Talking points for induced geo-electric fields working group, Adam Schultz, Oregon State University.

- There is growing experience with induction effects in critical infrastructure due to the interaction between different magnetic field models, real-world 3-D crust and mantle ("ground") conductivity, and the effects of integrating the induced ground vector electric fields that result along the paths of power transmission lines.

- Much of the current discussion around benchmark standards centers on peak amplitudes of the ground electric fields, generally from a probabilistic view, usually relating to "100-year storms".

- The inductive coupling between transmission lines and ground electric fields depends not only on the instantaneous intensity of those fields, but also their instantaneous orientation (polarization), as well as the orientation of each segment of the power transmission network. A large peak ground electric field polarized orthogonal to the power line path will induce no GIC, while a smaller electric field polarized parallel to the path will generate a GIC. By effectively considering ground electric fields to be scalar rather than vector quantity, are we at risk of biasing the estimated risk upward, and thereby end up overprotecting some critical assets, at great cost, and at some other locations potentially underprotecting others, at some peril?

- While there are examples where one can match measured neutral ground return currents (GICs) for a given GMD using a regionally averaged 1-D ground conductivity model in a given power flow solution, there are counter-examples from other locations that show that solutions that accommodate 3-D ground conductivity outperform 1-D solutions. This might be completely dependent on local and regional geoelectric structure and the topology and configuration of the power transmission system in a given regional setting.

- There are no extant examples (to my knowledge) comparing 1-D vs 3-D ground conductivity coupled power flow solution that examine the fidelity of matching other critical power system parameters such as phase distortion, harmonic distortion, and frequency instability. Rather comparisons are generally made with reference to measured GICs.

- Knowledge of the neutral ground return current, the power transmission system topology, configuration and state is not sufficient to predict the current or voltage waveform harmonic distortion, phase distortion or frequency instability. Generally when these parameters are simulated in a transmission line setting, the system loads are replaced with simple resistors, which does not represent the true state of the system.

- For example, during a GMD the neutral return current could trip ground relays when they shouldn't, and these relays could be coordinated via a Remedial Action Scheme that was programmed offline, affecting thousands of other devices systemwide. Small changes, big outages.

- Harmonic distortion and phase distortion could pinpoint an issue of power quality and this could be more toward the distribution level. This could have a strong effect on local resilience. Overall system frequency should in theory the same for all the system but there could be some 'warping' and indicators that there is an inertia issue; for example sub-area or inter area oscillations.

- Systems such as Hydro-Québec focus very much on Even Harmonic Distortion (EHD) of the transmission system voltage waveform and less so on GIC. We see the ground electric field that we actually measure in SW Maine in our MT installations correlating very well with the EHD as percentage of voltage waveform for one of Hydro-Québec's long transmission lines. In other examples in the upper Midwest we see strong correlations between phase instability as measured by synchrophasors, GICs and GMDs.

- For revised benchmarks, it would be worthwhile to consider avoiding assumptions that models are at or very close to the powerline fundamental frequency, and to consider how the ground electric fields interact with the entirety of the power grid to understand the impact on total quality of service, as reflected not only by GIC, but also harmonic distortion, phase distortion and frequency instability.

- Also I would like us to discuss a standard where, when such information is available, 3-D ground conductivity solutions (either through use of 3-D crust and mantle conductivity models, or through the projection of ground magnetic fields through measured full MT impedance tensors) be required when assessing the magnitude and the polarization of ground electric fields.

- Other factors to consider include applying downward continuation principles to magnetic field models defined at magnetospheric altitudes, to account for the spatial filtering effects on magnetic field structure as the field propagate down through the conductive ionosphere and low, but non-zero conductivity atmospheric layers.

- Finally, is the 1:100 year standard meaningful and appropriate? At one extreme there is growing evidence for much larger events in the past than the Carrington event, and by accepting a "hundred year storm" model, i.e. 1 chance in 100 of an event occurring in a given year, one doesn't preclude two of more events occurring back-to-back in a short period of time, with compounding impacts on a damaged grid. Also might we consider a human caused EMP as an alternative probabilistic basis for a benchmark standard – should we build to a standard against the greatest potential E3-phase EMP if that is seen to be a higher standard than the current model? The recent Executive Order on EMP includes both man-made and natural (GMD) events in its scope.