Power System Studies for Solar and Wind Farms

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Summary

The presentation will center around how the interconnection of a wind or solar farm will affect the design of a substation. It will discuss:

- Surge arrester and neutral grounding reactor sizing in relation to the collection system cable concentric neutrals.
- Main Power Transformer sizing with respect to the reactive power requirements.
- Choosing between DETC/OLTC: Substation voltage operating range
- DETC/OLTC tap selection: How it affects the collection system

Outline

- Mortenson & Mortenson Engineering Services
- Mortenson Studies Overview
- Studies Outline:
  - Reactive Power
  - Short Circuit
  - Transient Overvoltage (TOV)

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Mortenson Studies Overview

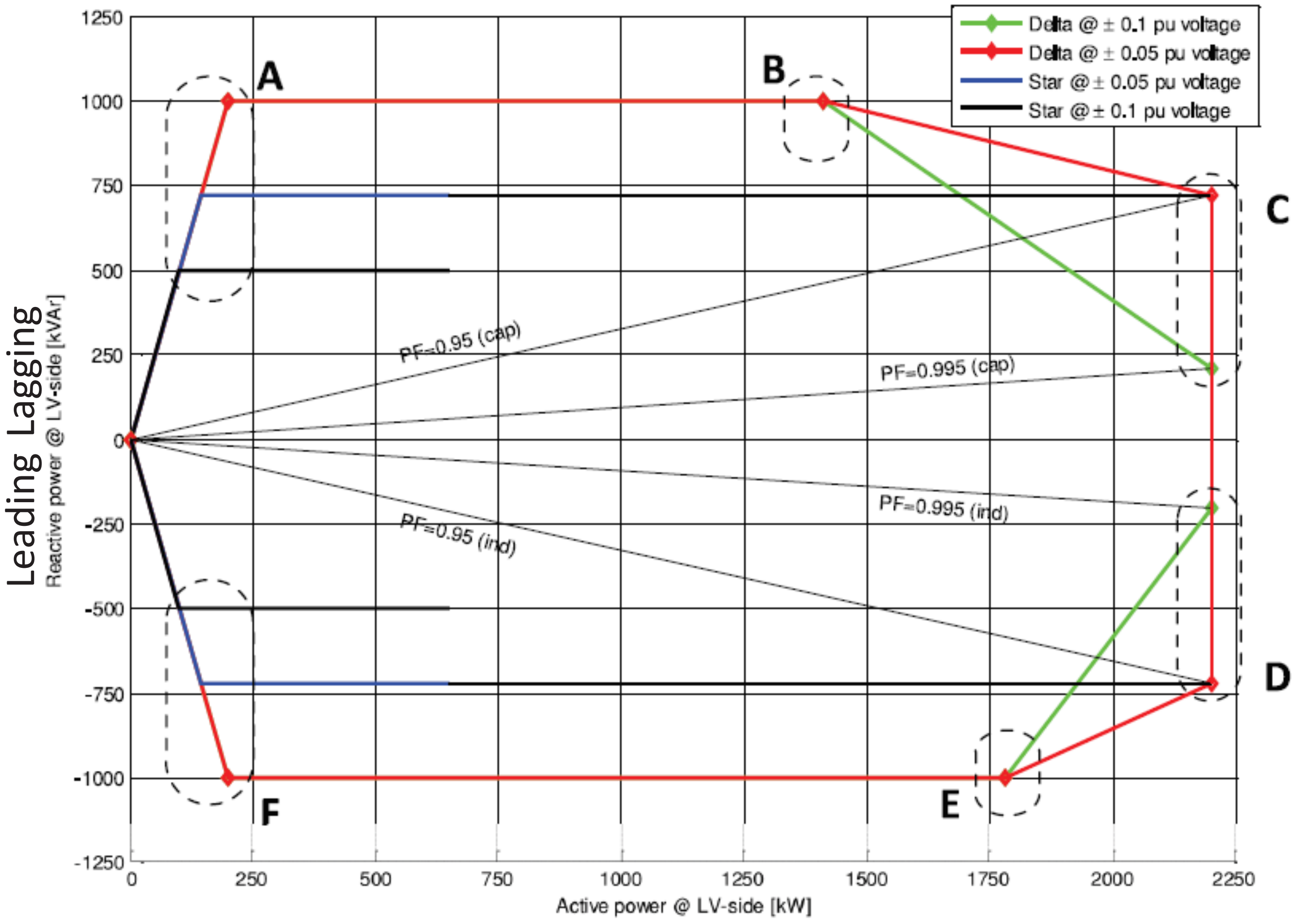
Study	Deliverable	Tool
Short Circuit	Fault current used for equipment sizing	PSSE
Losses	Maximum collection losses (contractual value of 2.5%)	
Reactive Power	Capacitor bank sizing and transformer tap settings	
Transient Over Voltage & Effective Grounding	Surge arrestor sizing, Current limiting reactors, Circuit breaker ratings, Critical fault clearing times	PSCAD
Harmonics	Capacitor bank step size, Harmonic filters, IEEE 519	ETAP
Arc Flash	Personal Protective Equipment	
NERC PRCs	Generator Voltage and Frequency Ride-through Settings	PSSE

Reactive Power Study

- **The objective of the study is to:**
  - Size capacitor banks or reactor banks to meet the power factor (PF) requirement
    - generally 0.95 PF at the POI, sometimes 0.95 at high side bus for the voltage range specified by TSP
  - Determine on-load tap changer (OLTC) or deenergized tap changer (DETC) setting of all transformers
  - Ensure the voltage across the collection system and inverter/turbine terminals is within acceptable limits (generally 10%)
  - Determine the top rating of the main power transformer (MPT)
  - Report the P-Q capability of the project (at high side or POI depending on PF requirement)

- **The objectives are interrelated:**
  - The OLTC set point has a high impact on capacitor bank size
    - since $Q \propto V^2$, if we choose to set the OLTC at 1.05 tap, then 10% less capacitor bank size is required
  - The OLTC set point affects the voltage across the collection system
  - The Capacitor bank determines top rating of the MPT
  - The study is completely decoupled from the short circuit and TOV studies

Reactive Power Study



	P [MW]	Q [MVAr]
A	0.20	1.0
B	1.41	1.0
E	1.75	-1.0
F	0.20	-1.0

	P [MW]	Q [MVAr]
C Δ 0.05pu	2.2	0.723
C Δ 0.1pu	2.2	0.210
D Δ 0.05pu	2.2	-0.723
D Δ 0.1pu	2.2	-0.204

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Reactive Power – MPT with OLTC

- **Two cases are needed to determine Capacitor Bank sizing:**

  - **Lowest POI Voltage:**
    - Generally 0.95 Vpu
    - Set inverters/turbines to produce maximum reactive power
    - Add capacitors to banks to meet 0.95 PF at POI
    - The OLTC is generally set to raise the voltage across collection system to its highest level possible in order to determine the minimum capacitor bank size.

  - **Max POI Voltage**
    - Generally 1.05 Vpu
    - Set inverters/turbines to produce maximum reactive power
      - Virtually all power plant controllers request dynamic MVArs before requesting capacitor bank MVArs
    - Determine if there is an MPT tap that would bring the low side voltage as stated above. If not, change capacitor bank size and repeat the first case. Generally there is no need to adjust the capacitor bank size and the low side voltage above is the OLTC set point.

- **The procedure is complicated if the turbines have reactive power capability that is voltage dependent:**
  - Only happens with wind turbines and not solar inverters
  - In general, solar inverters do not derate for voltage going above 1 Vpu but derate if voltage goes below 1 Vpu.
  - We never saw a terminal voltage less than 1 Vpu in the case of supplying reactive power. This makes analysis easier.

Reactive Power – MPT with DETC

- This approach is more complex as the ability to regulate the low side bus is lost and the DETC of the turbine transformers (PMT's) need tuning as well. However the main idea is similar in that capacitor banks need to be sized based on the lowest voltage possible:
  - **Lowest POI Voltage:**
    - Generally 0.95 Vpu
    - Set inverters/turbines to produce maximum reactive power
    - Add capacitors to banks to meet 0.95 PF at POI
    - Set the DETC to the appropriate level to lower the voltage across collection system
  - **Max POI Voltage:**
    - Generally 1.05 Vpu
    - Set inverters/turbines to produce maximum reactive power
    - Determine if there is an MPT tap that would bring the low side voltage as stated above to normal limits. If not, start adjusting the DETCs of the turbines/inverters to bring the voltage down. Generally the DETC of the MPT wouldn't be adjusted unless voltage on the 34.5 kV side is very high.
- This will be an iterative process to select the minimum capacitor bank size and the best DETC settings. The MPT DETC setting will also depend on the leading power factor cases, which complicates the iterative process.

Reactive Power Study

POI Voltage 0.95 Vpu
100% Dispatch

	POI PF	POI Real Power [MW]	POI Reactive Power [MVAr]	Tap Position	Substation Voltage [pu]	Min Terminal Voltage [pu]	Max Terminal Voltage [pu]	Min Collection Voltage [pu]	Max Collection Voltage [pu]
MPT has OLTC	0.902	-150.672	-72.072	-16	1.1346	1.1617	1.1692	1.1346	1.1423
	0.95	-150.039	-49.214	16	0.9388	0.9708	0.9795	0.9388	0.948
MPT has DETC	0.916	-150.538	-65.848	-2	1.0782	1.1066	1.1144	1.0782	1.0863
	0.923	-150.453	-62.917	-1	1.0521	1.0811	1.0891	1.0521	1.0604
	0.929	-150.375	-60.113	0	1.0274	1.057	1.0651	1.0274	1.0359
	0.934	-150.294	-57.285	1	1.0037	1.0339	1.0422	1.0037	1.0123
	0.94	-150.229	-54.545	2	0.9811	1.0119	1.0203	0.9811	0.9899

Short Circuit

- **Objective:**
  - Ensure that three phase (3Ph) faults are within the cable conductor withstand capability
  - Size the substation switchgear
  - Size the neutral ground reactor at the X0 bushing of the MPT to ensure that the SLG faults are within cable concentric neutrals withstand capability

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Short Circuit

- Three Phase Faults (3ph)
  - The only way to control 3ph faults is either by installing line reactors (expensive) or getting a high impedance MPT
  - Line reactors are always avoided due to TRV issues
  - A high impedance MPT is not always an option since the Owner typically purchases the MPT most of the time. A high impedance MPT also acts like a line reactor, which is not preferable
  - If high 3ph faults are identified, the only realistic solution is to have a larger cable cross section, which is naturally the case because the cable homerun is generally large (~1250 kcmil) due to ampacity requirements.
  - Never had issues with 3ph faults (typical numbers on next slide)

- Single Line to ground faults (SLG)
  - The cable concentric neutrals are given from the bid/proposal (can be dictated by the Owner)
  - Across the industry, there is trend of using the smallest cable concentric neutral possible to save cost
  - The NGR becomes the only tool to control the SLG fault current at the low side of the MPT

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Typical Cable withstand

35kV CABLE
1250 MCM AL, 1/12 CONCENTRIC NEUTRAL, 105°C
1000 MCM AL, 1/12 CONCENTRIC NEUTRAL, 105°C
750 MCM AL, 1/6 CONCENTRIC NEUTRAL, 105°C
500 MCM AL, 1/6 CONCENTRIC NEUTRAL, 105°C
4/0 AWG AL, 1/2 CONCENTRIC NEUTRAL, 105°C
1/0 AWG AL, 2/3 CONCENTRIC NEUTRAL, 105°C
TRENCH GROUND: 7 #8 COPPER CLAD STEEL

Table 1. Cable Fusing Currents at 8.5 Cycles

Cable	1250 MCM	1000 MCM	750 MCM	500 MCM	4/0 AWG	1/0 AWG	7#8 Neutral
Concentric Neutral (kA)	14.08	9.20	13.80	9.20	12.26	9.20	29.38
Phase Conductor (kA)	183.69	146.95	110.22	73.48	31.09	15.52	

- Clearly, 3ph fault currents are not an issue except for 1/0
- Increasing the coordination time and accounting for a breaker failure scenario would cause the withstand to drop (30% drop for 16 cycles)

The NGR

- The NGR size plays an exceedingly important role during SLG faults
- The voltage rise across the collection system is a direct function in the NGR size
- General practice is to size the NGR to keep the system effectively grounded (The phase voltage should not be more than 1.39 Vpu during fault conditions)
- Sometimes designing an effectively grounded system is not possible:
  - Once a SLG fault happens, the current splits between the cable concentric neutral, trench ground, and earth
  - There is no industry standard on the split factor of ground currents in undergrounded systems. Designs must assume that 100% of the fault current will be flowing in the cable concentric neutral.

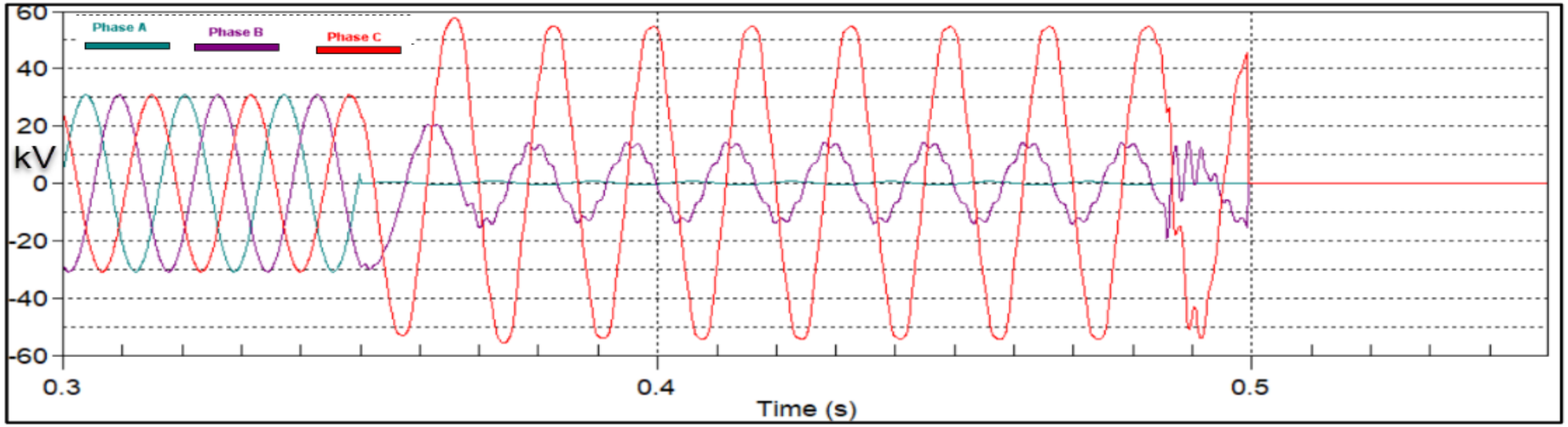
TOV

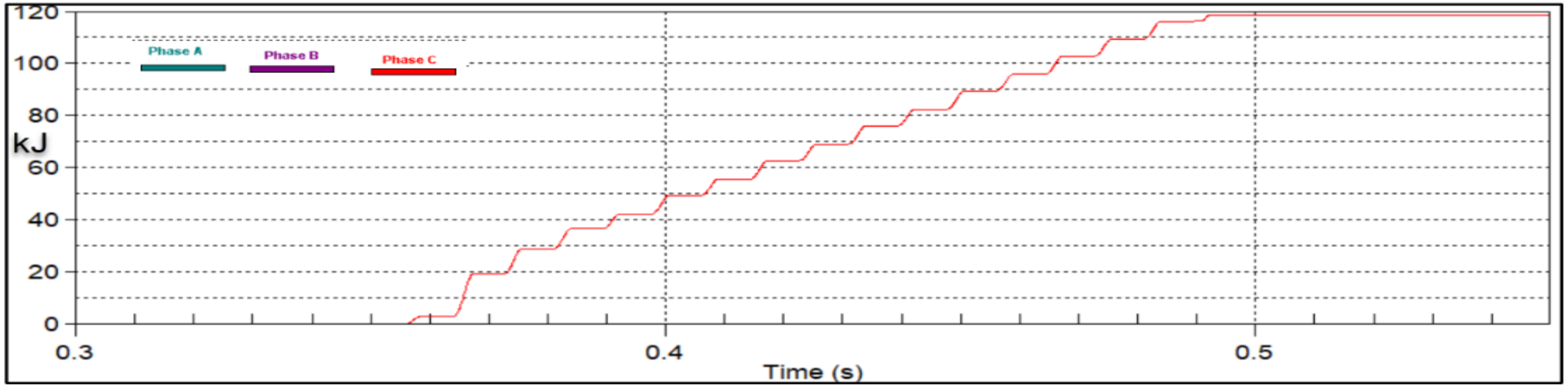
- Various scenarios are studied:
    - **Worst case capacitor switching**: Occurs at peak voltage.
    - **Surge arresters:** Conduction needs to be monitored. This is generally not a big deal (switching frequency is generally around 700 Hz and lasts for less than a cycle).
    - **Worst case faults:** This is a single line to ground fault downstream of the feeder breaker. This fault causes maximum voltage rise across collection system at the end of the collection circuit. Also, surge arrester conduction is monitored. Generally a very big deal and will be described next slide.
    - **Load rejection:** This is important for wind farms as turbines continue to produce power after a feeder is isolated. Generally less severe than SLG faults.
    - **Energization:** Make sure that no saturation occurs. Generally not a big deal.

TOV and NGR size

- During a SLG fault, the voltage rise is a function of the NGR size.
- If the system can not be designed to be effectively grounded, the surge arrester will be in conduction mode during SLG fault conditions.
- If the NGR size can not change, the protective relay tripping times must be made faster (decreased).
- Once the feeder breaker opens, the feeder becomes islanded or grounded
  - The feeder may be grounded if grounding breakers or grounding transformers are used
  - If not (which is becoming more normal for solar designs), severe voltage rise occurs and a detailed investigation needs to be undertaken to ensure that the system surge arresters will not be damaged.
  - Generally, faster tripping times would solve the problem (Note: Faster tripping times can cause miscoordination between the wind turbine switchgear and the substation protective relays).

Example of a non-effectively grounded system





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Summary

- The top MVA rating of the MPT comes out the reactive power study. It corresponds to the 100% MW output while meeting the PF lagging (project supplying MVArs) requirement.
- The OLTC of the MPT plays a major role in wind and solar plant operation. For large projects, PF requirements can't be attained with a DETC due to voltage limitations in collection system.
- The NGR size determines whether the system is effectively grounded and is generally driven by the economics of the project.
- The NGR size can have implications for the system surge arrester size. A moderate violation is generally tolerable.
- SLG faults, cable concentric neutral size, NGR size, relay coordination, and surge arresters go hand in hand.

QUESTIONS?

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