Over-voltages In Inverter-based Systems
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Introduction
Inverter vs. Rotating Machine

- Rotating machines (conventional): Synchronous and Induction (Types 1&2)
  - Rotating Inertia: Synchronous generator demonstrates continuous frequency response.
    - Synchronous voltage cannot jump
    - Inverter is based on PLL and software generated, limited to dc cap voltage
  - Magnetic Inertia: Large short circuit current.
    - Large units are cooled using liquid or gas
    - Synchronous: 8-10 times rated current
    - Induction: 5-6 times the rated current

Note: The above list neither is exclusive nor complete.
Inverter vs. Rotating machine

- **Inverter:**
  - Current limited switching devices
  - GTO, IGBT: Semiconductor wafer is thin and expensive
  - Low thermal inertia
  - Losses: $I^2R$, Switching losses
  - Maximum current is the design criteria
  - Short circuit current < 1.4 times the rated current (large units 1.1)
  - Six-pulse bridge
    - DC $\rightarrow$ AC

- Note: The above list neither is exclusive nor complete.
Inverter vs. Rotating Machine

- Dominant sources of energization of power systems have been synchronous generators.
  - Represented in power system analysis by a constant ac voltage source in series with a reactance.
- Inverter-based generators, however, generally behave like constant ac current (or power) sources.
  - Current source characteristic has impact on the overvoltages caused by ground faults,

- Assessment of system grounding, as defined in IEEE Std. C62.92, must properly consider behavior if inverter-coupled power sources dominate in a system.
Inverter Voltage Performance

Voltage ride-through (PRC-024-2)

- Above 120% for 0.16 s, ~ 10 cycles
- Inverter does not generate TOV above 120% for more than 10 cycles.
  - Canyon 2 Fire (NERC)
  - 400 MW OV tripping
Overvoltages

- Over-voltage protection is typically provided using Surge Arresters.
  - Surge arresters demonstrate low resistance for voltages above their MCOV and high resistance for voltages below their MCOV.
  - Limits transient overvoltages –not intended to limit temporary overvoltages.
  - Temporary overvoltages are caused by faults, load rejection, line energizing, resonance conditions, ferro-resonance, or by some combination of these factors.

- Note: inverters are harmonic sources, which can contribute to resonance conditions.
Arrester Power Frequency vs. Time

- TOV ratio versus arrester rated voltage drops with time.

- Arrester cannot handle 133% TOV longer than 1 second.

Source: ABB
Ground Fault
Ground Fault Overvoltage

- When a feeder is disconnected, the voltage of feeder collapse due to lack sources.

- Feeders with DER
  - island detection can be up to 2 seconds.

- Transmission-connected can have no load connected.

Source: IEEE
Ground Fault Overvoltage

Study methodologies

- **Symmetrical component**
  - +/−/0 components

- **Phasor study**
  - Ac system analysis

- **Time domain**
  - Inverter control scheme
    - Proprietary models
  - Many manufacturers provide compiled code in PSCAD

Source: EPRI
Ground Fault Overvoltage

- Inverters control scheme identifies and arrest conditions outside predetermined thresholds.
  - Transformer can impact inverter fault identification.

- Symmetrical Components: Inverter (current source mode)
  - Positive sequence: constant current source.
    - Phase inductor can be ignored.
  - Negative sequence: Dependent on control philosophy
    - Can range from phase inductor to infinity.
    - May actively cancel negative sequence currents
  - Zero sequence:
    - w/o neutral connection: Open circuit (more common)
    - w/ neutral connection: Dependent on control philosophy, can range from phase inductor to infinity.
  - Not valid under saturated condition (voltage source at limited output)
Ground Fault Overvoltage

- Sym. Components: Load
  - +/-/0: Shunts
  - Depending on the load type: Commercial, Residential, Motor, Service transformer

- $I_1$: pre-fault value
- $Z_2$: Variable, worst case
- $Z_{GT}$: Typically open circuit

- $Z_{L1}=Z_{L2}=V^2/S_{load}$
- $Z_{L0}$: Critical & Load dependent
Ground Fault Overvoltage

- How good the system is grounded?
- Effectively grounded:
  - Grounded through a connection of sufficiently low impedance (inherent, intentionally added or both) that a ground fault that may occur cannot build up voltages in excess of limits established for apparatus, circuits, or systems so grounded.
  - Coefficient of Grounding is the ratio of the highest line-ground voltage during a fault to the line-line voltage with fault removed (location).
  - COG does not exceed 80%; i.e. \(0.8\cdot\sqrt{3} = 1.386\).
    - ratio of the zero-sequence reactance to the positive-sequence reactance \((X_0/X_1)\) is positive and < 3, and
    - ratio of the zero-sequence resistance to the positive-sequence reactance \((R_0/X_1)\) is positive and < 1.

Source: IEEE
Non-fault Situations

- High Inverter Output to Load ratios
  - For an isolated DER and load an overvoltage can result if the source power output exceeds the load demand.
  - Load Rejection Overvoltage (LROV)
  - Constant current (source) x Constant impedance (load)
    - Grounding is irrelevant
  - Compounded with ground fault may result in TOV, where the sequence components become unsuitable, and time domain analysis including emtp-type studies will be needed.

Source: IEEE
Ground Fault Overvoltage

Impact of supplemental ground

- Pre-fault

- Post-fault
  - $\alpha$: ratio of pre-fault generation to connected load
Ground Fault Overvoltage

- Maximum phase voltage vs. pre-fault current
- Excess generation
- Can be compounded with load rejection overvoltage (LROV)
  - Inverter controls only the LROV
- Load pf = 1.0
- GT = Infinite
Ground Fault Overvoltage

- Maximum phase voltage vs. Ratio of grounded load
- Load = Generation
- Impact of load pf on TOV
  - Over-compensation
  - Ungrounded load
  - $Z_2 = 0.1+j1$
  - GT = Infinite

$$\text{Max. Phase voltage (pu)} = 1.39 = 0.8 \times \sqrt{3}$$
Ground Fault Overvoltage

- Impact of inverter negative sequence
- Sensitive for large $X_2/R_2$
  - Load = Generation
  - Pf = 1.0
  - GT = Infinite

![Graph showing the relationship between Inverter X2 (pu) and Max. Phase voltage (pu)]

- $X_2/R_2 = 10$
- $X_2/R_2 = 1$
- $X_2/R_2 = 0.1$
Ground Fault Overvoltage

- Impact of supplemental ground
- $X_{GT} = 0.6 \text{ pu}$
  - $X/R = 4$
- $Z_2$ large
  - Active cancelation
- TOV increases with GT
- Depends on $pf$
Ground Fault Overvoltage

- Impact of supplemental grounding
- Grounding may increase TOV

- Load = Generation
- Pf = 1
Additional Cases
Other Situations

- Constant Power Regulation
  - Fault normally causes a decrease in the voltage.
  - If the source regulates power the current increases to maintain reference power level.
  - Thus it can increase the un-faulted phase voltages.
  - Practically constant power control is implemented as an outer loop, hierarchical, and is sufficiently slow.
    - Thus the source will trip.
  - In case of faster scheme, feed-forward, it can cause voltage rise proportional to the allowable current; i.e. 110-120%

Source: IEEE
Other Situations

- **Load Unbalanced**
  - The simple sequence network is not valid for substantial phase unbalance under islanded mode.
    - Detailed network or time-domain analysis

- **Zero-sequence Isolation**
  - COG = 100%
    - Full neutral shift
  - Load < 125% Inverter P
    - Mitigation needed

\[ V = \sqrt{3} I_1 Z_L \]
\[ V_2 = 0 \]
\[ V_1 = -V_0 \]
Banks of single-phase sources w/o coordinated control

- Single-phase inverters may not be aware of other phases
  - 120° separation not guaranteed
- Load balanced and grounded star connected.
  - No inter-phase coupling
  - No overvoltages during ground fault
Banks of single-phase sources w/o coordinated control

- Single-phase inverters may not be aware of other phases
  - 120° separation not guaranteed
- Load balanced, but not grounded
  - Post-fault the current sources of un-faulted phases will be in-phase
  - Un-faulted phase voltage $I_{\text{source}} \cdot Z_Y = I_{\text{source}} \cdot Z_\Delta / 3$
  - If pre-fault output exceeds $\frac{1}{3}$ of the load, sources reach their output voltage limits
Banks of single-phase sources w/o coordinated control

- Single-phase inverters may not be aware of other phases
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  - If pre-fault output exceeds $\frac{1}{3}$ of the load, sources may reach their output voltage limits
Mitigation measures

- Effective grounding
  - COG is the measure
- Adequate load relative to Inverter Output
  - Supplemental ground may be needed
- Coordinated transfer trip
  - Inverter disconnected before feeder opens
- Fast Inverter overvoltage tripping
  - Inverter may not see TOV on primary side
- Fast islanding detection
- Sacrificial arrester
  - Difficult
Conclusion

- Ground fault on inverter-based systems can cause TOV
- Symmetrical component analysis can provide practical insight
- Sequence impedance of the Inverter and load can impact the resultant TOV
- Time domain simulation, including inverter control scheme, provides better resolution
- Inductive supplemental grounding can increase TOV
- Islanding can compound TOV due to mismatch between DER power to connected load, LROV, worsens under reverse power flow
- Better modelling should be used for planning studies
References

2. IEEE Std. 1313.1, “Standard for Insulation Coordination”
3. UL-1742, “Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources”
5. NERC, “Recommended Practices for Modeling Momentary Cessation”
Questions?