Are SM are fundamentally different as energy is required to get SM back to speed after initial support provided by inertia.	At the risk of oversimplifying: the physics of the SM are such that the energy acquired during a fault needs to be dissipated quickly in order to return to speed. The familiar equal-area criteria gives a good proxy or visualization. There has to be "room" and synchronizing strength to do so. For some IBR sources, like batteries and PV, there's no extra energy to dissipate. For wind turbines, there is, but the speed is decoupled from the grid, so the "urgency" to dissipate the acquired energy is removed.
For the GFM IBR, was this a 'virtual synchronous generator' as opposed to an ideal voltage source?	see #10

How have you studied PV components as PQ sources and not as voltage sources? Edit or BESS, Wind, etc. (edited)	Not as such. In the time frames and structure of PSCAD, the distinction between the two is less meaningful. In this transient world, there is no such thing as an ideal PQ source. As noted in our answers here, there's a lot of room to experiment more with control designs.
@Matt: what is the reason causing the residual DC components in the plots for Voltage step tests. EMT simulations do not naturally show it without any reason.	Discrete switching events applied as stimuli in the model result in sudden changes in voltages and current in the circuit - particularly in inductive elements, which cause small, decaying DC components. And, as I noted, we deliberately avoided significant signal filtering, so that we could "see" the really fast stuff. It makes the signals a little noisy.
imagine a system with long lines and 10% synchronous machine power How stable can that be	Not quite sure of the context. If you mean *only* 10% from SMs, then very lightly loaded, long AC lines have their own stability querks. Synchronous generation tends to be deeply underexcited for such conditions, creating synchronizing strength concerns. We *speculate* that IBRs will be less susceptible to that worry. If your question meant: 10% SM + a lot of IBR exporting, then we would expect to see some of the multi-modal interaction we showed. We further *speculate* that the IBR behavior could be tuned so as to beneficially impact the stability of the SMs. Ground for further investigation for certain.
But if many IBR's were GFM, couldn't they counteract each other and have a negative effect, e.g., if they were out of step? Or is there no chance of that?	Undesirable interaction between GFMs in electrical proximity is absolutely a concern that needs to be fully vetted. As others have noted, we are moving into a world where there appear to be myriad opportunities to create new (and possibly unexpected) control instabilities. As we said "this is a journey".
How do you consider the combination of mechanical inertia and GFL "inertia"? Do you need both, can the system survive on just GFL inertia? Consider SCC needs to	This investigation was deliberately framed with a receiving system of substantial strength and inertia. The receiving system isn't an infinite bus, but it's big. We consciously did not wrestle with the systemic level inertia and RoCoF issues in this study. It is not that we think it's unimportant, but rather we are trying to parse the challenges into manageable pieces and address them in (our) order of priority. Having said that, we are of the opinion that the major interconnections in the US, especially the EI and WI, are far from having problems with system-wide lack of inertia. But, we see the export from wind/solar rich remote areas as a extremely pressing concern.

Did you try variety of droop settings in the GFM? Were the droops a match for governor and exciter of synch machine. Did the GFL have any droop?	We did not investigate tuning of the parameters core to the GFM controls in this analysis, but this is a natural and logical question. Now that we understand the type of responses possible, the GFM responses could theoretically be customized for a particular application. GFL had voltage droop and frequency droop applied, but the dynamics of these are different -- especially in the first hundreds of msec.
Slide 13. Was GFM working at 100% of rated power before phase step? Or was it at less than 100%?	Good question. The GFM, GFL, and SM were all modeled at 1200MVA nameplate, operating at ~1000MW. Some moderate headroom was intentionally applied equally.
What are the operational implications of limiting event duration with GFMs compared to SMs?	See previous answer. For the stability events we investigated, we didn't see problems related to limits. You see the limit behavior in the big phase jump test. The behavior is radically different. We don't see that the limit-hitting behavior is *necessarily* problematic for the system. And indeed in some aspects, we think it might even be beneficial. So, we don't want to jump to the conclusion that smacking into limits is necessarily bad, or that extra capability is needed on that basis. We absolutely have not explored that aspect sufficiently to make judgement. The topic certainly needs more work.
@Nicholas: what is the inertia constant of the SC used in the GFL+SC study?	This case was H=5 on 200MVA machine. We did many variations on MVA, H and location of the SC.
Why is analysis in "steam age" synchronous machine terminology? Would it not be better to use control system theory gain and phase margin analysis?	There are numerous approaches for analyzing stability of systems. This was a starting point but not the end-point. As you see here in the questions here, non-linearities are a major concern.
V on slide 14 might not be representative for all IBR Are you only looking at low freq or also fast transients in voltage and SynCon interaction with plant ctrl	Agreed - we were very clear that this is not representative of all IBR behavior. But it provides insight on what to watch out for. Other IBR are different, both better and worse in these respects.
In the case that DC bus dynamics were considered, was PWM saturation observed during the large steps? Did this cause issues?	We didn't see any problems.

If CCT is a misleading stability metric for the future, what are better metrics going forward? Thanks, great presentation.	see answers 8 & 21. We think that it is possible that more static metrics based on the network characteristics are likely to be more useful. That is high on our list to investigate! Thanks.
Besides the very narrow margin from stable to unstable, what is not to love about GFM?	see #13. We are excited, but caution is warranted!
Assuming that batteries using GFM inverters can improve stability as shown in the presentation, should these batteries be located on the sending end of a long-distance AC line, or in the middle of the long-distance line?	Great question - this aspect is still a work-in-progress - please stay-tuned!