Mechanism Analysis of Dynamic Phenomena in Power Grids with High Penetrations of Inverter- Based Resources Q&A

Lingling Fan

1. How do we get slip in Synchronous Machine? Is it during transient conditions?

Answer: By definition,

$$\text{slip} = 1 - \frac{\omega_m}{\omega_s} = 1 - \frac{j\omega_m}{j\omega_s} \tag{1}$$

where ω_s is the synchronous speed or the stator's frequency, and ω_m is the rotating speed or the corresponding electric frequency. Both are in the same unit: rad/s.

At steady state operation, a synchronous machine's motion speed is the synchronous speed and the slip is 0. On the other hand, for any rotating speed ω_m under any stator frequency, slip can be expressed more generally as a dynamic expression

$$\text{slip}(s) = 1 - \frac{j\omega_m}{s} \tag{2}$$

where s is the Laplace transform variable and $s = j\omega_s$ is to evaluate the above dynamic expression at a certain stator frequency.

This dynamic expression of slip is a frequency domain expression. For a series LC mode with a frequency less than the rotating speed $\omega_{\text{LC}} < \omega_m$, we may end up with a negative slip if s is evaluated at that frequency.

$$\text{slip}(j\omega_{\text{LC}}) = 1 - \frac{j\omega_m}{j\omega_{\text{LC}}} < 0. \tag{3}$$

In turn, the equivalent rotor resistance is negative. At a subsynchrnous frequency, both induction machines and synchronous machines may have negative rotor resistance. This is the root cause of induction generator effect.

In summary, a synchronous machine can be viewed as an induction generator if the stator exciting frequency is not at nominal frequency. Detailed derivations on slip, type-3 wind turbine circuit, and the generalized synchronous machine circuit can be found in [1] and [2].

2. Is TCSC also a solution for series-compensation associated oscillation ?

Answer: A quick search of TCSC in Google shows that in 1997 a TCSC was installed by ABB in the Sweden power grid for subsynchronous resonance (SSR) mitigation. In US, Slatt TCSC is a project in WECC's 500-kV system. A 1996 paper [3] by GE shows that the field test results show that Slatt TCSC does not participate in SSR. Based on the Sweden project, TCSC can be seen as a solution of SSR.

On the other hand, in Texas, fixed capacitors have been predominantly used as series compensation. If there is no TCSC installed, solutions of series compensation associated oscillations may come from other

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L. Fan is with the Department of Electrical Engineering, University of South Florida, Tampa, FL, 33620 (e-mail: linglingfan at usf dot edu).

means, e.g., special control with wind generators, resonance damping at the wind farms or at the series capacitors.

In short, any realistic solution has to be evaluated for costs and tradeoffs.

3. are there any research for solving the real world stability issues with grid-forming controller?

Answer: I'll try to answer the question from two perspectives. First, are there real-world stability issues associated with grid-forming controllers? For this question, in the transmission grid, large-scale deployment of grid-forming controllers is not there yet. Hence, the literature is scarce on stability issues related to grid-forming controllers in transmission grids. On the other hand, grid-forming controllers have been used in microgrids. IEEE PES task force on microgrid stability has published a report TR-66 and a transaction paper [4] to document various of stability issues in microgrids, some associated with grid-forming control. This speaker has contributed one example based on EMT simulation showing two parallel inverters oscillating against each other under certain droop setting [5].

Second, can grid-forming controllers solve real-world stability issues? For this question, this talk has showcased many types of dynamics and stability issues. System-level stability, e.g,, voltage stability, is determined by the steady-state power transfer limit. This limit will not be lifted by changing grid-following to grid-forming control. In fact, voltage stability, interarea oscillations, are all associated with synchronous generator dominant systems. The basic idea of GFM is to have an inverter be more like a synchronous generator. Therefore, those stability issues will still be there. Our study on a 100% IBR system shows that 3-Hz inter-area oscillation mode pops up in such a system [6]. Compared to the quarter Hz oscillations due to the interaction of machine electrotechnical dynamics and a meshed network, the frequency of the new type of interarea oscillations appears much larger. They are due to the interactions of inverter control dynamics interacting with the meshed network.

In many cases, if stability issues are due to inverter control, tuning control parameters can mitigate the issue and this is a cheap solution. AEMO's 7-Hz oscillations were mitigated by PLL parameter tuning.

Real-world experience on GFM applications in Australia has also shown that GFM has its own challenges. Please see Babak Badrzadeh's presentation in ESIG Fall 2022 workshop "Assessment of GFL and GFM Inverter and Synchronous Condenser Connection in Australia: Lessons Learned." With GFM, more control interactions are expected and control coordination will be necessary.

4. Thanks for sharing many real-world events. I agree that the mechanism is important. How do we avoid these oscillations in the planning stage? Do we need to conduct the full EMT simulation? In addition, for most of the real-world events, are these oscillatory modes are the local modes or system-level interactive modes? If they are the local modes, could they be properly tuned before we integrate them into the grid? If they are the system-level modes, how could we know these risks in advance? Thanks.

Answer: The grid is a complicated system with many components owned by different entities. The power gird is considered as a highly reliable system thanks to the continuous effort of reliability entities such as NERC.

Based on the history of more than a hundred years of grid operation, stability issues are always there. Power system engineers are getting better and better on understanding stability issues. For the synchronous generator dominated power grids, we almost take it for granted that the system is so reliable.

There is a learning process for operating IBR penetrated power grids. Grid operators have acted quickly to have lessons learned. Tool wise, NERC is pushing for EMT based simulation to capture wideband dynamics and pushing for accurate model representation of IBRs. So it is possible that many abnormal dynamic performance can be captured at the planning stage. CIGRE Brochure 881 edited by Babak Badrzadeh is on Electromagnetic transient simulation models for large-scale system impact studies in power systems having a high penetration of inverter-connected generation. This brochure shares the international experience of large-scale EMT study in Australia, Tasmania, Belgium, Ireland, Denmark, Texas, etc. On the other hand, putting an entire EI into EMT simulation is not realistic. EMT study is an area requiring training. Fortunately, NERC IRPS now has a subgroup putting a guideline on EMT study.

Generally speaking, voltage stability and inter-area oscillations are system level stability issues influencing large geographic areas, while series compensation related SSR is considered as a local event. On the other hand, in Texas, SSR screening has now become a necessary system-level study procedure since the grid has many series compensated lines. In addition, events reported by NERC IRPS are all considered as system level events. The dynamic events mentioned in the talk were all created by the interactions of inverters and grid characteristics. So all can be viewed as system related. OEMs usually conducted thorough tests for inverter controls. However, there are many different grid characteristics that probably have not been met. That is why operation experiences can help reshape and enhance inverter control.

Many real-world events required years of investigation to understand the root causes. Practice of the industry is to keep learning and accumulating experiences. In IEEE PES and CIGRE, many task forces and working groups have been formed to study and document lessons learned, e.g., IEEE IBR SSO TF, CIGRE C4.71 WG. That is also a goal of our project: develop fundamental understandings and share lessons learned. These efforts facilitate grid operators to come up with guidelines on studies, help relay manufacturers come up with protection schemes, and help OEMs better understand grid characteristics' influence on IBR and upgrade IBR controls and protection.

5. can these instabilities/oscillation occur simultaneously in multiple interconnected systems. What can we do as a preventive measure to mitigate this occurrence.

Answer: In North America, there are three interconnected systems: Eastern Interconnection (EI), Texas, and West Interconnection (WECC). The three systems are interconnected by HVDC links and can be viewed each as an independent system. For independent systems, incidents in one system do not interfere with another system.

Power grids are very reliable and blackouts rarely happened as there are many measures to have a reliable system, starting from the planning stage to real-time operation. Maintaining reliability is a priority of the grid industry. The short answer on preventive measure is to have a competitive workforce with the capability to keep lights on. Fortunately, we have NERC, WECC, ERCOT, etc to watch for grid reliability. We also have DOE SETO to support R&D and workforce training .

6. Thanks for the nice and informative presentation. It is very helpful. Frequency and voltage of grids with high penetration of renewables seem to change significantly even for small disturbances. Also, SSOs are composed of both low and high frequencies due to high penetration of IBR. Can you please elaborate on inverters' small-signal models in capturing actual SSOs and dynamics of power systems with high penetration of renewables (80 % penetration)? Do we need different models as the penetration increases or existing models will be sufficient?

Answer: Our experiences show that dynamics can be successfully replicated as long as the relevant inverter control and grid characteristics are modeled. General practice is to use different models for different time scale or different dynamics. So the determining factor is not the level of penetration, rather what type of dynamics we are interested in. If we are interested in examining steady-state optimal power flow, we use algebraic models. If we are interested in understanding 0.1-Hz oscillations, phasor-based models (ignoring electromagnetic transients) are good. For very fast dynamics, e.g., subcycle overvoltage, then electromagnetic transients (EMT) of the grid and the fast inner controls of IBRs have to be considered.

The bottleneck identified by the grid industry is that many a times IBR EMT models provided to the grid operators do not reflect their real performance. Improving model accuracy has been a focus of today's industry.

7. Fixed capacitors at solar end -whether ll compensate the grid voltage during LVRT, HVRT condition?

Answer: LVRT and HVRT are usually taken care of by IBRs, which have LVRT and HVRT control logics equipped. IBRs will export more reactive power when the sensed voltage is below a threshold. Fixed capacitors, on the other hand, reduce their reactive power output if voltage becomes low. In the grid, dynamic reactive power compensation can also be provided by special devices, e.g., synchronous condensers or STATCOM.

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