BECKWITH ELECTRIC

DISTRIBUTED ENERGY RESOURCES

Operation, Protection, and Control

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Distribution Protection and Control Track
Tuesday, August 5, 2025
Day 2 – Session 3

HUBBELL

Objectives (1/2)

- Define DER
- Explore Types of DERs
- Why DER?
- Utility and Facility Drivers for DER
- Mission Critical Power and Conversion to DER
- Rates and DER Operational Sequences
- Industry Concerns
- IEEE 1547: Industry DER Guide

Objectives (2/2)

- Interconnection Protection: “The Five Food Groups”
- Interconnection Transformer Impacts
- Generator Types and Impacts
  - Synchronous
  - Induction
  - Asynchronous (Inverter Based)
- Example Protection Applications
- Distribution Protection Coordination Issues
- Smart Grid/Microgrid and DER
- Impact of IEEE 1547
- DER Variability/Energy Storage
- DER Harmonics/THD & TDD
- Summary and Q&A

What is DER?

- Generation of electricity from small energy sources
  - Typically, <=10MW but much larger size deployments of wind and solar farms interconnected at the transmission voltage level are also increasing
- May be based at facilities, including industrial, commercial and residential, as well as utilities
- We will be discussing DERs connected into distribution mainly
- Use of Distributed Energy Resource (DER) allows collection of energy from many sources and may provide lower environmental impacts and improved security of supply

What is DER?

Also called:

- Distributed Generation (DG)
- Distributed Resource (DR)
- Dispersed Generation (DG)
- Embedded Generation
- Decentralized Generation
- Dispersed Storage & Generation (DSP)
- Decentralized Energy
- Distributed Energy
- Independent Power Producer (IPP)
- Non-Utility Generator (NUG)

A Brief DER History

- Up until the Public Utility Regulatory Policies Act (PURPA) in 1978, U.S. utilities were not required to interconnect with small generators
  - Started DER
  - Hot until late 1980’s when tax incentive was terminated
- Late 1990’s DER hot again
  - Driven by high utility rates and de-regulation
  - DERs can generate cheaper at the source of consumption
  - Peak Shaving and Load Following (demand reduction saves $$$$)
  - Hot until early 2000’s when natural gas prices increased
- Late 2000’s Green Power drives resurgence of DERs
  - Regulation requires utilities to generate a portion of their power from green sources

Types of DER: Sorted by Utility Connection

Prime Power

- On-site generation provides power to loads
- No connection to a utility grid
- Does not require DER interconnection protection
- Things change if utility power is brought to site

Types of DER: Sorted by Utility Connection

Emergency Power

- Normally power from the utility; in the event of utility power failure, on-site generation is used
- Momentary parallel connection of onsite power to utility grid allowed (<=100 ms)
- Does not require DER interconnection protection

Types of DER: Sorted by Utility Connection

Grid Paralleled (Emergency Power + Grid Paralleled Operation)

- Power from utility, onsite power, or combination of utility and onsite power in long-term parallel operation
- Uses circuit breakers to control and allow parallel operation
- Utility DER interconnection protection is required

DER: Green or Conventional by Energy Source

Conventional (Not Green)

- Burn conventional fuel
  - Diesel
  - Oil
  - Gasoline
  - Natural Gas (seen as “greener”)

DER: Green or Conventional by Energy Source

Green (Renewable)

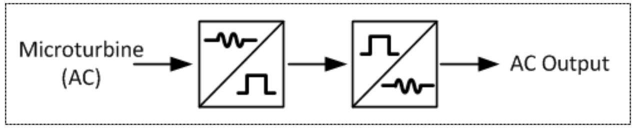
- Use renewable sources to reduce reliance on fossil fuels:
  - Hydro
  - Solar (PV)
  - Solar (thermal to steam)
  - Wind
  - Biodiesel
  - Biogas (methane decomposition)
  - Biomass (direct burn/gasification)
  - Tidal
  - Storage (battery)

Conventional DER

Industrial Gas Turbine

Reciprocating Diesel

Microturbine Gaseous Fuel

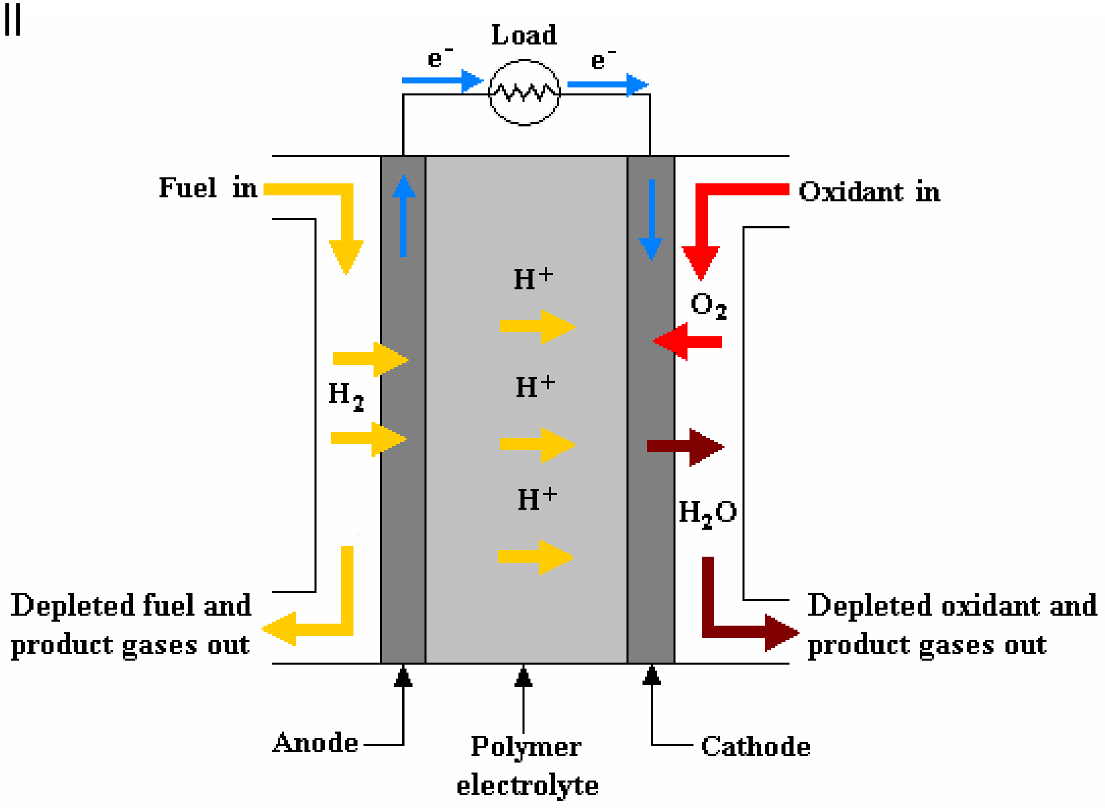


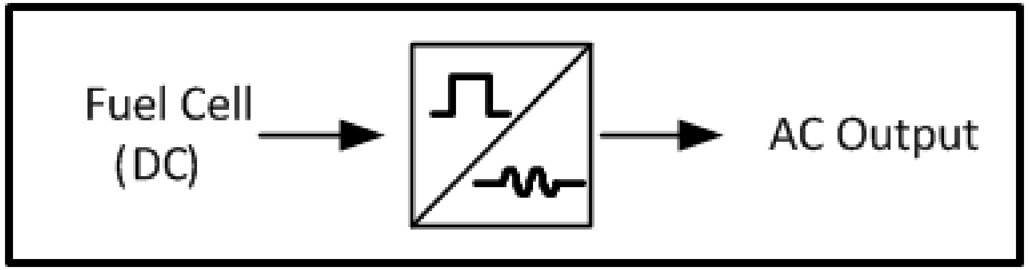
Reciprocating Gaseous Fuel

Reciprocating aka: Internal Combustion Engine (ICE)

Conventional DER

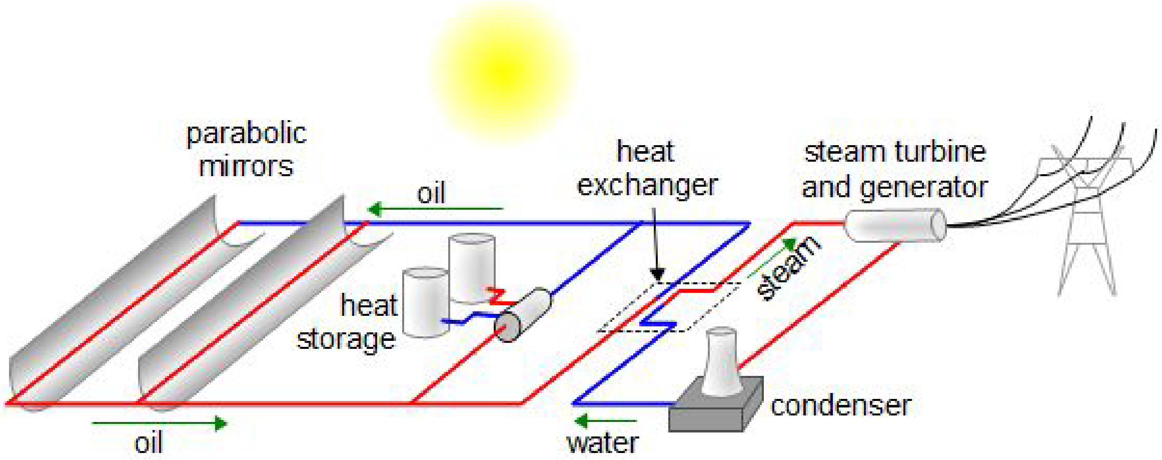
Fuel Cell



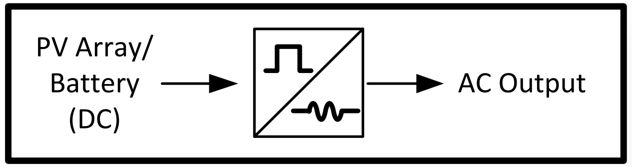


Renewable DER

Solar (Thermal)



Solar (PV)



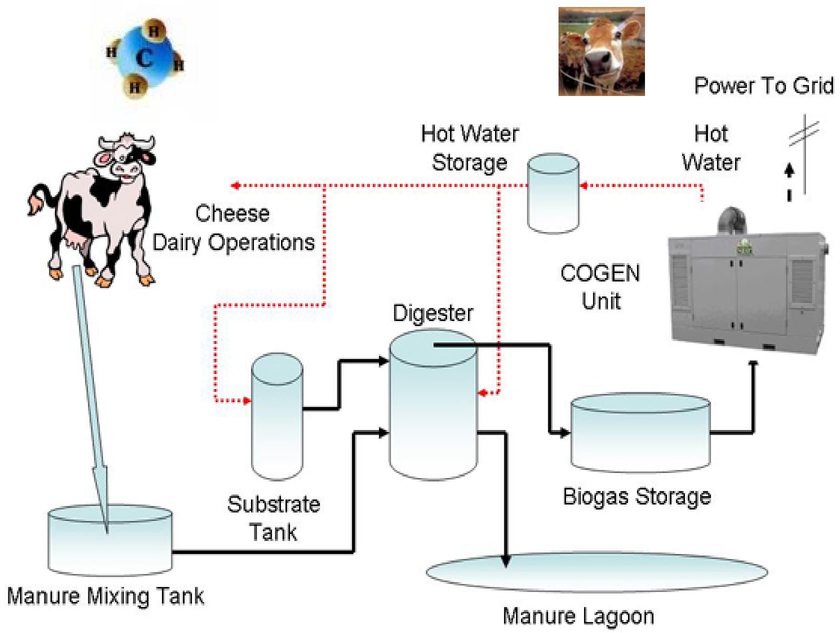
Small Hydro

Renewable DER

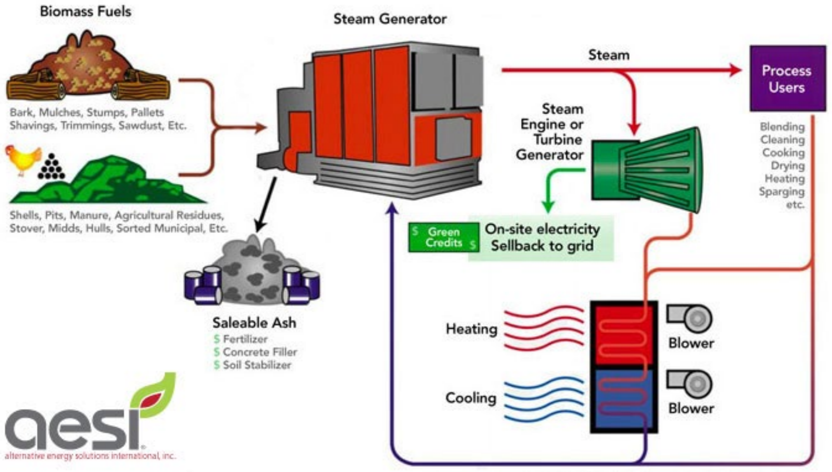
Wind

- May be induction or synchronous generator output
- May be mixture of generator and inverter output

Biogas

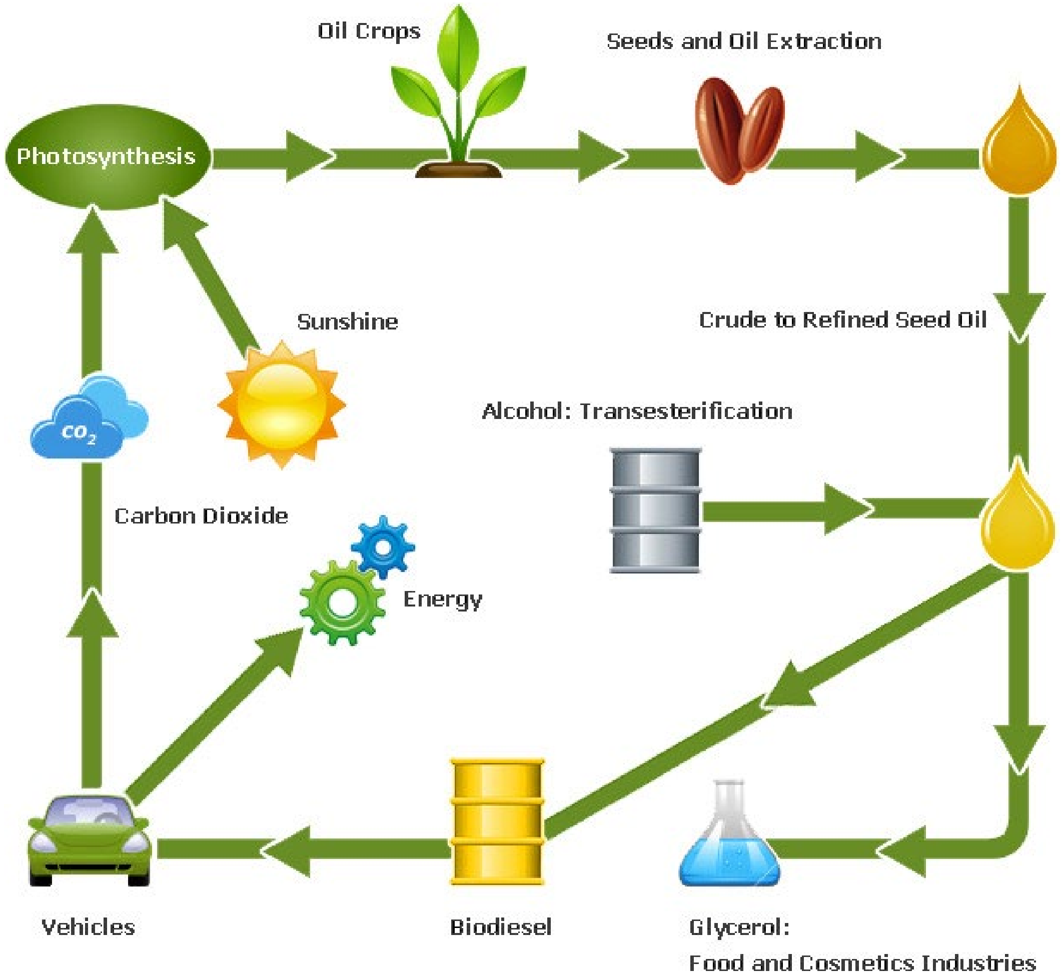


Biomass

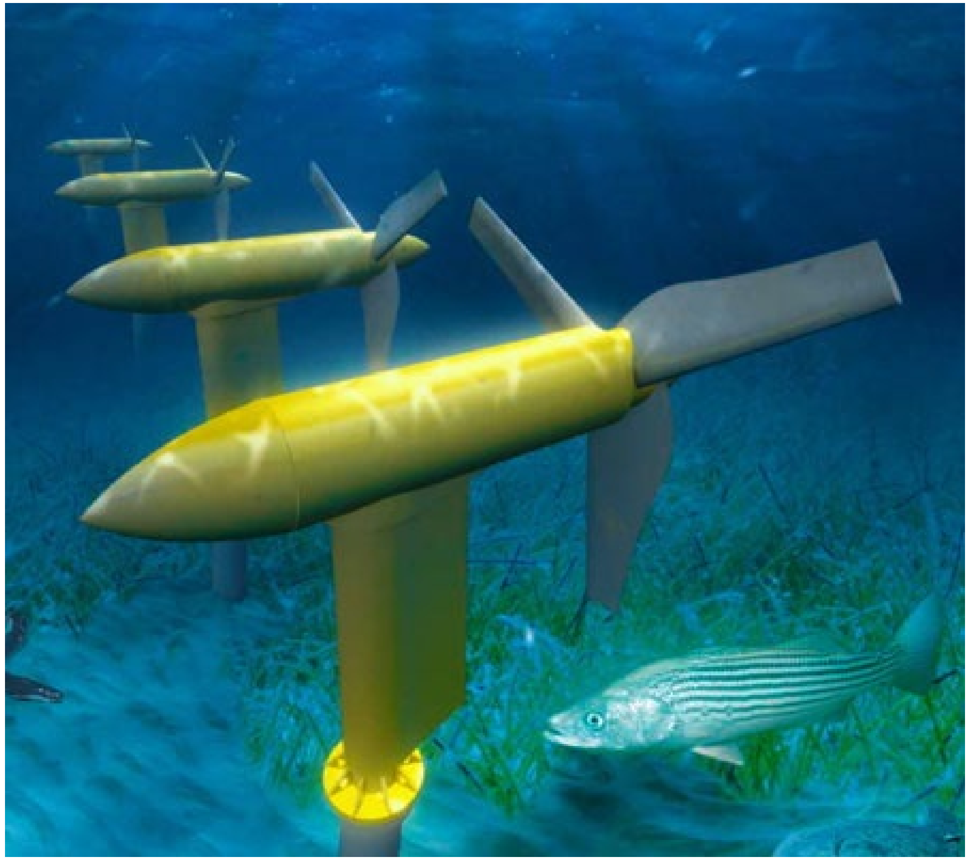


Renewable DER

Biodiesel

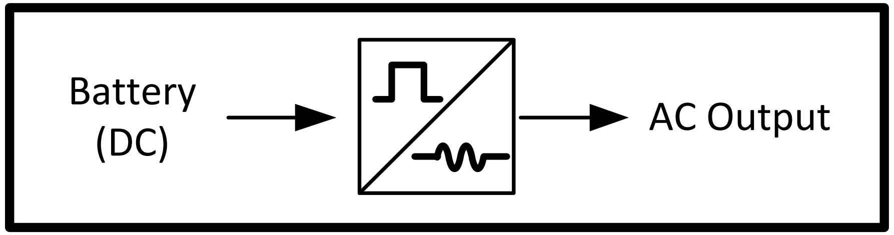


Tidal



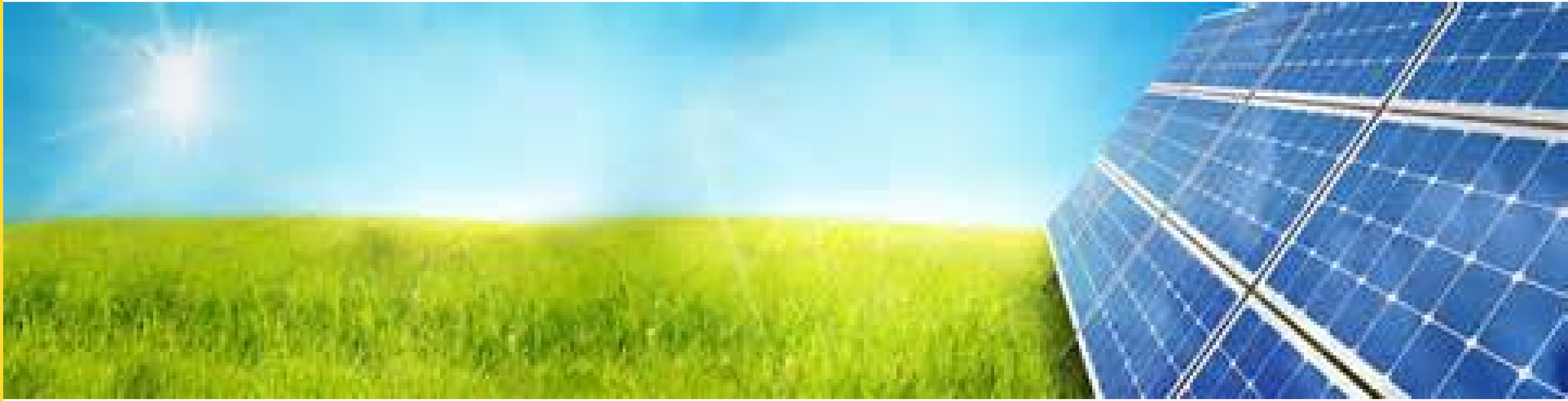
Renewable DER

Storage Battery



Why Green Power? (aka: Renewable Energy)

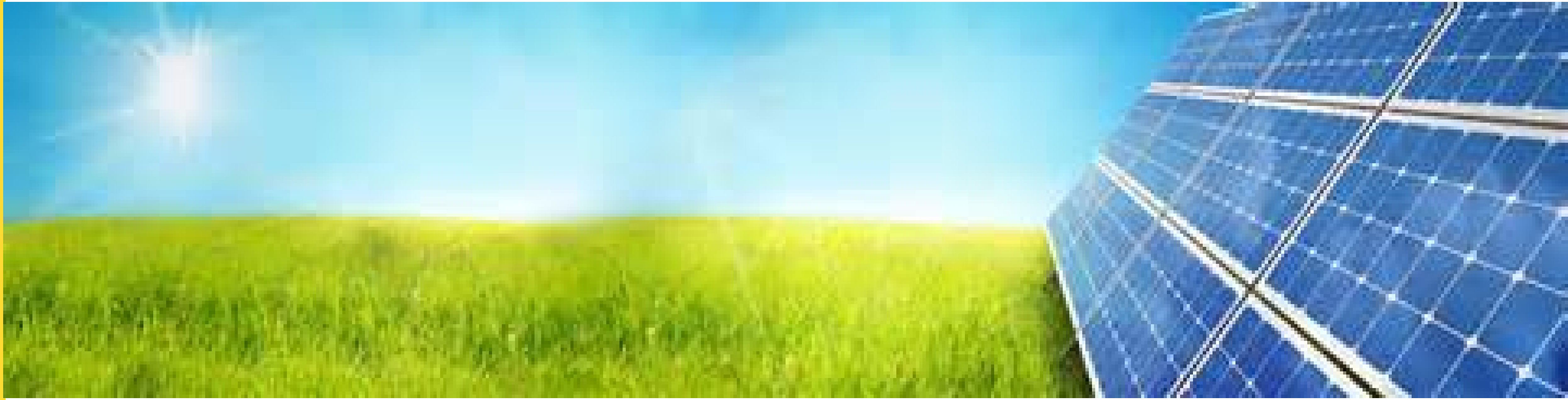
- Federal and State Governments Push for Renewable Resources
  “Green Power Is In.”
- Technological advances have reduced green power costs



Why Green Power? (aka: Renewable Energy)

Basic Penetration Drivers:

- Public Utility Commissions (PUC) mandate that a percentage of generation is green by a given date
  - This typically fosters installation of large blocks of green energy installation such as wind farms and large scale PV connected to transmission systems
- Increase the buy back rate and let market forces install green generation. This typically fosters smaller generators connected to distribution systems.



Why DER: Utility Drivers

T&D Issues

- Decrease losses
  - DER at the point of use is not subject to transport loss
  - T&D losses range 3-7%

Demand Response

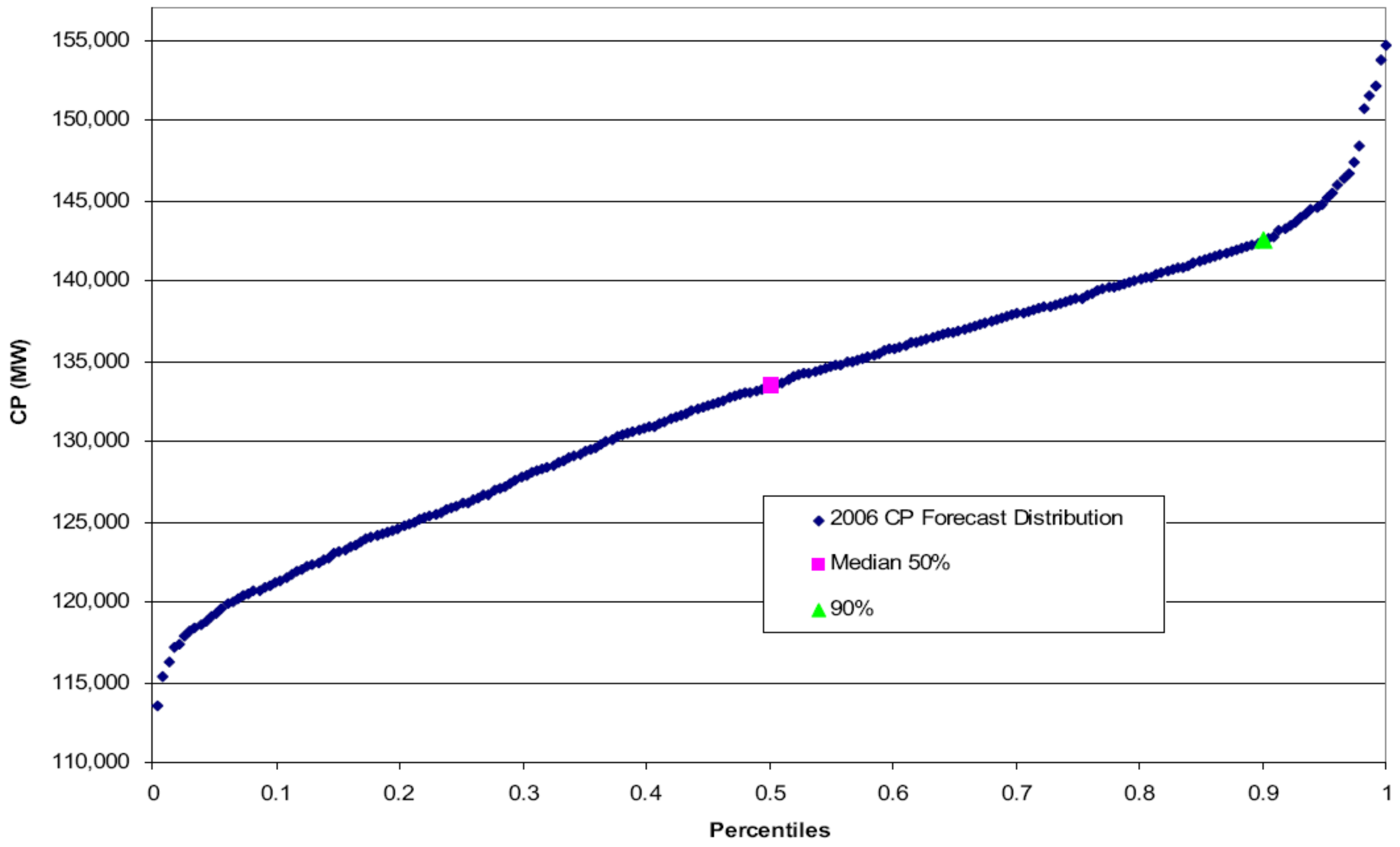
- Turn On Local DER to Turn Off Load to System
- No prebound/rebound effects in callable application
- Allows larger critical process C&I Customers to participate in demand response programs
- aka: Peak Reduction

Why DER: Utility Drivers



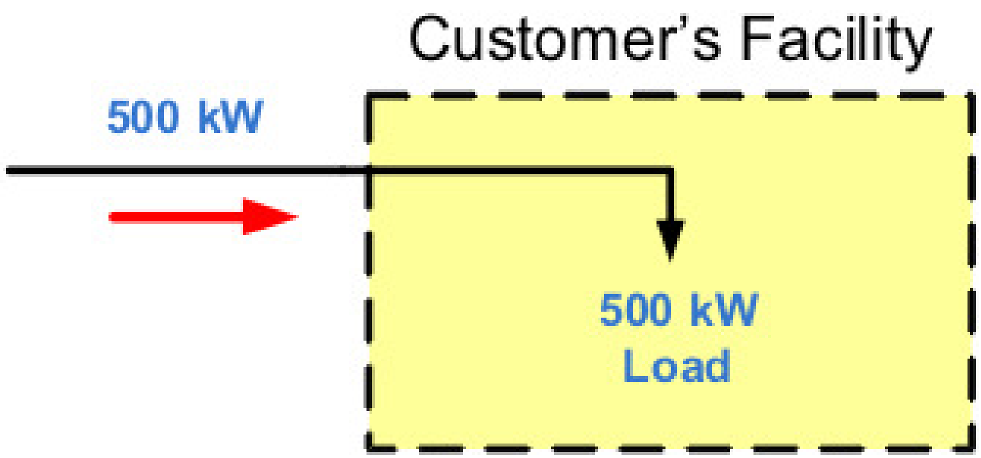
- Transmission decongestion
- Distribution decongestion
- Distribution build-out deferral
- Grid Support
  - Ancillary Services
    - Voltage regulation
    - VAR Support

Reality of Grid Load Dynamics (Peak Demand)

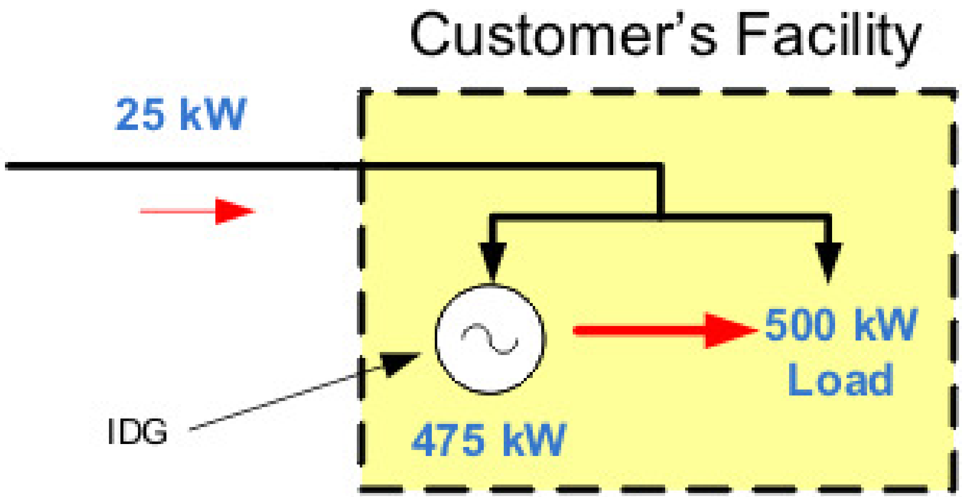


- Accumulated Annual Demand of Highest 5% occurs about 400 hrs/year
- 100s of Billions of $ of equipment and capacity idle for most of the time

DER in a Demand Response Role

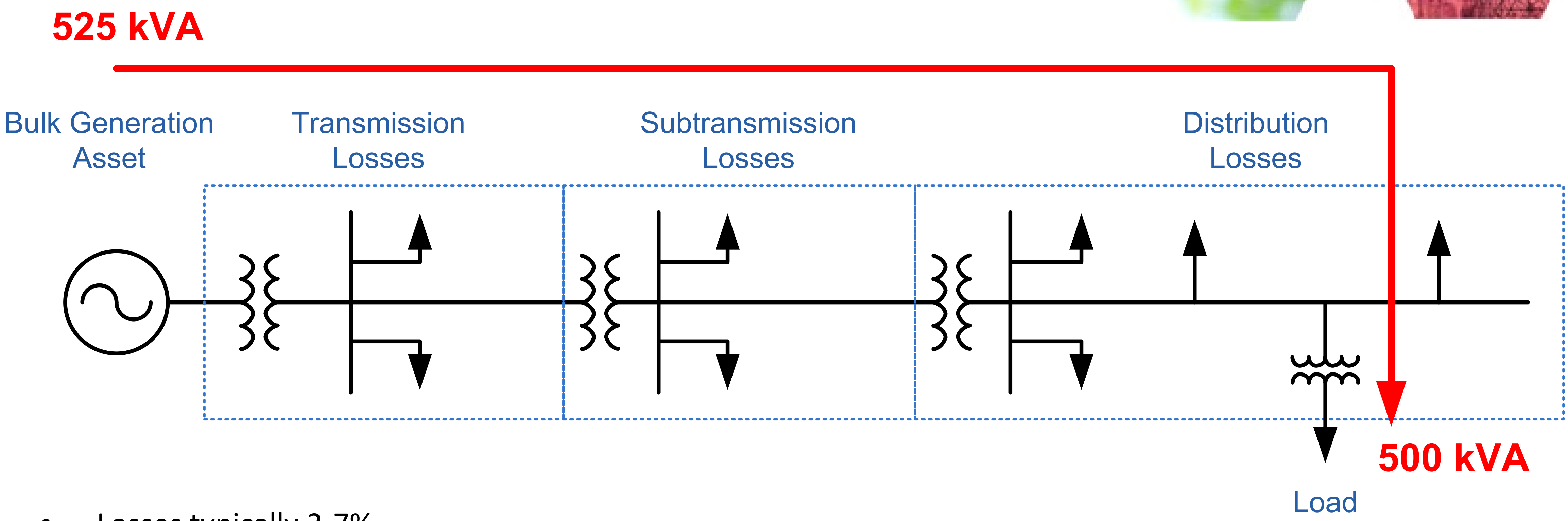


Without DER



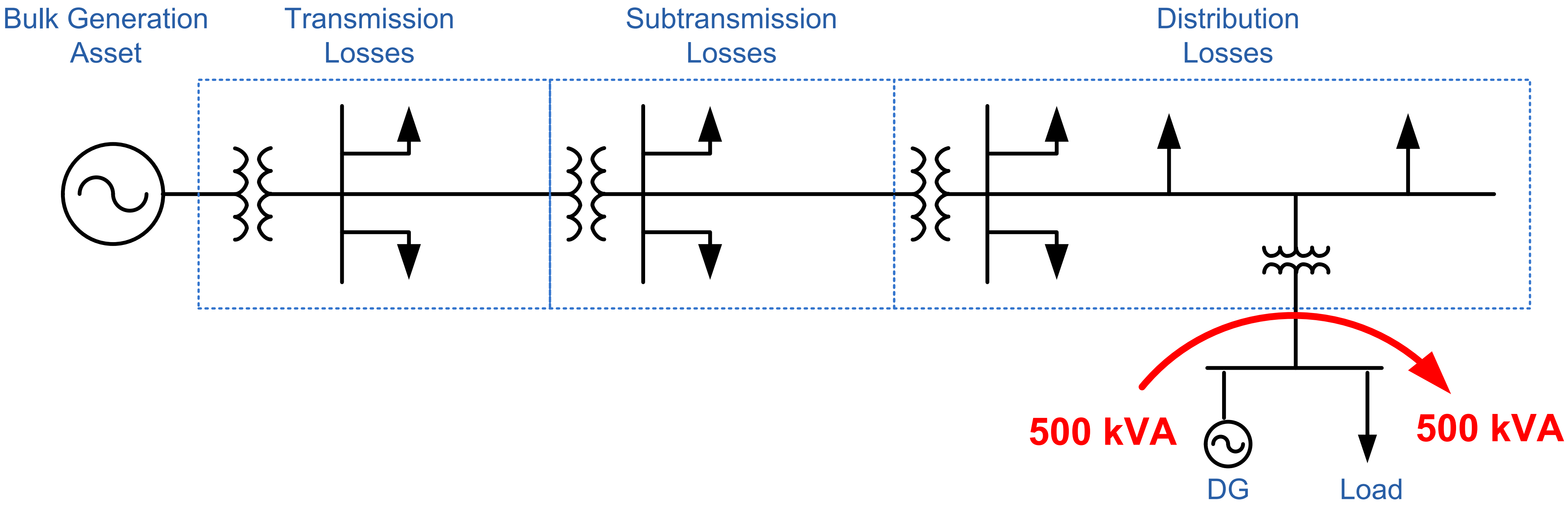
With DER

Sustainability & Losses: Conventional Power Delivery



- Losses typically 3-7%
- 5% used in this example

Sustainability & Losses: Conventional Power Delivery



- [1] California Energy Commission; http://www.energy.ca.gov/distgen/equipment/reciprocating_engines/reciprocating_engines.html
- [2] California Energy Commission; http://www.energy.ca.gov/distgen/equipment/combustion_turbines/combustion_turbines.html
- [3] http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html

Why DER: Utility Drivers

Divestiture of generation by utilities (capacity issues)

- Dwindling utility reserve margins
  - Summer of 2000 Midwest “Generation Crisis”
  - California capacity crisis
  - August 2003 blackout
  - 2021 Texas power crisis

Why DER: Consumer Drivers

Rate Incentives

- Demand Reduction
- Interruptible Rates
- Load Curtailment Rates
- Energy Reduction (if power produced is less expensive than utility)

Increase in CHP for greater fuel-to-power efficacy (>90% possible)

- CHP: Combined Cooling, Heating and Power
  - Also called “TriGen”
  - Uses cheap natural gas and heat recovery

Power Security

- Emergency Power Systems
  - 1st rule of power quality, “you gotta have some”
  - Emergency Power Systems can be repurposed and used for demand rate reduction incentives

Critical Power Systems: Where Applied?

Network Centered Sectors

- Electric Power
- IT and Comms
- Banking & Finance
- Oil and gas
- Rail and Air
- Water

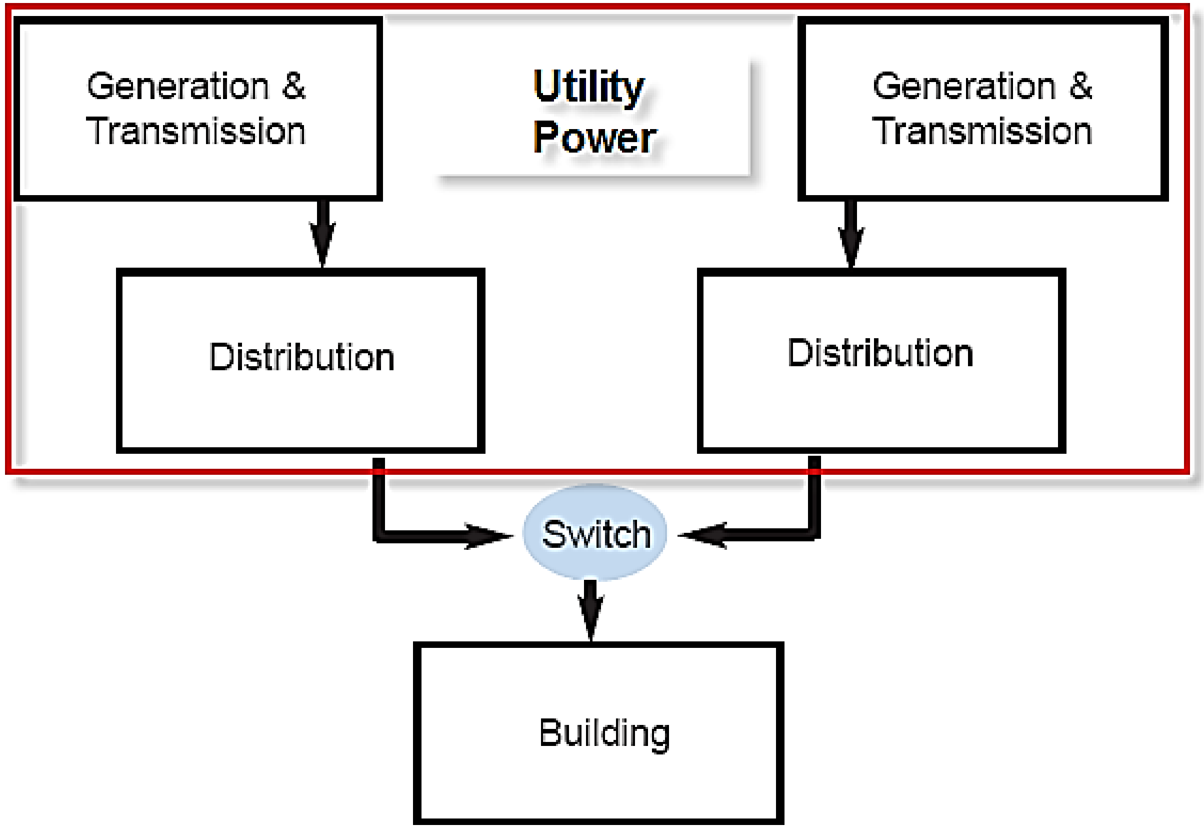
Critical Service Sectors

- Government
- Law Enforcement
- Emergency Services
- Health Services
- Municipal Services

Not a coincidence …

this is where much of the utility-interconnected DER is installed

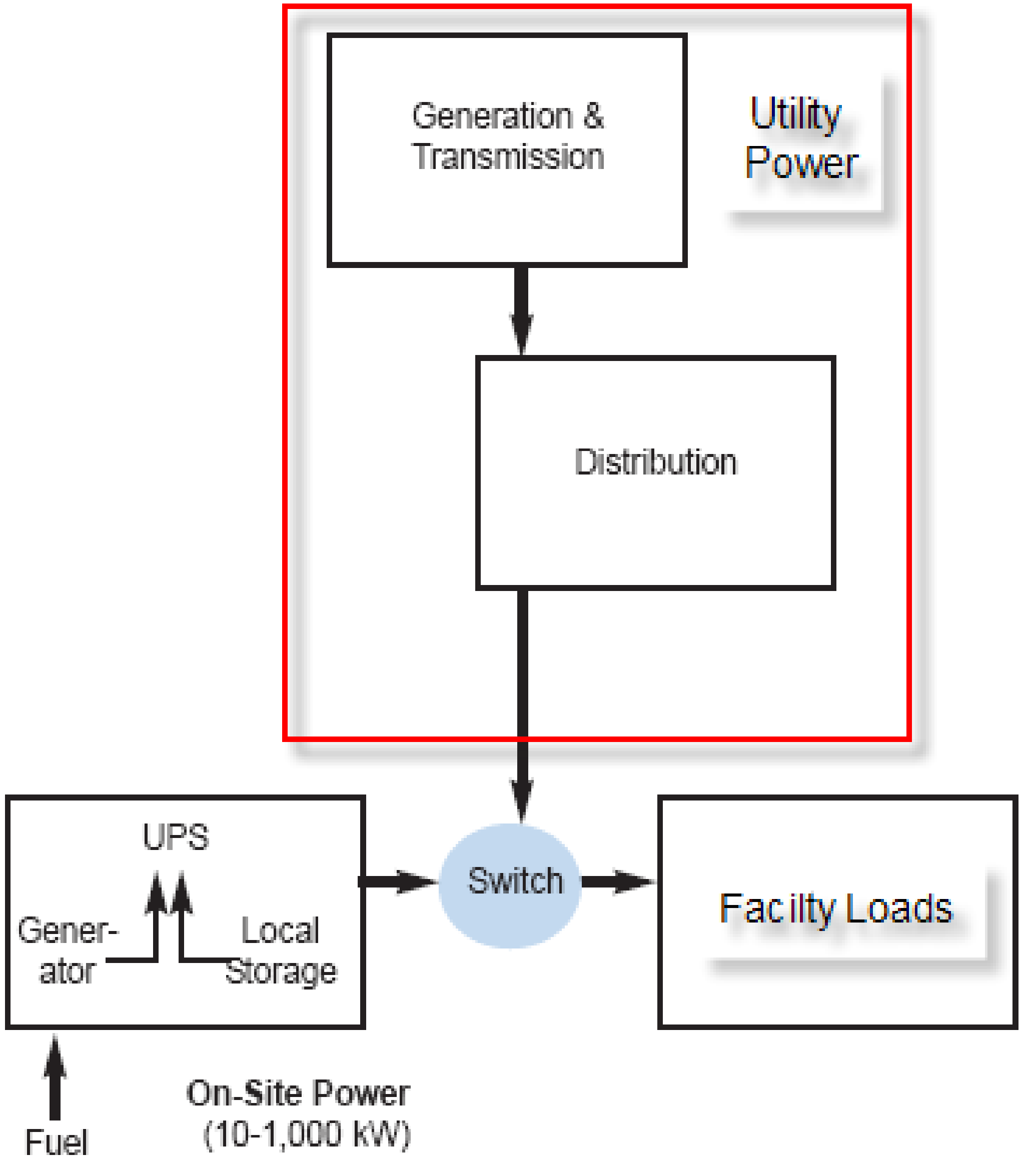
Fault Tolerance: Utility Outages



- Employs redundant feeds from utility
- Still susceptible to outages from complete utility failure

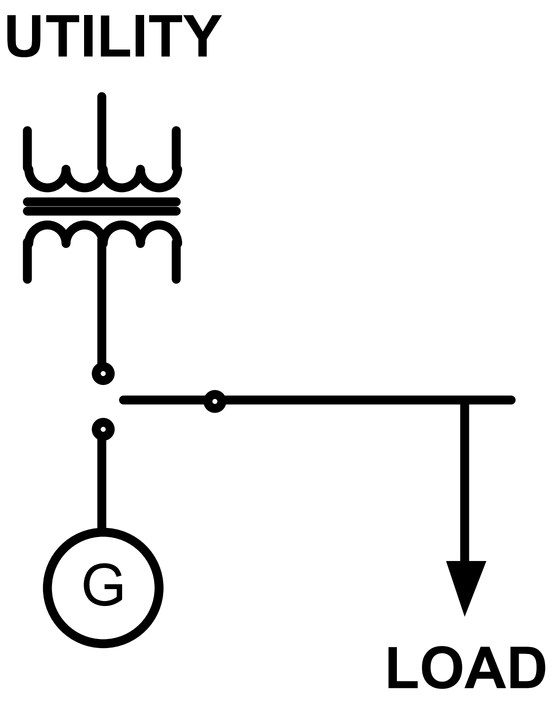
Fault Tolerance: Utility Outages

- Employ utility feed(s) and onsite power
- Onsite power functional even in the event of total utility failure

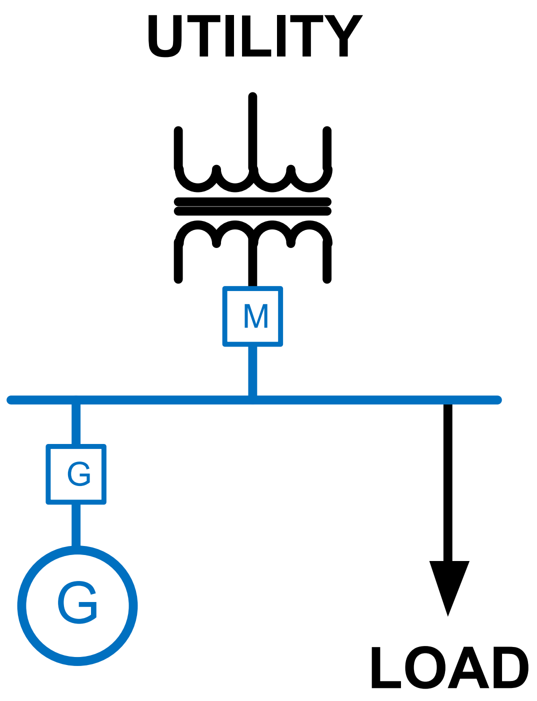


ATS vs. Circuit Breakers

- ATS does not protect
- ATS cannot long-term parallel
- Circuit Breakers cost more than an ATS, but provide protection and operational flexibility

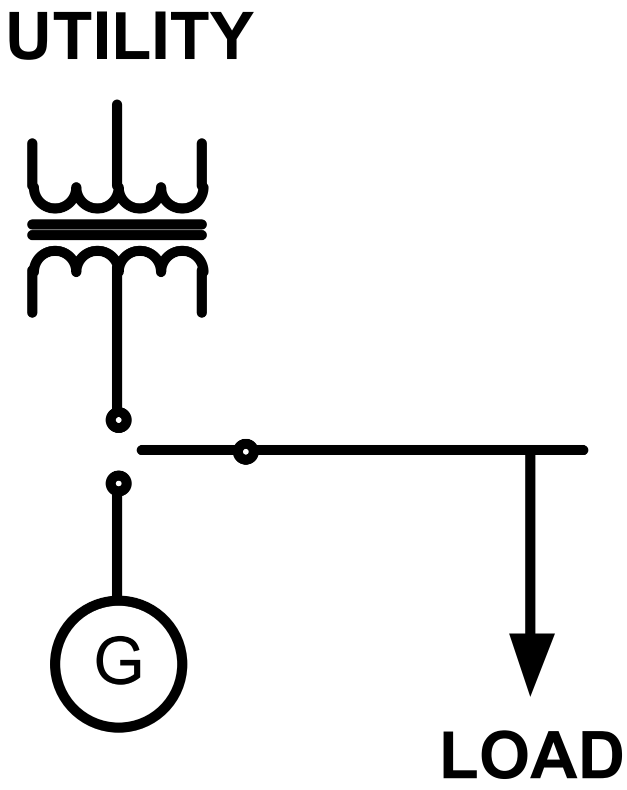


ATS

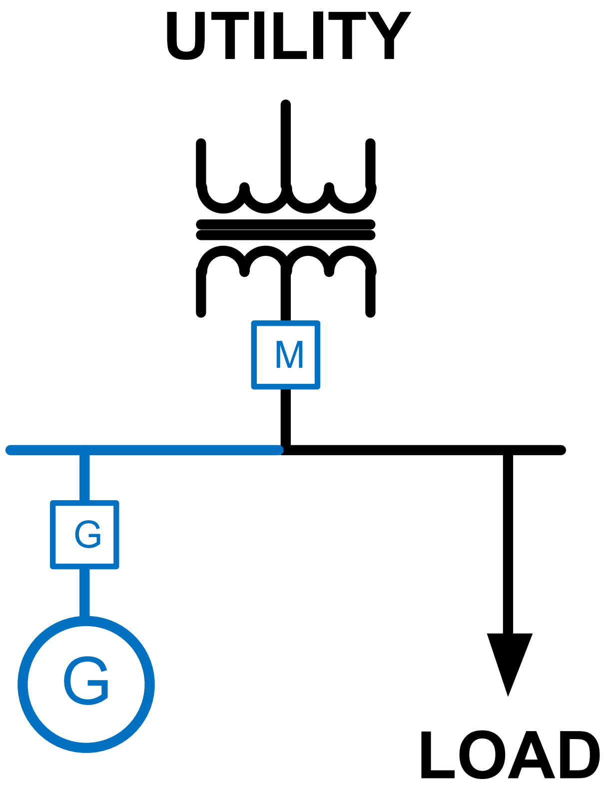


Circuit Breakers

Conversion of ATS-based emergency system to dual purpose emergency and "bumpless" peak shaving system

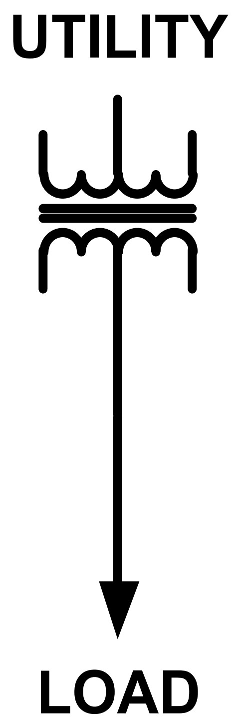


Existing Facility

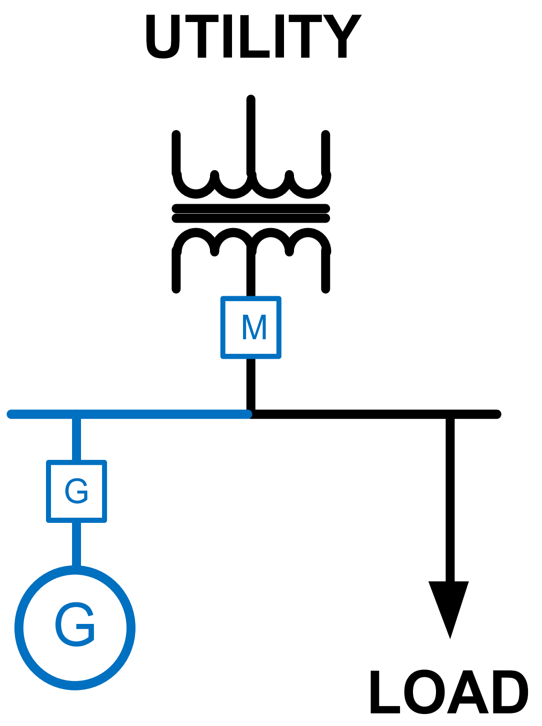


Facility Retrofit with Switchgear/ Protection/Controls for Grid Paralleled Generator Operation

Greenfield dual-purpose emergency and "bumpless" peak shaving system

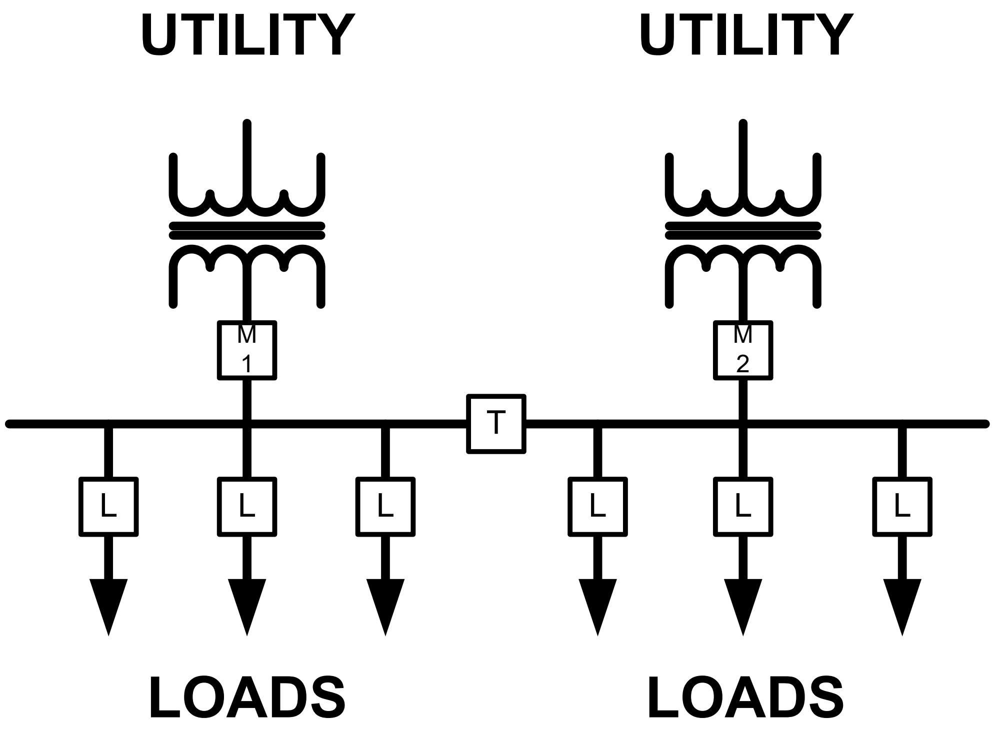


Existing Facility

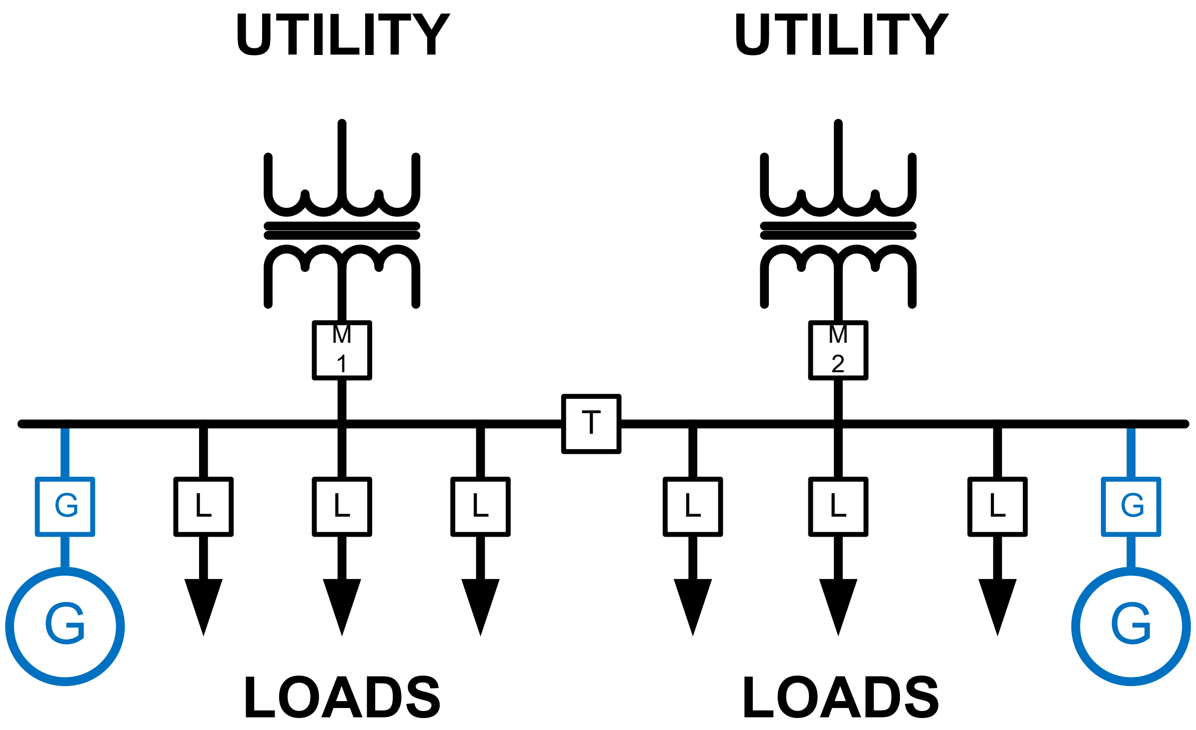


Facility with Generator and Switchgear/Protection/Controls Added

Complex Application: Dual-Fed Facility Main-Tie-Main

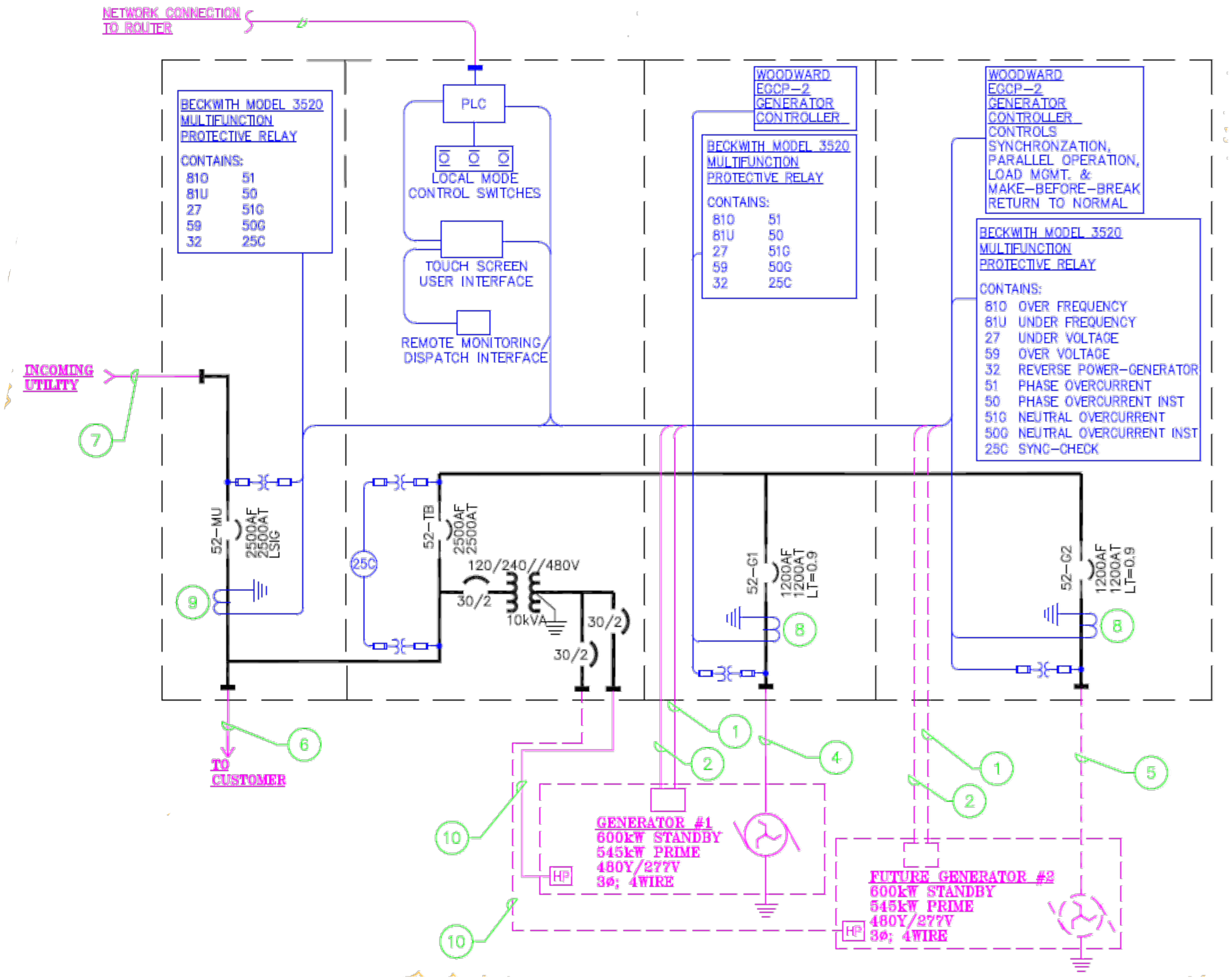


Existing Facility



Facility with Generators and Switchgear/Controls Added

Small LV Appl cation



Source: PowerSecure

Prime Power (No Utility Connection)

- Onsite Generation is supplying the facility without any connection to the utility.
  - Off-Grid Power
  - Emergency Power (Standby)
- Generation is controlled to maintain a constant speed (frequency) and voltage.
- As the isolated Facility’s load changes, the generator must alter its output for both the real load (watts) and reactive load (VARs)

Prime Power (No Utility Connection)

The control system will accomplish this to the limits of the generation:

- As **real power demand increases**, the governor is signaled to **increase the fuel to the generation** to maintain rated frequency output.
- As **real power demand decreases**, the governor is signaled to **decrease the fuel to the generation** to maintain rated Hz frequency output.
- As **reactive power demand increases**, the voltage regulator is signaled **to increase the field current**, thereby increasing VAR output to maintain rated voltage.
- As **reactive power demand decreases**, the voltage regulator is signaled to **decrease the field current**, thereby decreasing VAR output to maintain rated voltage.

Paralleled Operation (Interconnected to Utility)

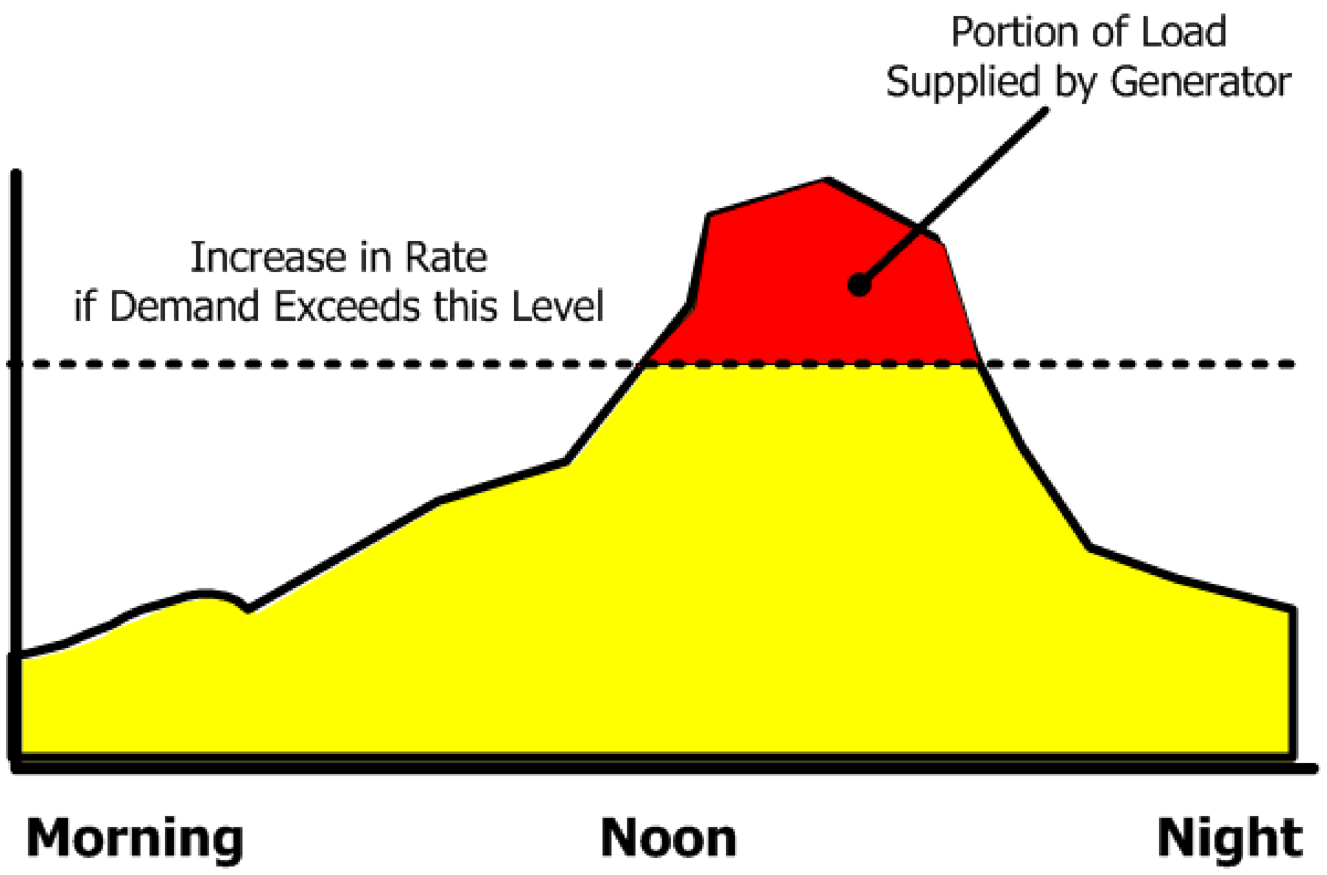
- Onsite generation and utility are operating in parallel to supply the facility off-grid power
  - Load Management (Peak Shaving)
  - Transfer Transition (short- or long-term)
- Generation is controlled to maintain real power and reactive power output per watt and power factor setpoints respectively.

Paralleled Operation (Interconnected to Utility)

As the utility-interconnected facility's load changes, the generator must alter its output for both the real load (watts) and reactive load (VARs).

- As **real power demand increases**, the governor is signaled to **increase the fuel to the generator** per the watt output setpoint.
- As **real power demand decreases**, the governor is signaled to **decrease the fuel to the generator** per the watt output setpoint.
- As **reactive power demand increases**, the voltage regulator is signaled to **increase the field current**, thereby increasing VAR output to maintain power factor per the setpoint.
- As **reactive power demand decreases**, the voltage regulator is signaled to **decrease the field current**, thereby decreasing VAR output to maintain power factor per the setpoint.

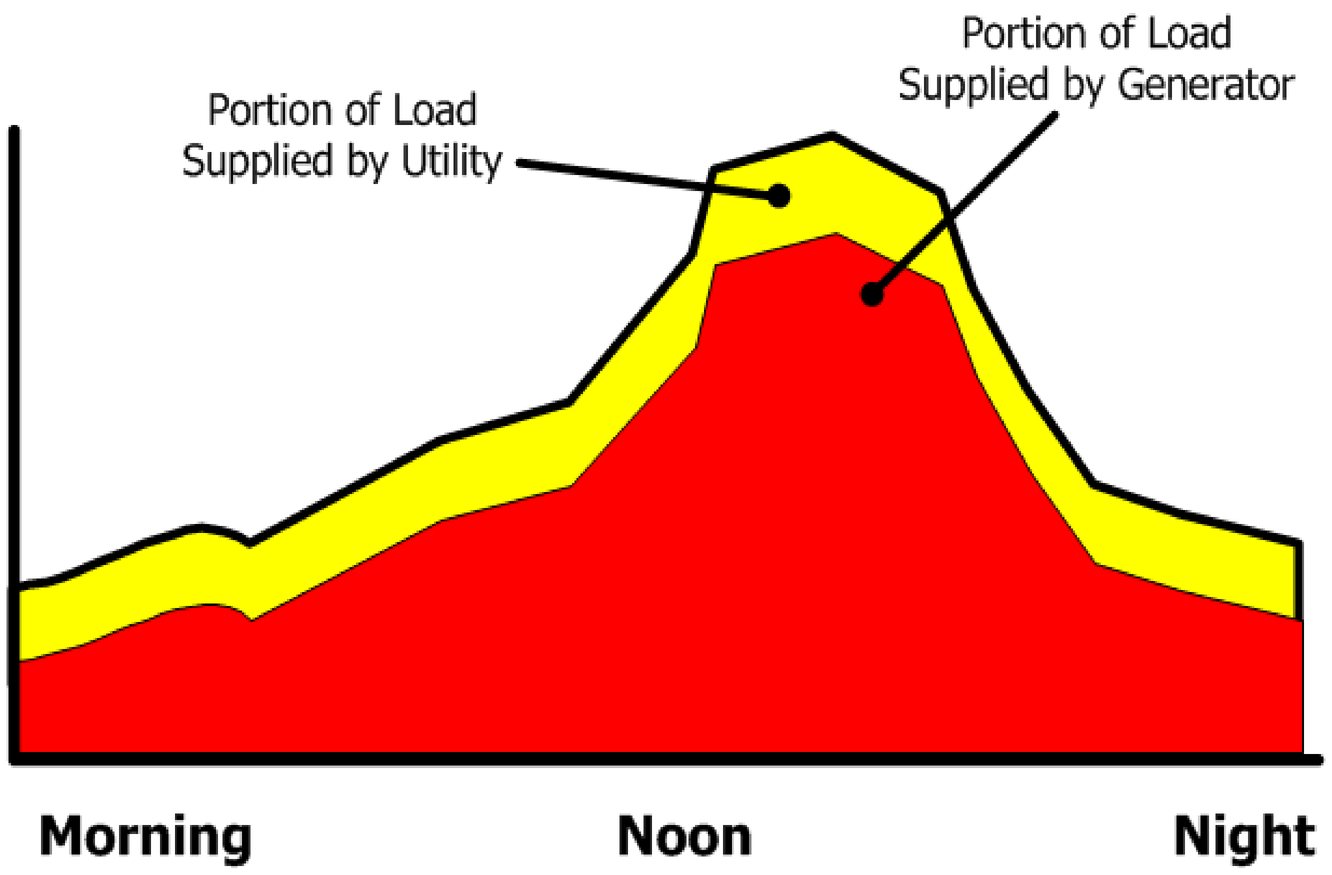
Consumer Demand Reduction Strategies



Peak Shaving

No electrical export to Utility

Consumer Demand Reduction Strategies



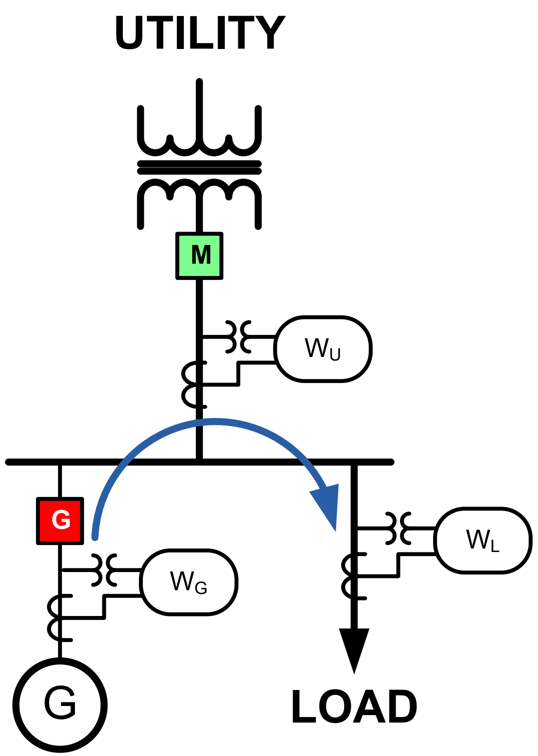
Load Following

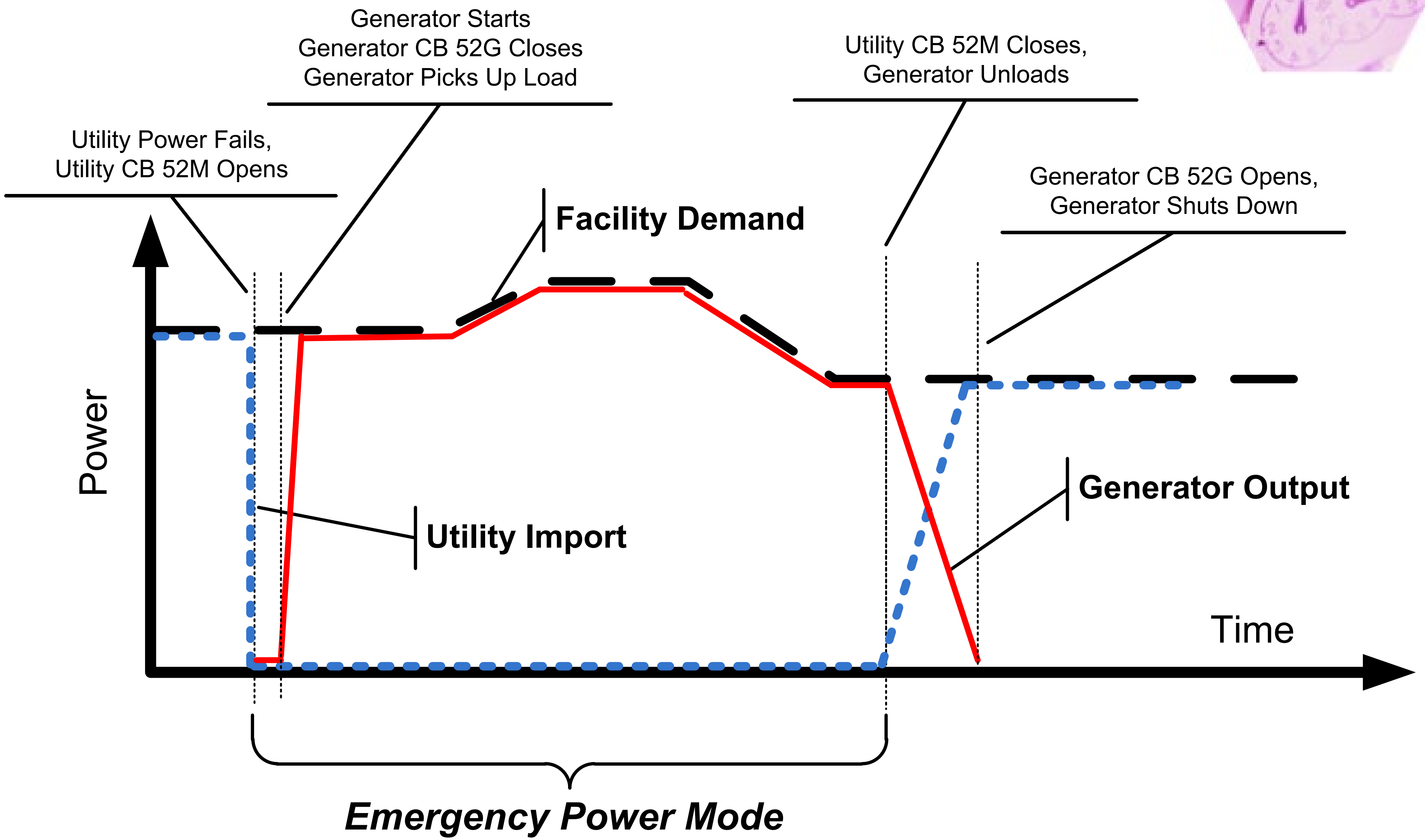
No electrical export to Utility

Operational Sequence Details

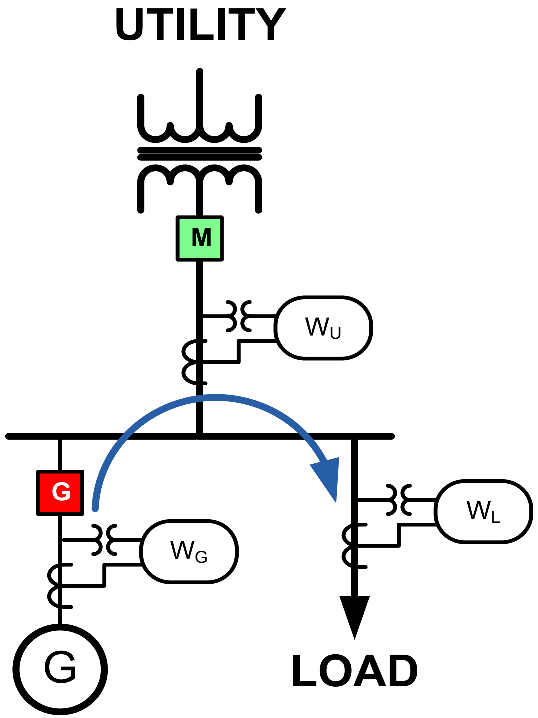
- Emergency Power
- Load Isolation
- Load Following
- Export
  - To know how DER is controlled in parallel with a utility is important for DER Interconnection protection application
  - When control fails, protection is the safety net

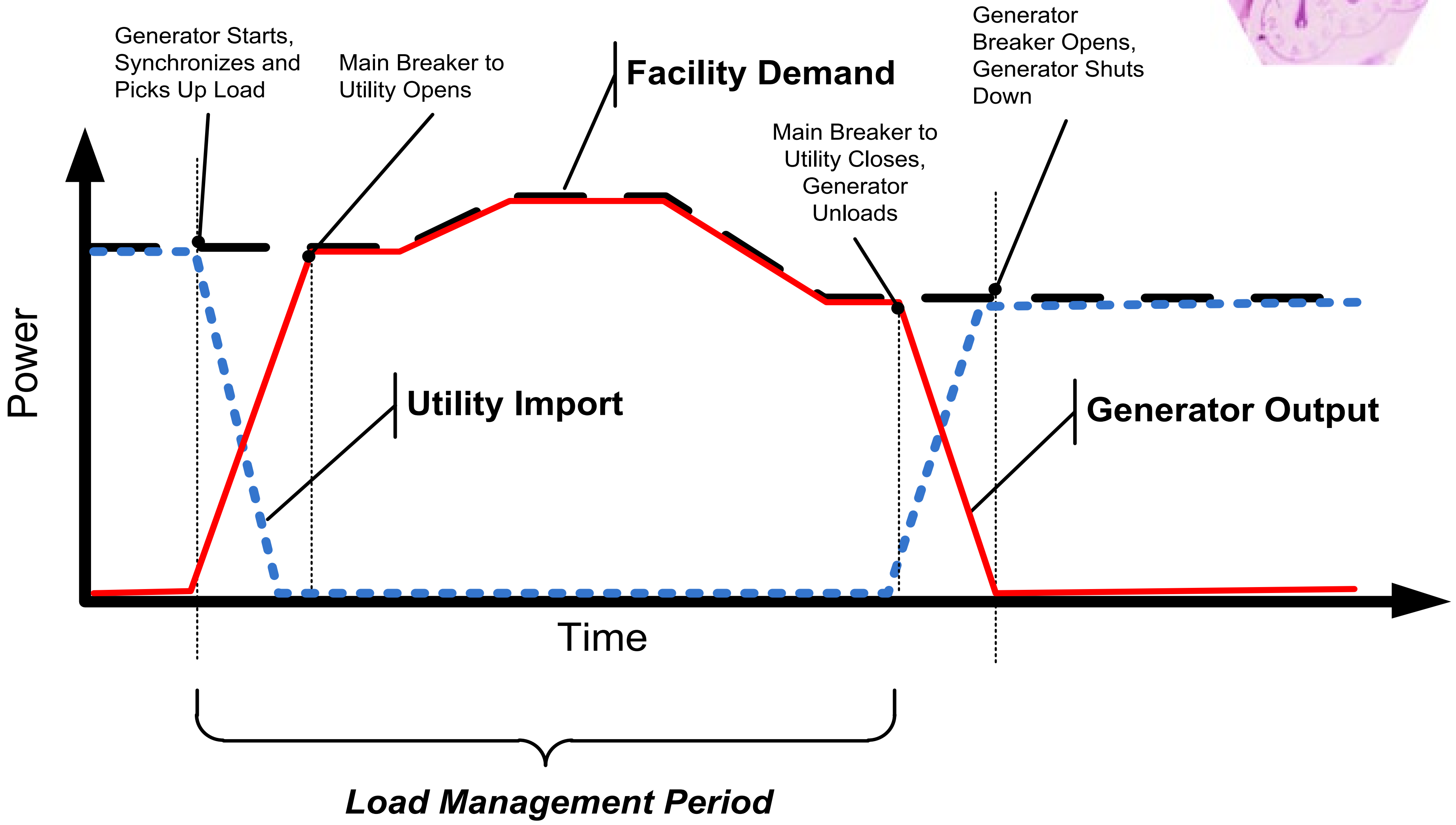
Emergency Power: Details



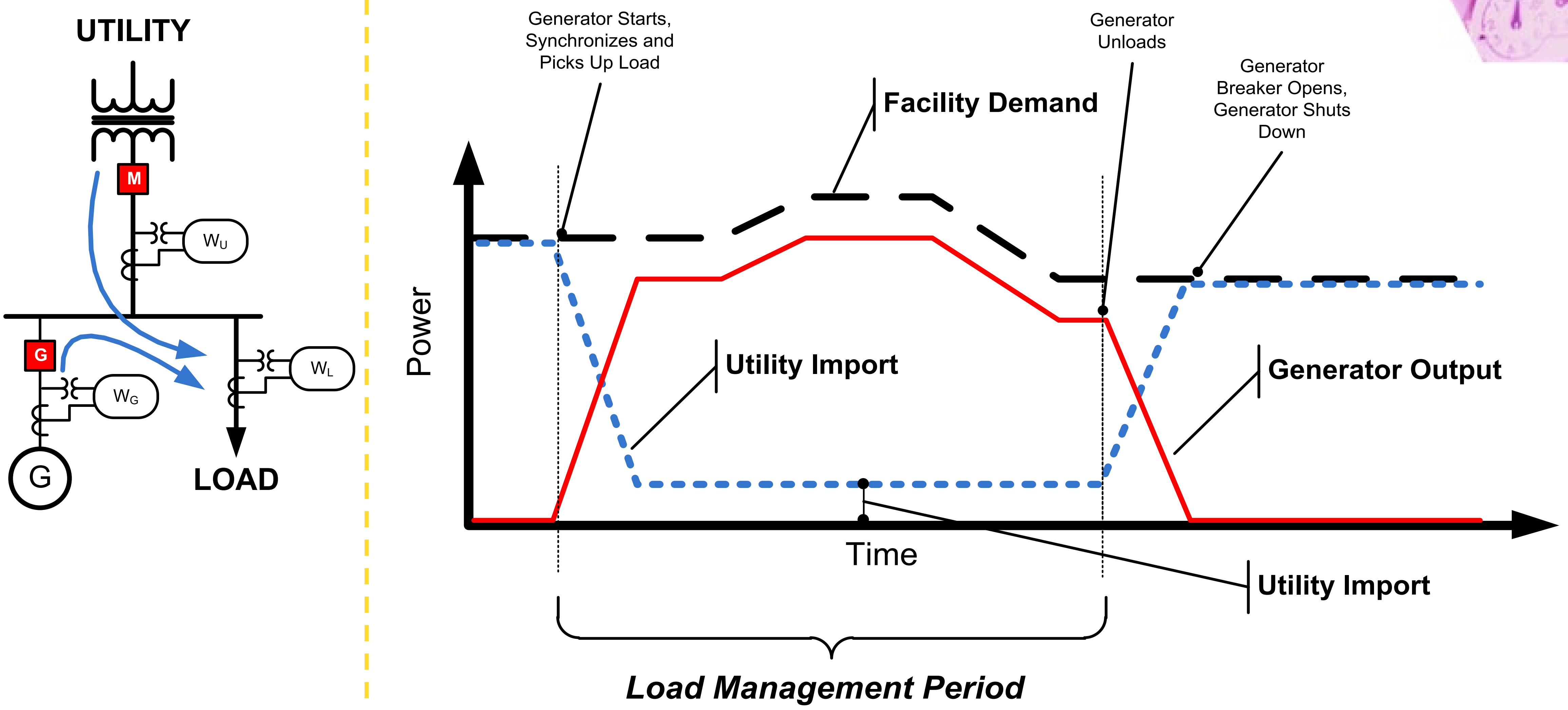


Load Isolation: Details

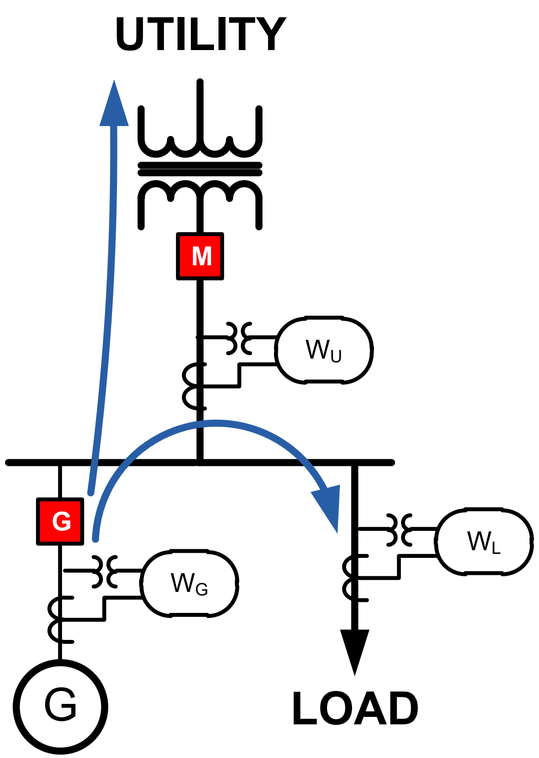


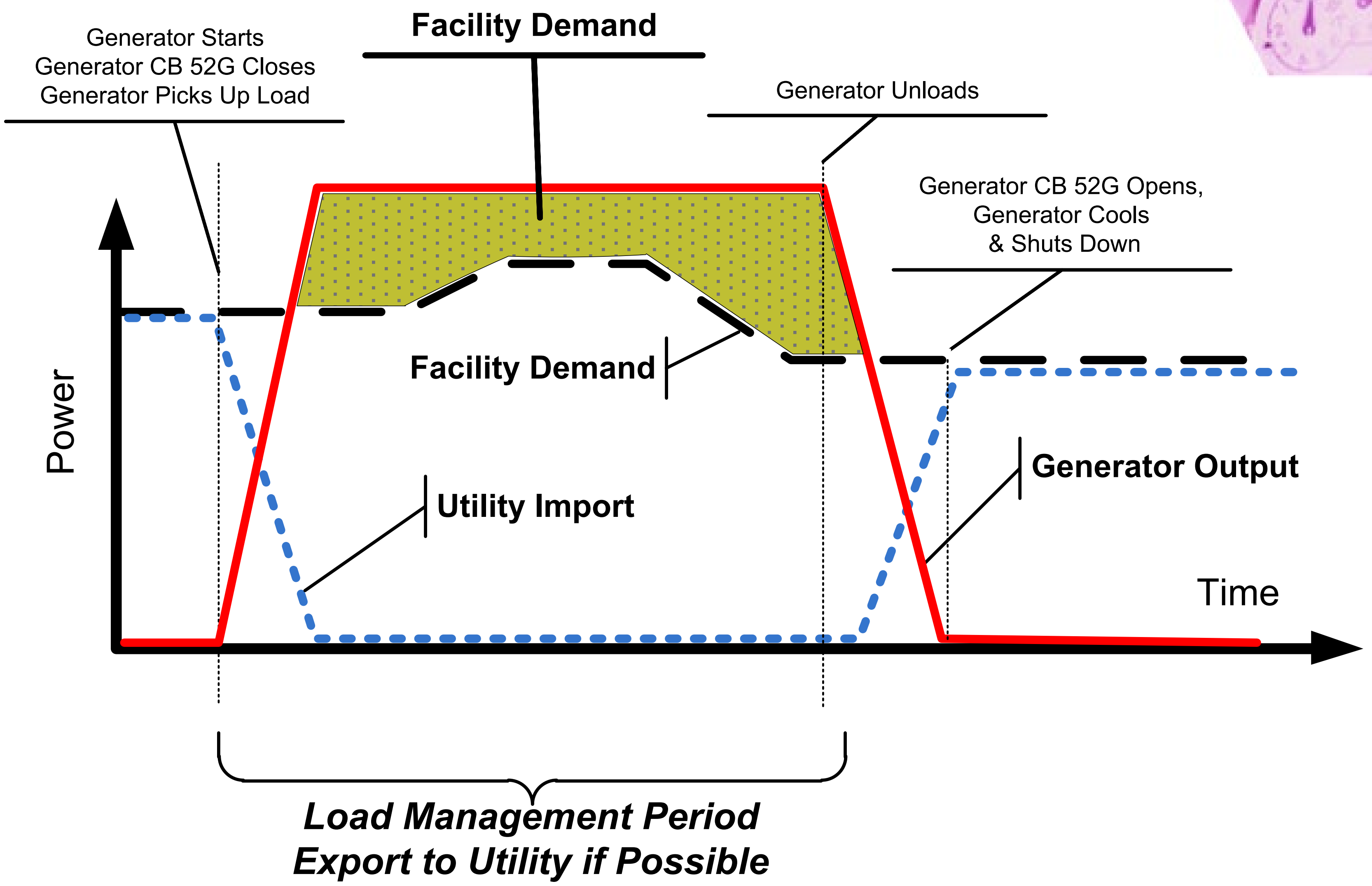


Load Following: Details

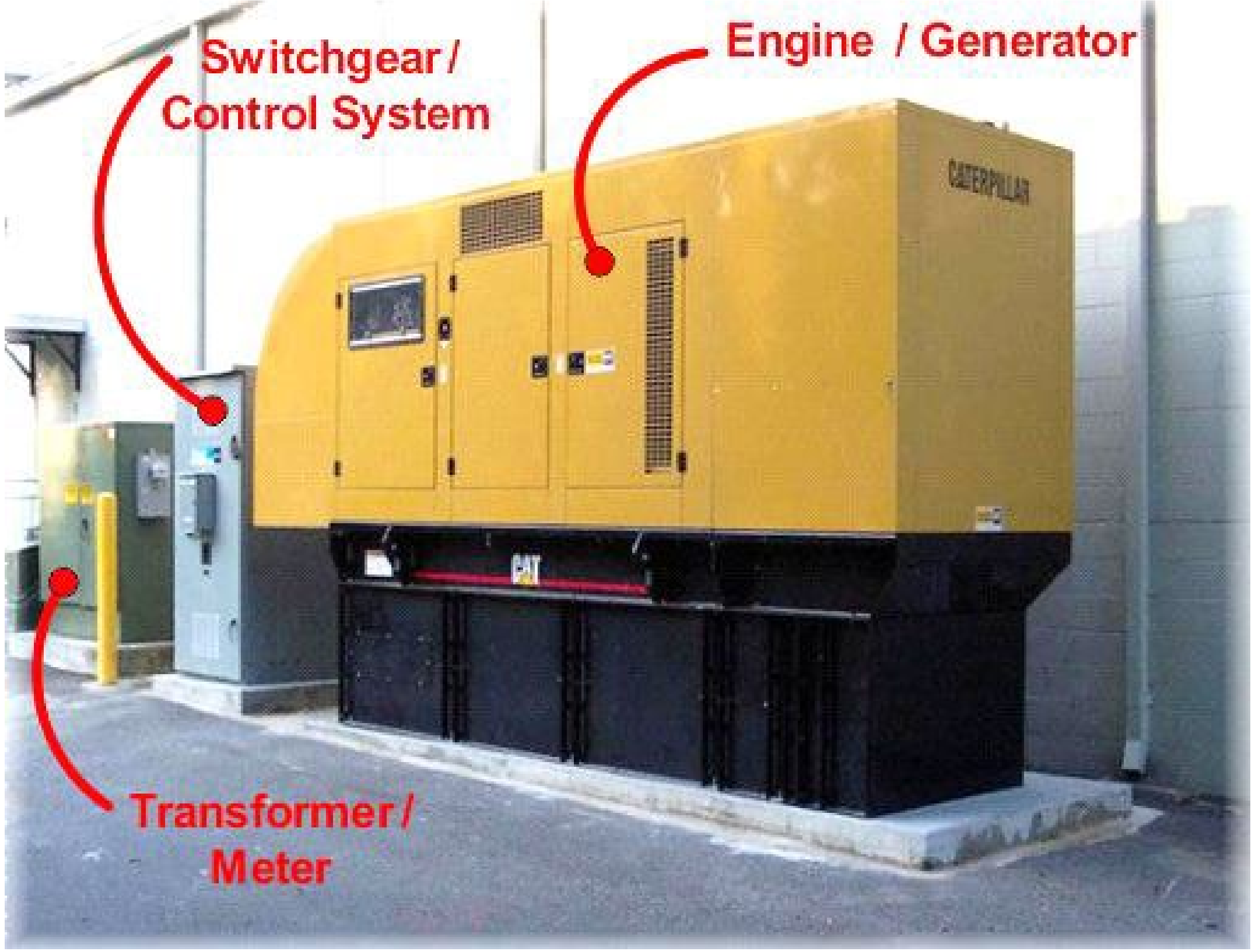


Export: Details



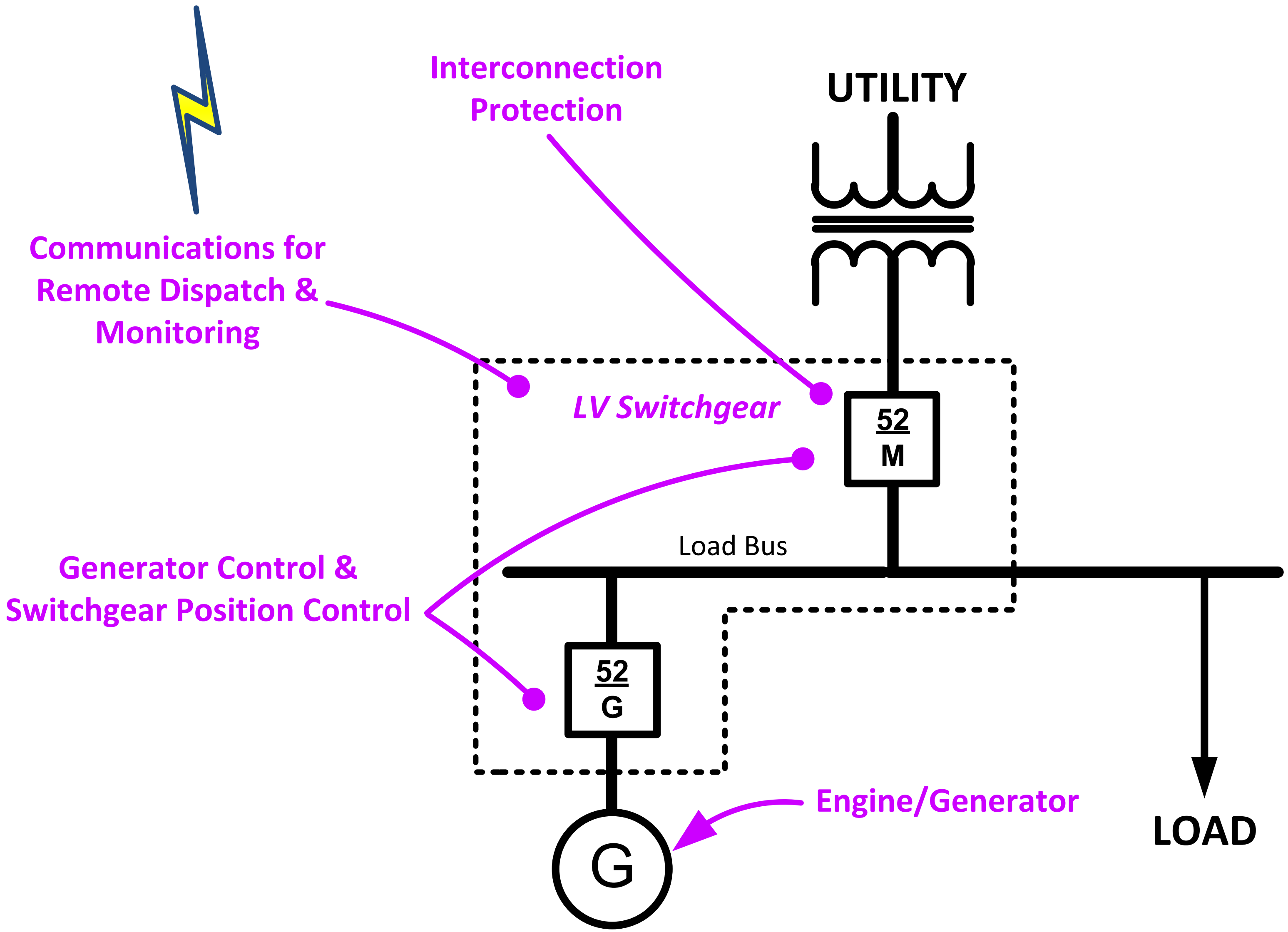


Example DER System

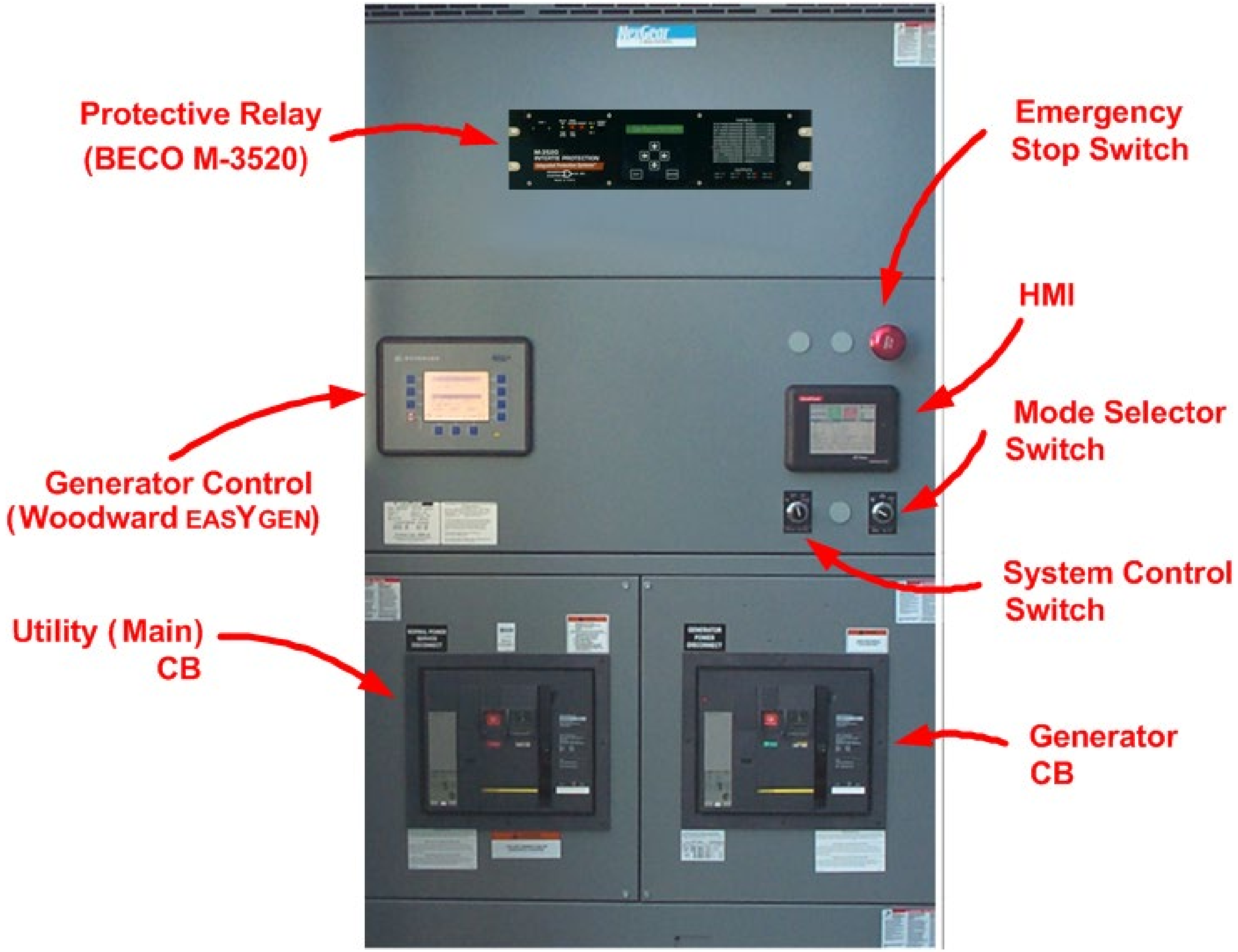


Source: PowerSecure Installation

Interconnection Protection in LV Switchgear

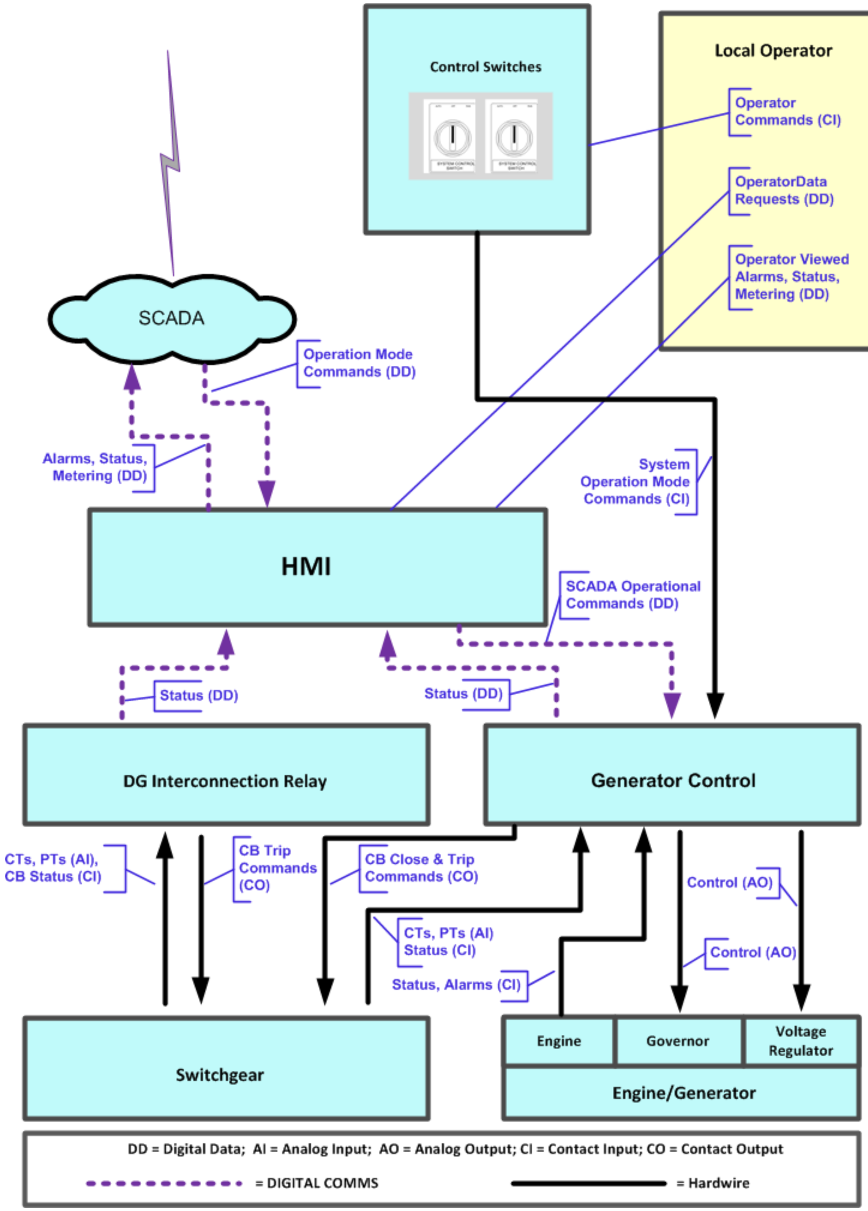


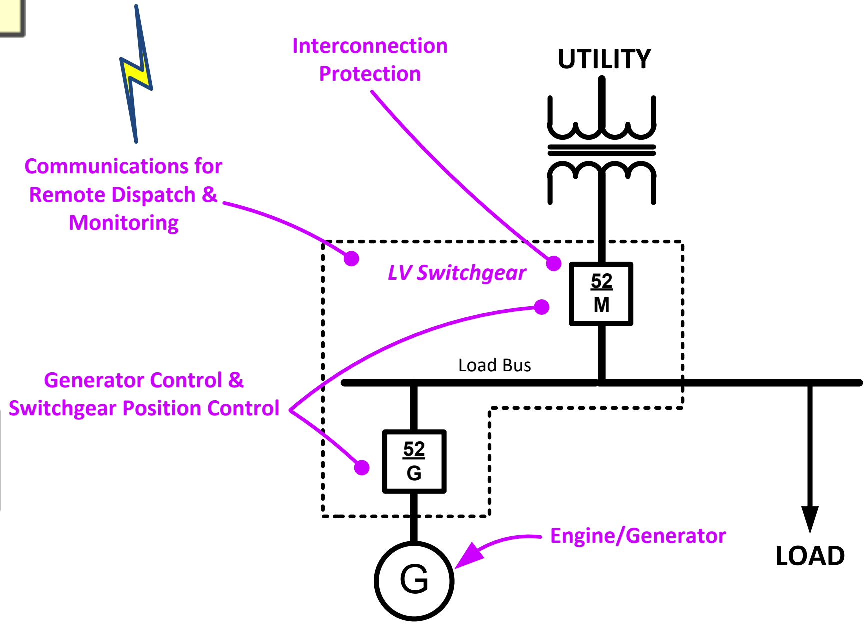
Interconnection Protection in LV Switchgear



Source: PowerSecure Installation

Protection and Control





Factors that discourage DER installations:

- Capital Equipment Cost
  - Generator, prime mover, infrastructure
- EPC Cost
- Cost of DER interconnection protection
- Utility charges
  - Studies
  - Infrastructure, control and protection changes
  - Cost for transfer trip (if required)
- Cost for telemetry equipment (if required)
- Increase in fuel costs

Industry Concerns

Utility Concerns

- Safety of personnel (utility and public)
- Safe work practices (disconnects)
- Fault duty limitation
- Not exceeding load carrying and interrupting capabilities of utility equipment
- Prevent mis-operation of utility protection and control equipment
  - Relays, reclosers, fuses, regulators, caps
- Power quality issues

Industry Concerns

- Protection that allows the DER to operate in parallel to utility
- Large non-utility generators **do not** require specific interconnection protection
  - Integrated into transmission system
  - Interconnection breaker(s) are tripped by transmission line/bus/transformer protection.
- Smaller DERs **do** require specific interconnection protection
  - Goes for conventional as well as inverter-based systems

What is DER Interconnection Protection?

Utility Concerns

- Safety of personnel (utility and public)
- Safe work practices (disconnects)
- Fault duty limitation
- Not exceeding load carrying and interrupting capabilities of utility equipment
- Prevent mis-operation of utility protection and control equipment
    - Relays, reclosers, fuses, regulators, caps
- Power quality issues

Protection Objectives: Utility Perspective

- Personnel safety after deliberate feeder de-energizing
- Minimize/prevent DER fault backfeed contribution
  - Coordination issues with other protective elements
    - Breakers/relays and reclosers on affected feeder
    - Breakers/relays and reclosers in adjacent feeders off the same bus as affected feeder
  - Damage to equipment
  - Transient overvoltage
  - Ferroresonance
- Avoid damage to utility equipment and customer loads from abnormal operating conditions during islanding
  - Voltage issues
  - Frequency issues
  - Harmonic/PQ issues
- Simplify restoration
  - Easier reclosing without synchronizing at utility breakers

Protection Objectives: DER Perspective

- Avoid mal-synchronization damage
  - Can occur after utility reclosing after initial feeder clearing
  - Out-of-phase closing (shaft torque stress; motors and generators)
- Minimize/prevent damage to **DER** by pumping current into utility fault
- Detection of abnormal operating conditions at utility that can cause damage to **DER** and facility
  - Over/under voltage
  - Over/under frequency
  - Overexcitation
  - Unbalanced voltages/single phasing

DER Protection Engineering Challenges

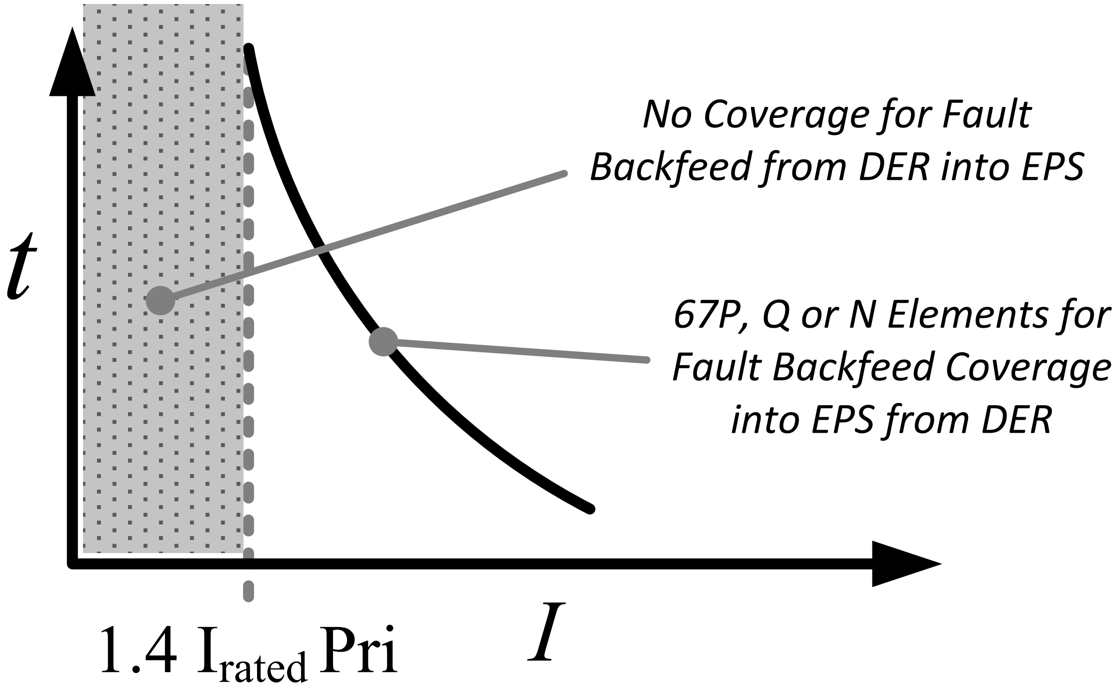
- Seamless integration of DERs into utility protection system despite:
  - "Too many cooks in the kitchen"
    - Owner, Consultant, Packager, Utility
  - Ownership boundaries
  - Conflicting objectives of DER Owners vs. Utility
    - DER Owner: "We do not want to pay for anything."
    - Utility: "We want everything and for you to pay for it."
- Ensuring protection is correct over the life of installation
  - Settings are properly developed
  - If installation or EPS changes, assess impact on existing protection

Challenges with Inverter-Based DER Protection

- Inverter-based DER produces very little fault current
  - 1.0-1.3x rated current at full output
  - Fault current even less when output is lower then rated
    - Solar PV late in day; low irradiance = low output
- Fault backfeed protection (overcurrent) cannot be set below load for fear of nuisance tripping
- Resultant large NDZ (non-detection zone)
  - Transfer Trip anyone $$$$$$$?????

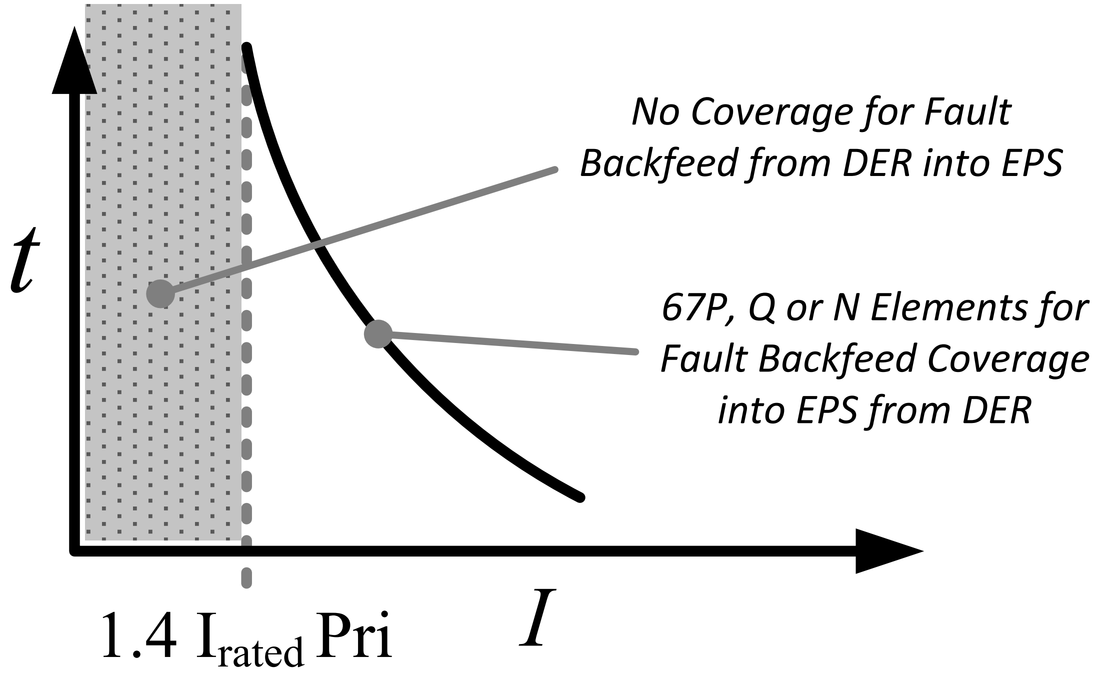
Inverter Fault Current Level

- Inverters typically develop fault current of 1.1-1.3x rated current
- To avoid tripping on normal power output, the overcurrent elements may be set above the DER's rated output current
- For an inverter-based DER, this overcurrent pickup value is typically 1.2–1.4x the DER's rated output current



Inverter Fault Current Level

- This tactic decreases sensitivity to detect DER fault infeed into the EPS
- This current value is essentially the same as load with margin for overload
- If the inverter-based DER is supplied by some variable source, such as a PV array, and as the PV output decreases below rated, the output current for both load and faulted EPS conditions also decreases below rated, making fault detection even more difficult.



Industry Developments

- IEEE has developed DER Standards and Guides
- UL has developed DER Standards and Guides
- Utilities have developed DER Interconnection Guides
  - These typically reference IEEE 1547-2018 for base requirements for distribution interconnection: **IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces**
  - For transmission level interconnection IEEE 2800-2022 will be referenced: **IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems**
  - Some utilities add on requirements
- Interest from Federal Energy Regulatory Commission (FERC)
- To supply DER interconnection needs, manufacturers have developed **protective relay systems** and **self-protecting power electronic systems** (embedded in UL-1741 compliant inverters)

DER Interconnection Guides

- IEEE 1001 – 1988 (Withdrawn)
  - IEEE Guide for Interfacing Dispersed Storage and Generation Facilities with Utility Systems
  - Published in 1988
  - First standard addressing DER protection
  - Although withdrawn, still a good work and full of application information
- IEEE 929 – 2000
  - Covers small inverter-based systems sourced from PV, Fuel Cells, Microturbines, Battery Storage. Harmonized with UL 1741.

DER Interconnection Guides

- UL 1741 - 2005
  - Covers testing of inverters, converters, charge controllers, and interconnection system equipment intended for use in utility-interactive (grid-connected) power systems. Harmonized with IEEE 929.
- IEEE-1547 (Multiple Guides; Base, .1 to .9)
  - A “universal” DER interconnection protection document set to use as a minimum technical requirement base
  - Harmonized with UL 1741
  - http://grouper.ieee.org/groups/scc21/

IEEE SCC21: IEEE 1547's "Home"

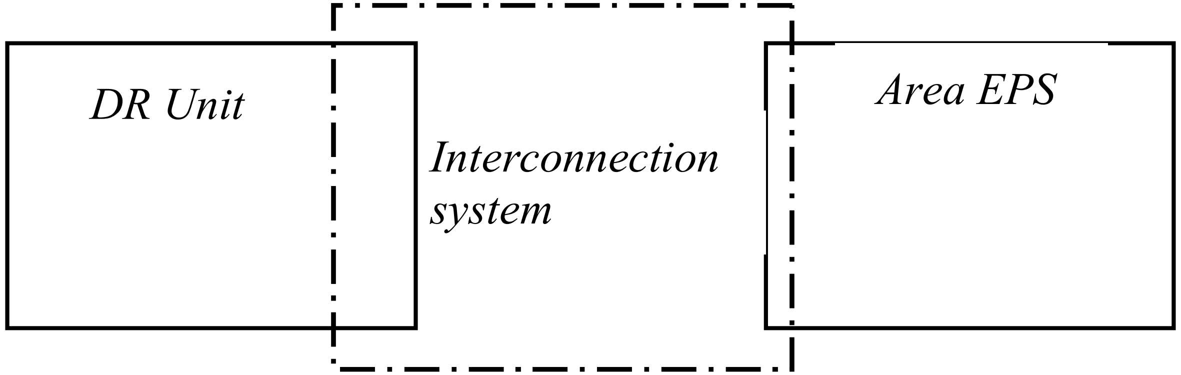
IEEE SCC21 Standards Coordinating Committee:

- Fuel Cells, PV, Dispersed Generation, and Energy Storage
- Oversees the development of standards in the areas of fuel cells, PV, dispersed generation, and energy storage
- Coordinates efforts in these fields among the various IEEE Societies and other affected organizations to ensure that all standards are consistent and properly reflect the views of all applicable disciplines.
- Reviews all proposed IEEE standards in these fields before their submission to the IEEE Standards Association for approval and coordinates submission to other organizations.

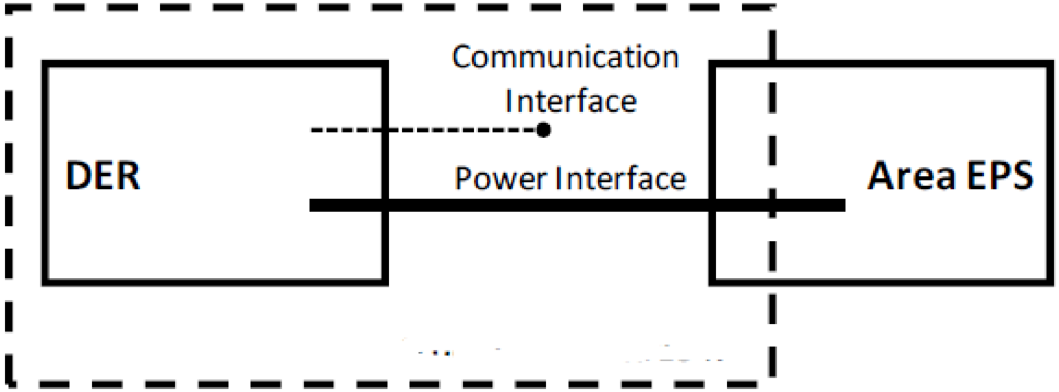
IEEE 1547 Series of Distributed Energy Resources Interconnection and Interoperability Standards, Guides, and Recommended Practices *(as of February 2023)*

Standard Number	Year (reaffirmed)	Title
1547	2018	IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces
1547a	2020	IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces– Amendment 1: To Provide More Flexibility for Adoption of Abnormal Operating Performance Category III
1547.1	2020	IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems and Associated Interfaces
1547.1a	2015	IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems – Amendment 1
1547.2	2023	IEEE Application Guide for IEEE Std 1547(TM), IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems
1547.3	2023	IEEE Guide for Cybersecurity of Distributed Energy Resources Interconnected with Electric Power Systems
1547.4	2011	IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems
1547.6	2011	IEEE Recommended Practice for Interconnecting Distributed Resources with Electric Power Systems Distribution Secondary Networks
1547.7	2013	IEEE Guide for Conducting Distribution Impact Studies for DR Interconnection
1547.8	Draft	Recommended Practice for Establishing Methods and Procedures that Provide Supplemental Support for Implementation Strategies for Expanded Use of IEEE Standard 1547 Logistics
1547.9	2022	Guide to Using IEEE Standard 1547 for Interconnection of Energy Storage Distributed Energy Resources with Electric Power Systems
P1547.10	New Project	Recommended Practice for Distributed Energy Resources (DER) Gateway Platforms

IEEE 1547 Definitions



Old 1547

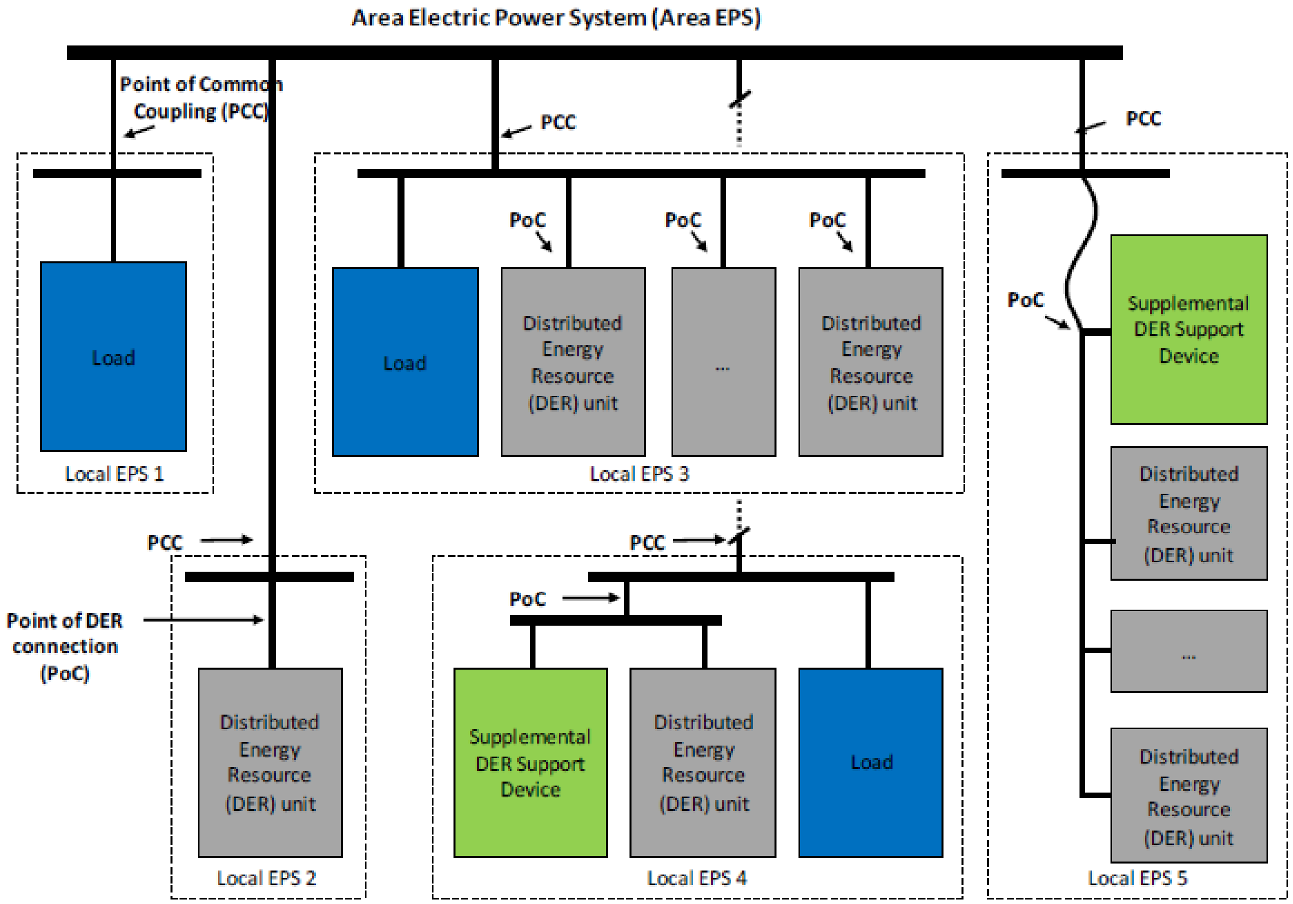


New 1547

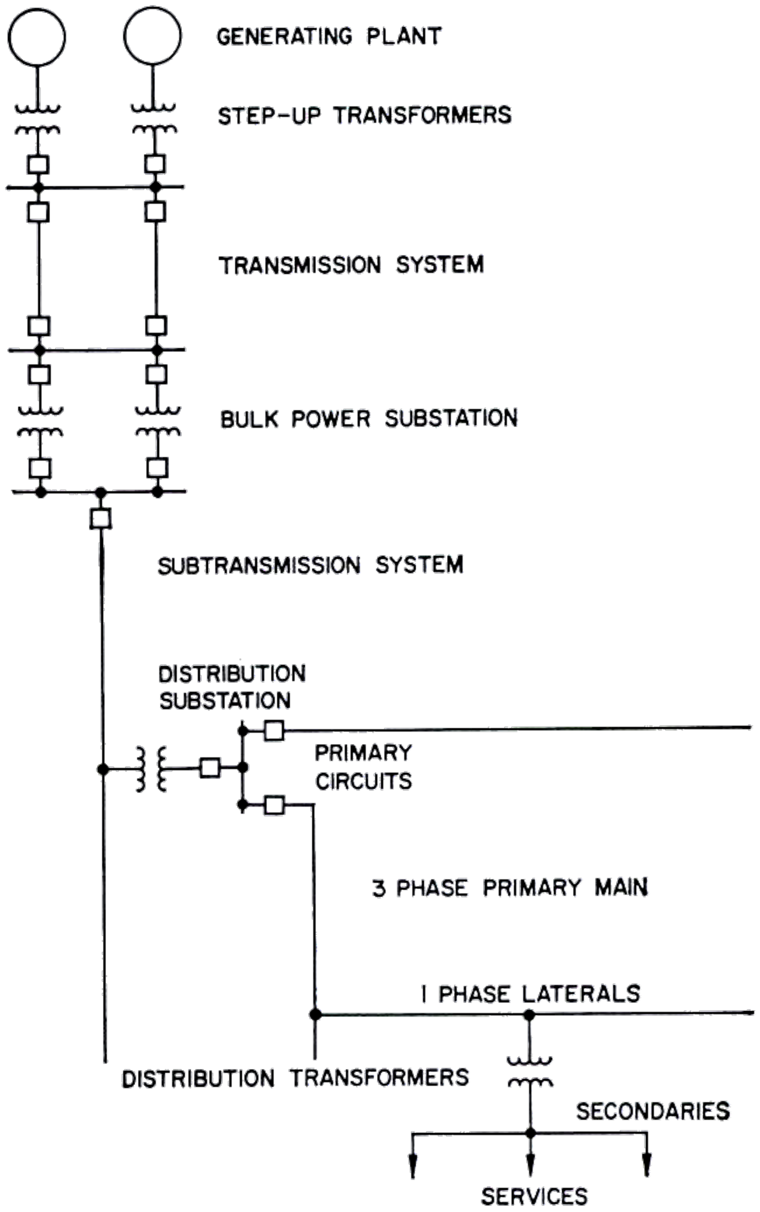
- **DER**: Distributed Energy Resource (was Distributed Resource, DR)
- **EPS**: Electric Power System
- **Interconnection**: The result of the process of adding DER to an Area EPS
- **Interconnection Equipment:** Individual or multiple devices used in an interconnection system.
- **Interconnection System**: The collection of all interconnection equipment and functions, taken as a group, used to interconnect DER unit(s) to an Area EPS.

IEEE 1547 Definitions

- EPS: Electric Power System
- PCC: Point of Common Coupling (EPS to Facility)
- PoC: Point of Connection (DER to Facility) (was PI)



Area EPS



- Area EPS is the portion of the power system that is impacted by the DER
- Typically, the distribution system, including the connected substation
- If DER capacity is large, transmission could possibly be affected

IEEE-1547: 50,000' Overview

Safety

- Personnel working on a utility system must be protected from backfeed or accidental energization from DER

Impact of size

- Intended to cover up to 10 MW

Local Disturbances

- Quality of service on the utility system should not be degraded (voltage, frequency, harmonic limits)

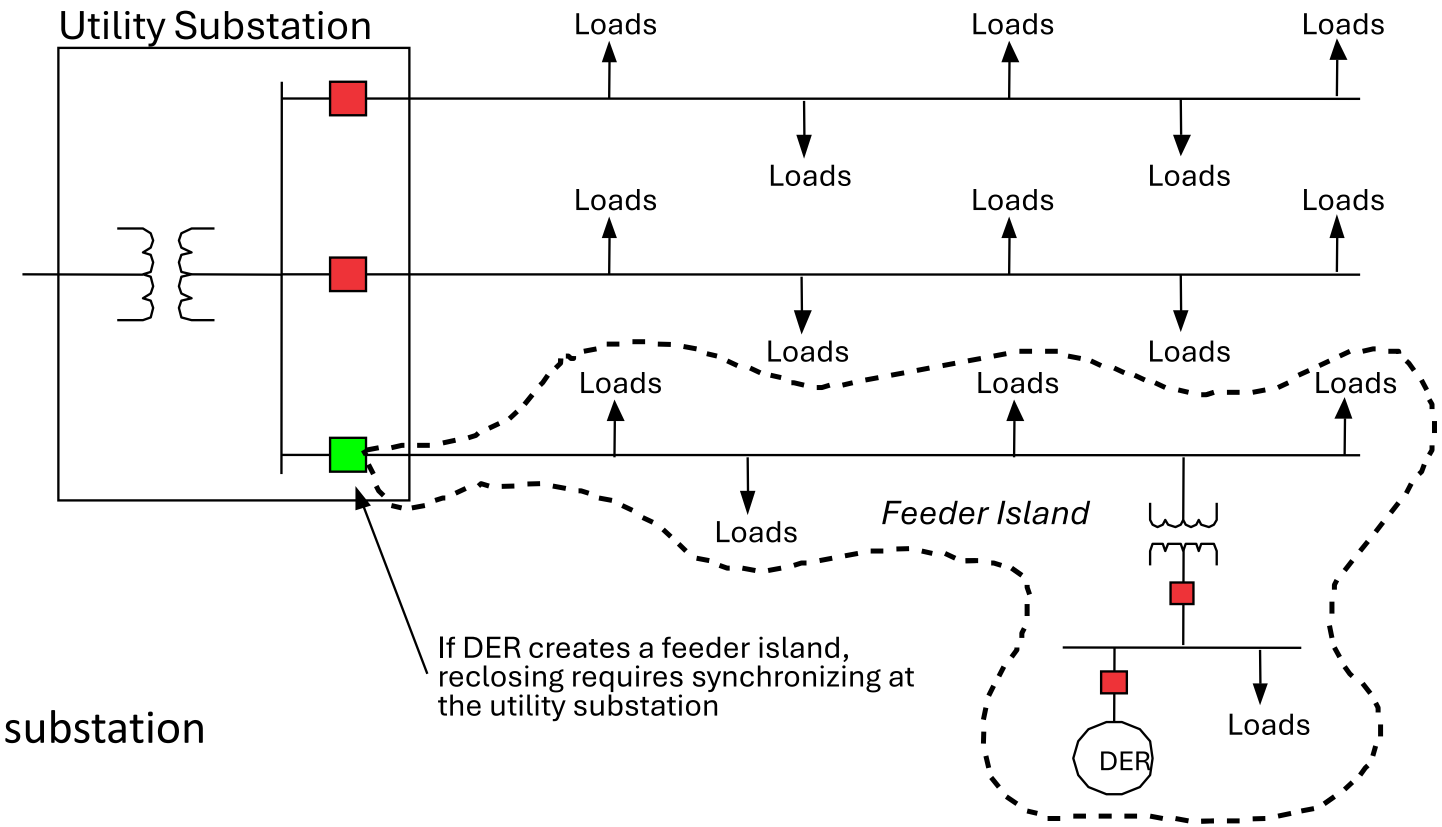
Impact to Existing Distribution Protection

- Dealing with bi-directional power flows and coordination in radial systems turned multiple source systems

Impact of Islanding

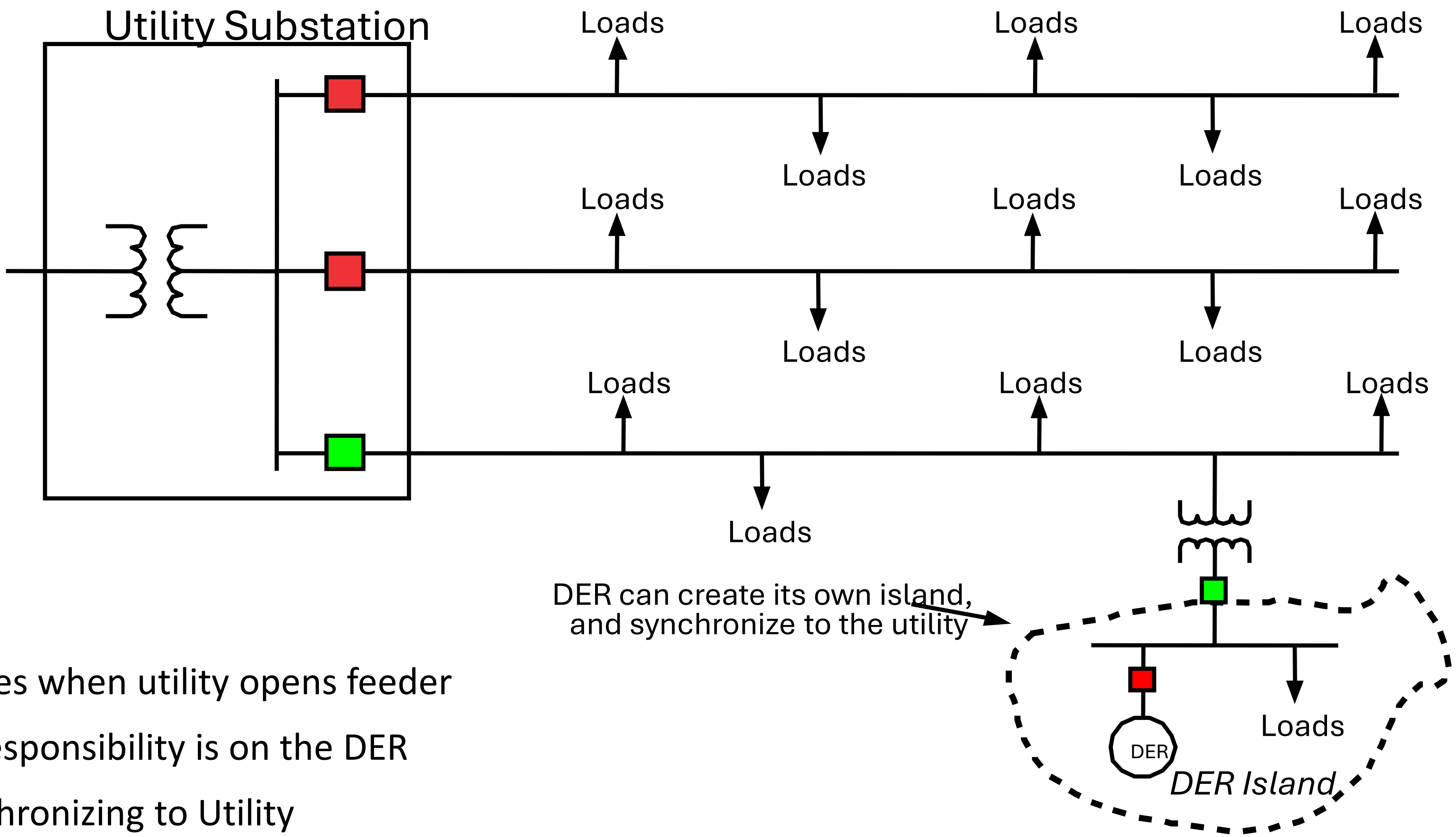
- Creation of unintentional islands must be detected and eliminated as fast as possible

Islanded Operation of DER with Utility Load Is Generally Not Allowed



- Greatly complicates restoration
  - Requires synchronizing at utility substation
  - Inhibits automatic reclosing
- Power quality issue
  - DER may not be able to maintain voltage, frequency, and harmonics within acceptable levels (load ≠ generation; no harmonic "sink")
- Smart Grid and Microgrid may allow islanding in future

DER Facility Islanding to the Utility is Allowed



- Feeder de-energizes when utility opens feeder
  - Restoration responsibility is on the DER
  - Requires synchronizing to Utility

IEEE 1547 Standard Series: Addressed Areas

Transformer connections

- Effect on EPS fault duties
- Effect on possible overvoltage conditions
- Interaction with generator connections
- System modifications

Grounding of the DER system

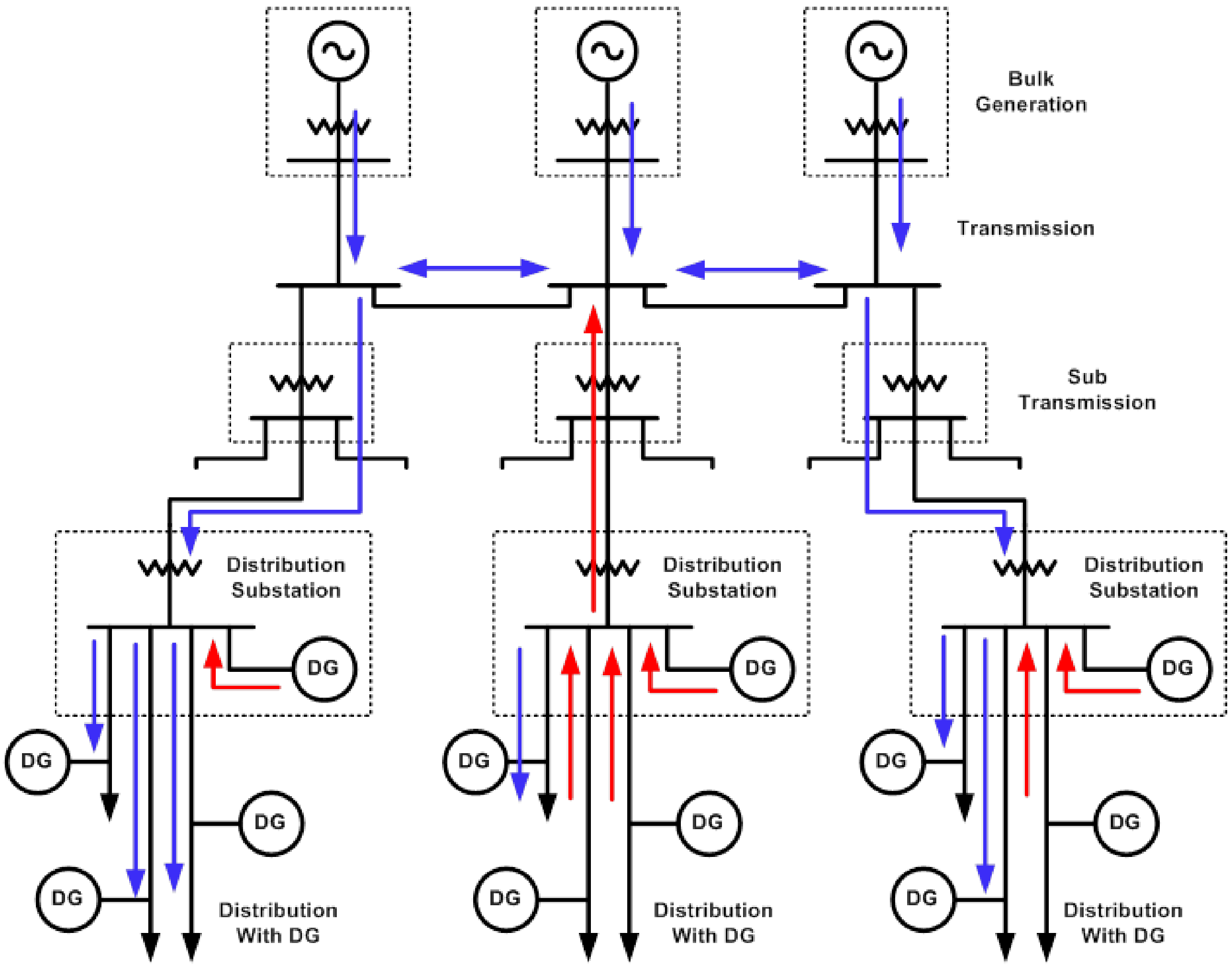
- Grounding for safety
- Effect on EPS ground protection

Abnormal system configurations

- Alternate source
- Abnormal sectionalizing
- Alternate breaker or transfer bus

IEEE 1547 Standard Series: Addressed Areas

- Radial versus bidirectional power flow
  - Effect on protective equipment
  - Effect on voltage regulators
  - System modifications
  - System costs
- Voltage deviations
  - Three-phase
  - Single-phase
  - Induction versus synchronous
  - Voltage rise phenomenon
  - Surges, sags, and swells



IEEE 1547 Standard Series: Addressed Areas

- Unintended islanding
- Reclosing
  - Main or source circuit breaker
  - Reclosers and sectionalizers
  - DR equipment
- Harmonics
- Flicker

IEEE 1547 Standard Series Addressed Areas

- Synchronization
- Loss of synchronism
- Operational safety practices
- System capability
  - Short-circuit capability of EPS equipment
  - Loading capability of Area EPS

What Utilities Generally Specify

- Utility-Grade interconnection relays
  - Pass all pertinent ANSI standards
  - C37.90-1,2,3
- CT and VT requirements (quantities sensed)
- Winding configuration of interconnection transformers
- Functional protection
  - 81U/O, 27, 59, etc.
  - Settings of some interconnection functions
    - Pick ups
    - Trip times

Protection Elements and Use

- Loss of Parallel Operation (utility disconnected)
    - Anti-Islanding
- Abnormal Power Flow
    - Anti-Islanding
- Fault Backfeed Removal
- Detection of Damaging System Conditions
- Restoration

Impact on interconnection protection

- Interconnection transformer configuration
- Various types of DERs
    - Induction, Synchronous, Asynchronous (Inverters)

Interconnection Protection

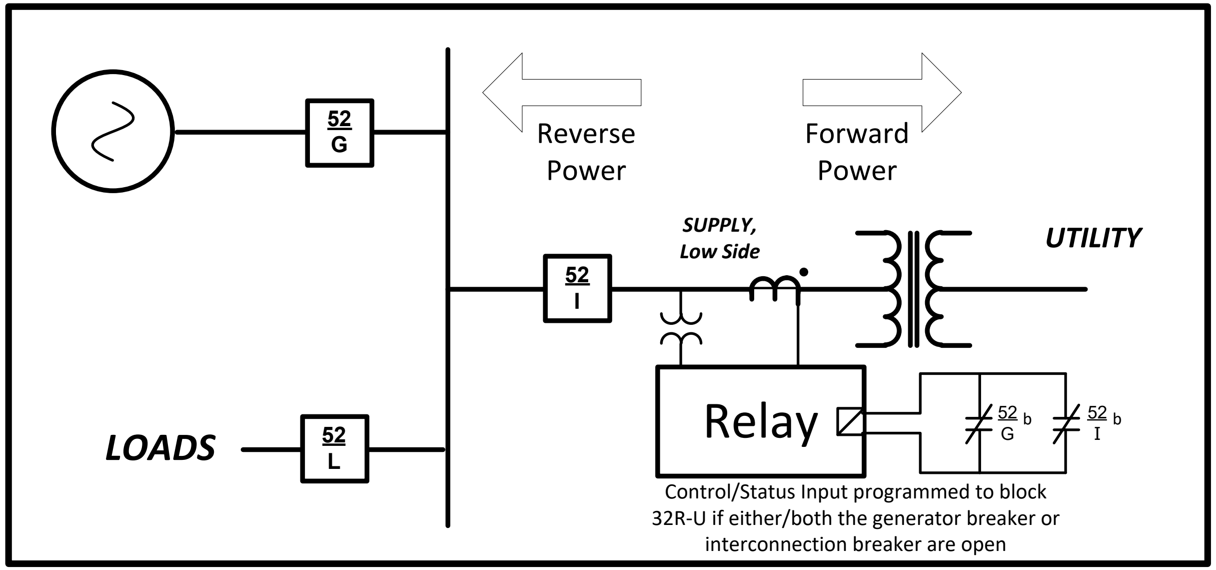
Loss of Utility Parallel (Anti-Islanding)

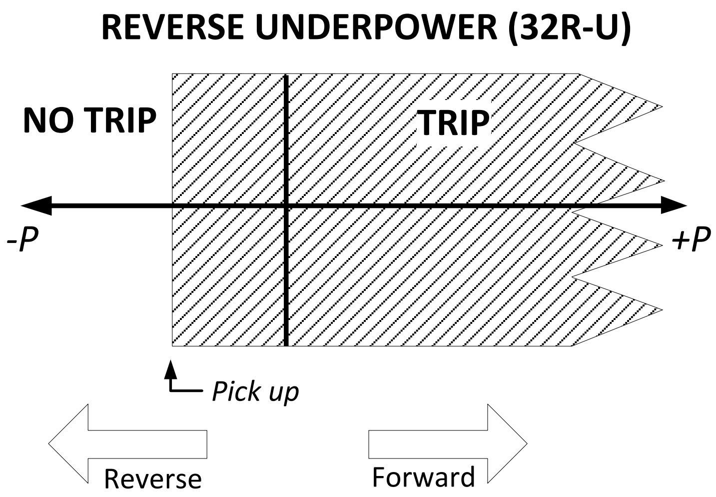
- Voltage and frequency (27, 59, 81-U, 81-O)
- Rate-of-change of frequency (81R, aka ROCOF)
- **Based on load (real and reactive) not equaling generation**

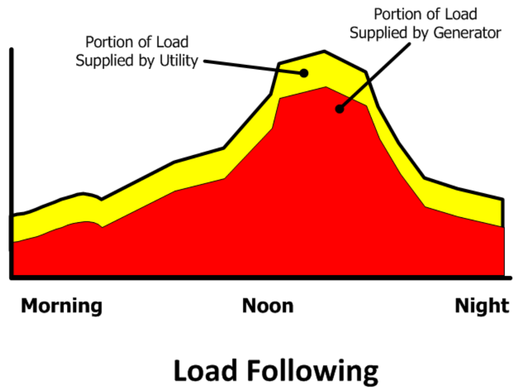
Abnormal Power Flow (Anti-Islanding)

- Power (32F, 32R-U)
- **Based on power flow violations across the PCC**

Low Import Power: 32R-U

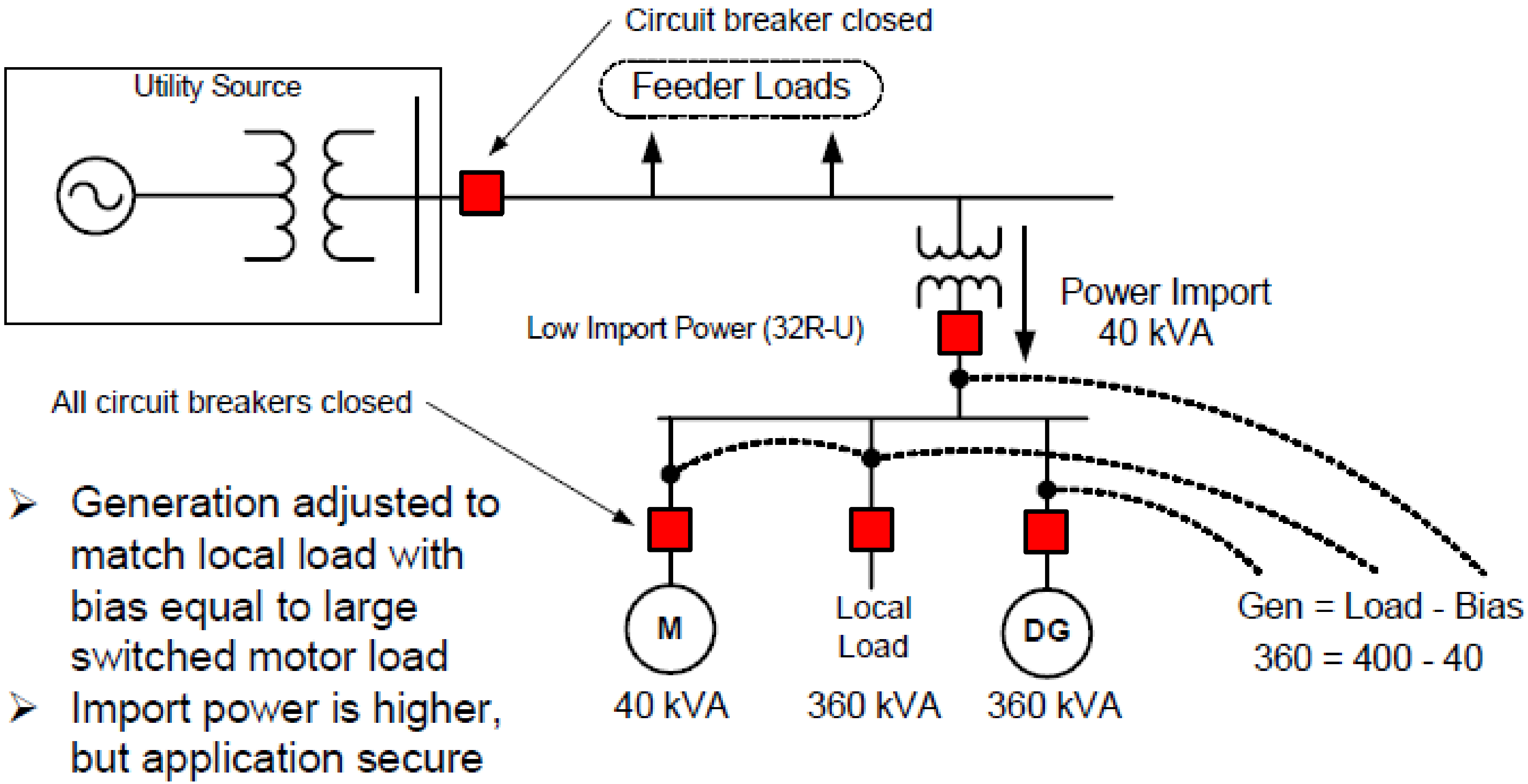






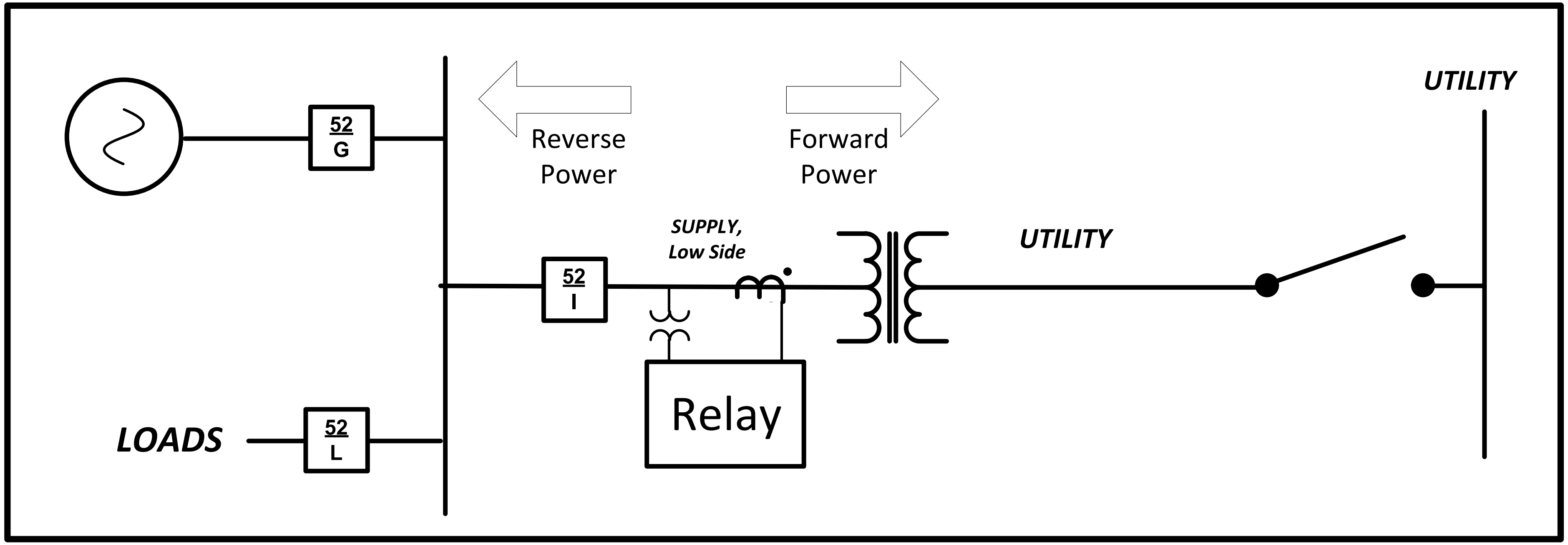
- 32R-U Relay pickup set to at least 5% of total connected generator rated KVA
- 32R-U Relay programmed to trip when imported power falls below the pick-up level
- Switching off a large amount of facility load may cause nuisance tripping
- Generator Control should have proper bias power margin set

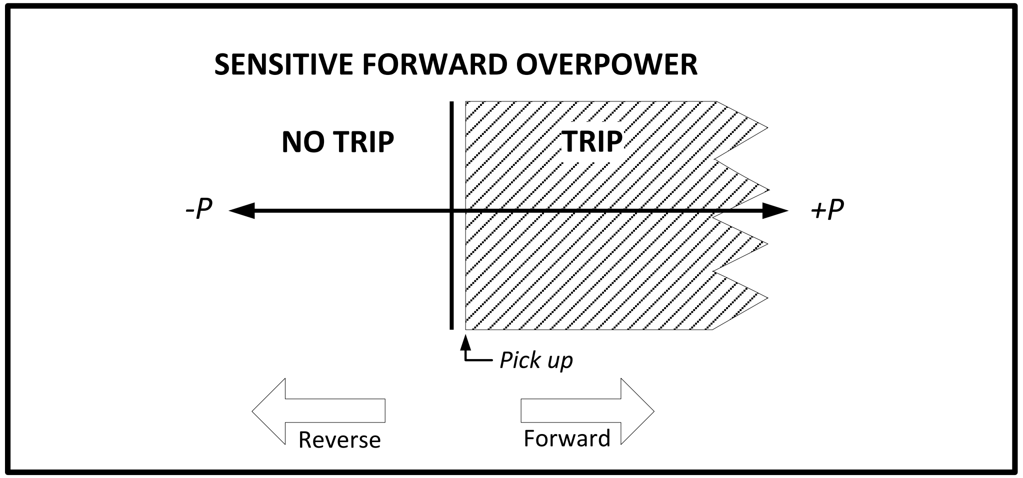
Low Import Power: 32R-U



- Bias is made in the genset controller to ensure import of 40 kW when paralleled
- 32R-U is set lower with appropriate margin (trips if import goes below genset control setpoint)

Sensitive Forward Power: 32F





- 32F relay set to operate on transformer excitation or magnetizing current
  - Typically, about 0.1% of transformer rating
- Need transformer test sheet data to calculate value of magnetizing watts

Interconnection Protection

Fault Back-feed Detection

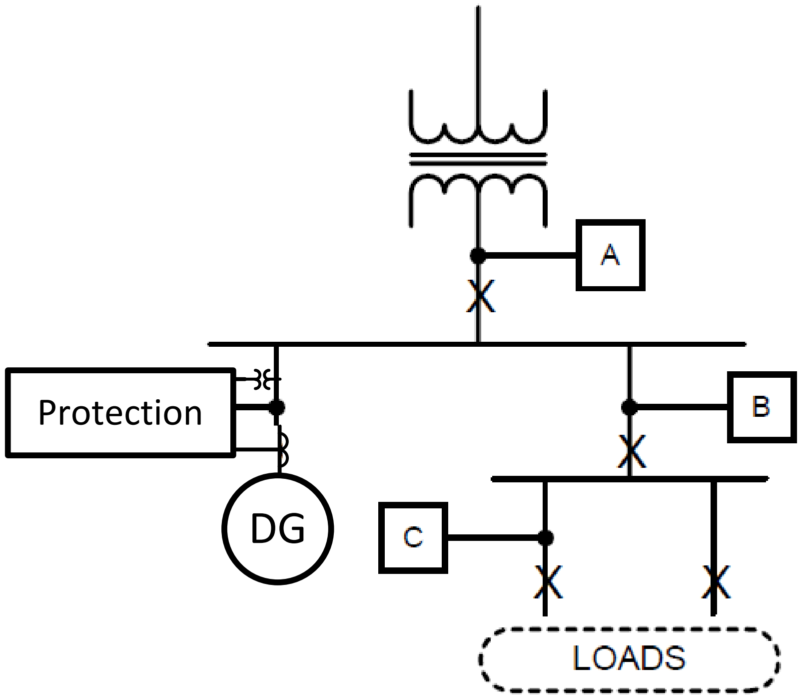
- Phase and overcurrent (51V, 51), grounded systems
  - Directional overcurrent (67) or impedance (21) may be used
- Ground overcurrent (50N/51N) for grounded systems
  - Directional ground overcurrent (67N) may be used
- Ground over/under voltage (27N, 27N/59N) for ungrounded systems
- Negative sequence overcurrent (46)
- **Based on abnormally high current or abnormally low/high voltage as a result of faults**

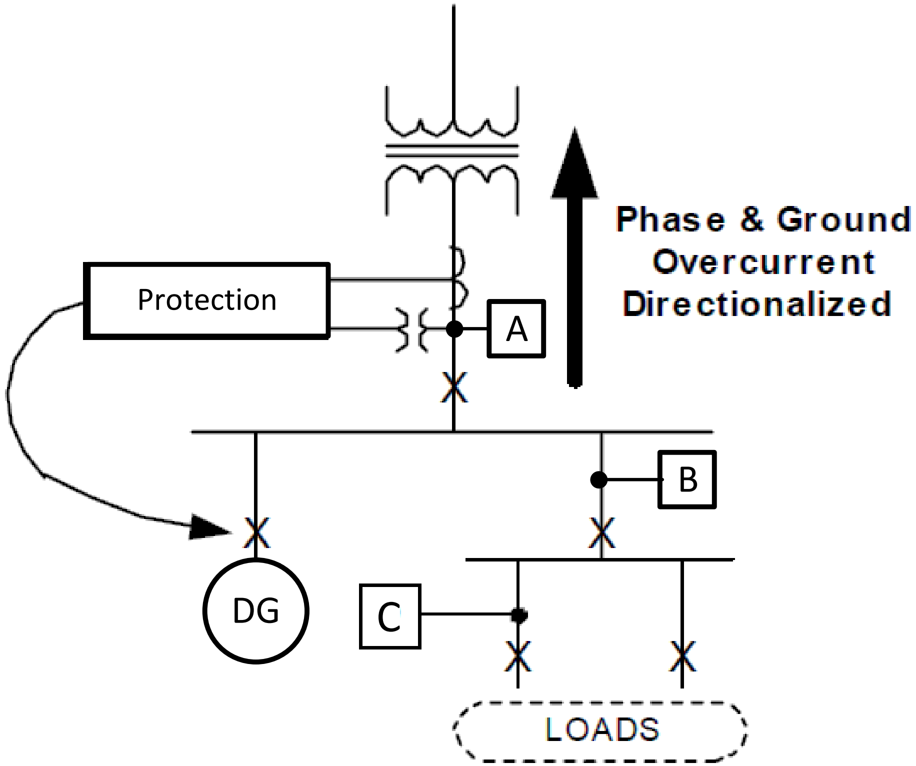
Phase Overcurrent vs. Phase Distance

- Time overcurrent protection (51P) on DER will have variable time response based on fault position and fault current
- Instantaneous overcurrent (50P) will trip at different reaches down the line toward the fault due to fault impedance
- Phase distance (21P) will trip for predictable times up to the reach setting. As voltage and current are used, reach on the line can be set.
  - This is useful to discriminate if utility faults are on a connected feeder, or behind a substation transformer.
  - As 21P is definite time, you have predictable tripping time for the DER
  - As 21P is inherently directional, you do not have coordination concerns for protection within the DER’s facility
  - Disadvantage: Cost - 51P is a less expensive element

Direction vs. Non-Direction Elements at the PCC

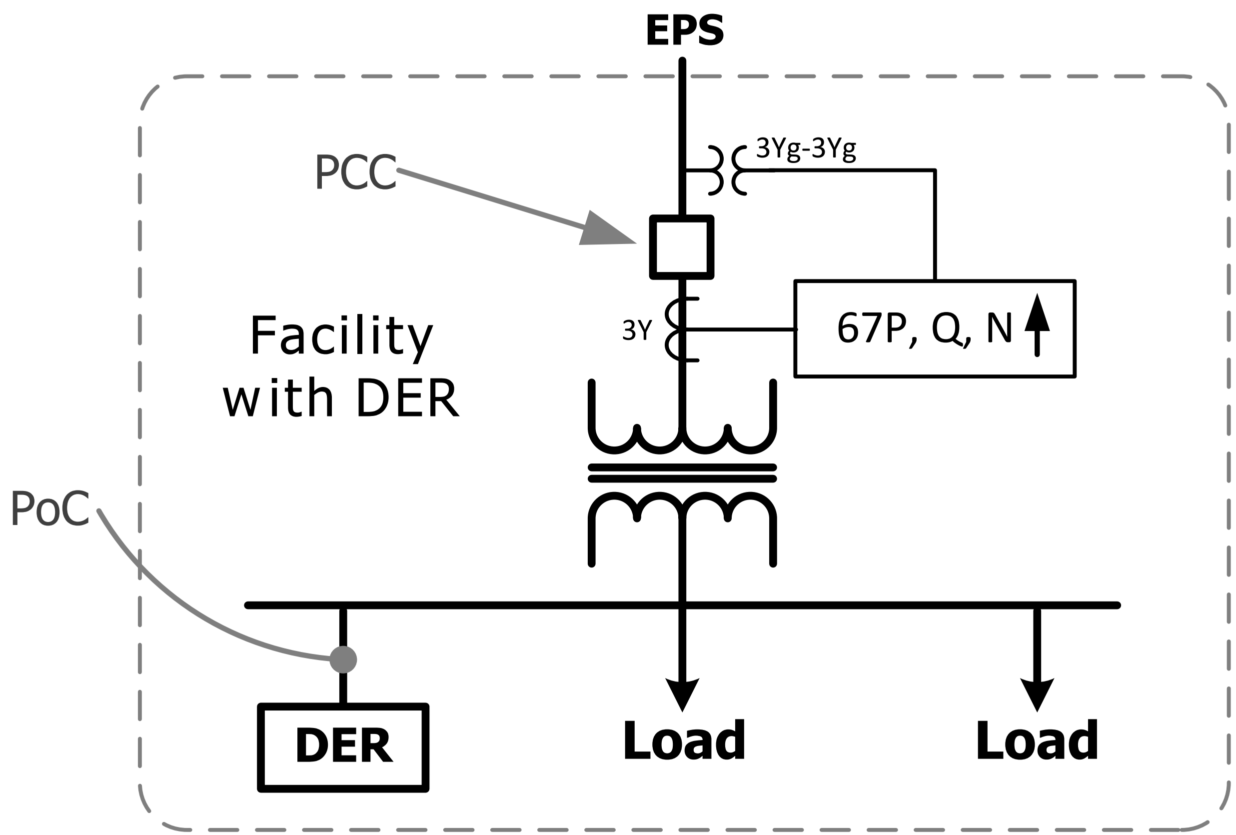
- When applying non-directional phase or ground elements for fault backfeed protection (50P, 50N, 51P, 51N), they must be coordinated for faults in the facility and on the utility.
- This could lead to longer clearing times for utility faults.
- To speed up response of utility faults, use of directional elements (67, 67N, 21P), set to only trip in the utility's direction, will provide maximum trip speed.





Focused Directional Overcurrent (FDO) Concept

- Use of focused directional overcurrent (FDO) elements (67P, 67Q, 67N) for Distributed Energy Resource (DER) Interconnection Protection (IP)
- Applicable at the PCC

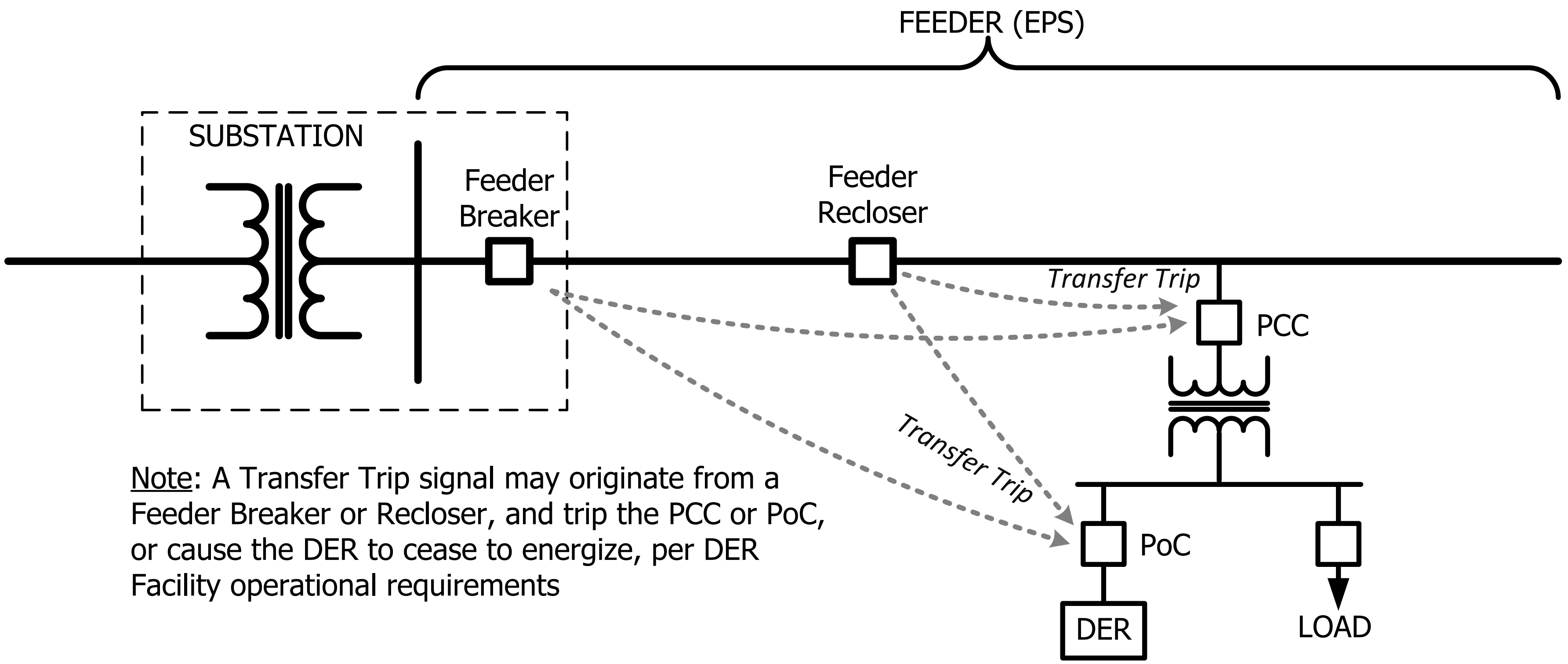


Traditional Directional Control vs. FDO

- Different from traditional directional overcurrent elements that employ a 180° forward/reverse directional decision
- FDO concept uses a tunable angle characteristic that can be set to detect single and multiphase inductive faults, such as those found on overhead distribution feeder circuits
  - Ignores load and normal VAR output of active-VAR DER units.
- Able to detect fault backfeed into EPS by conventional (rotating machine based) DER
- Improves both sensitivity for increased dependability and selectivity for increased security.

Islanding Issue

- With DER exporting power to the EPS, it is difficult to discriminate between a fault backfeed and non-faulted power output
- To guarantee a trip for an islanded feeder, transfer trip may need to be applied

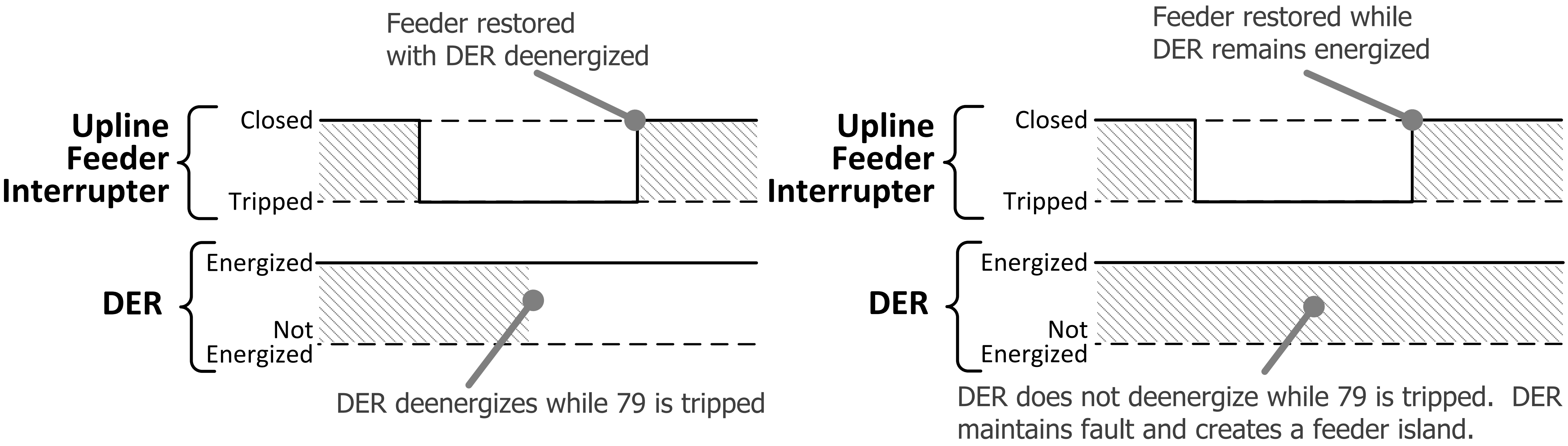


<u>Note</u>: A Transfer Trip signal may originate from a Feeder Breaker or Recloser, and trip the PCC or PoC, or cause the DER to cease to energize, per DER Facility operational requirements

$$$$$ Transfer Trip = High CAPEX and OPEX $$$$$

Reclosing Issue

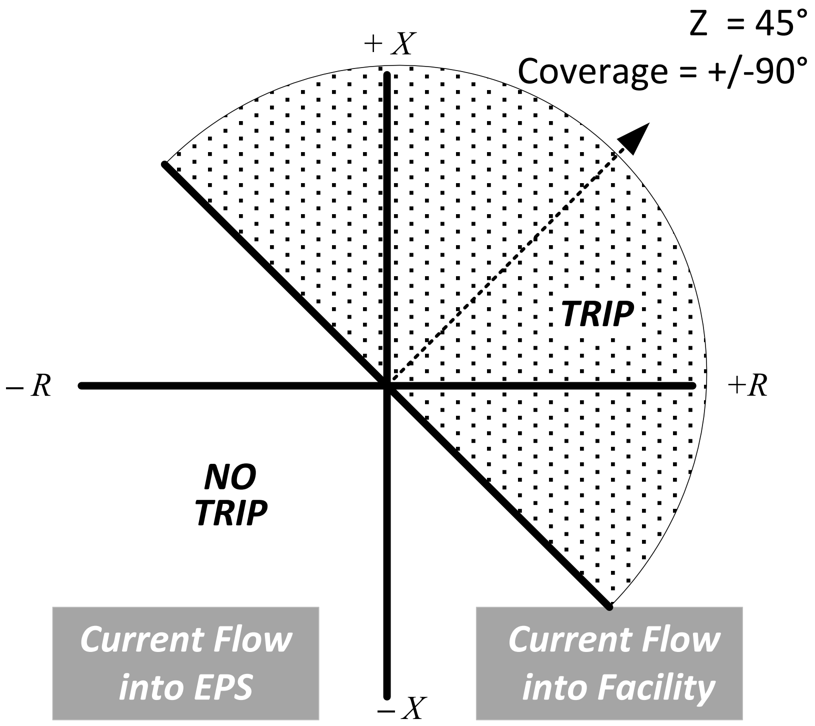
- If the DER remains energized and supplying fault current during the EPS reclosing cycle, the fault may not be extinguished
- DER and/or DER facility's loads may be damaged by the EPS upline interrupter out-of-phase closing between the DER facility and the EPS



Feeder Reclosing Sequence with DER Deenergized and Remaining Energized

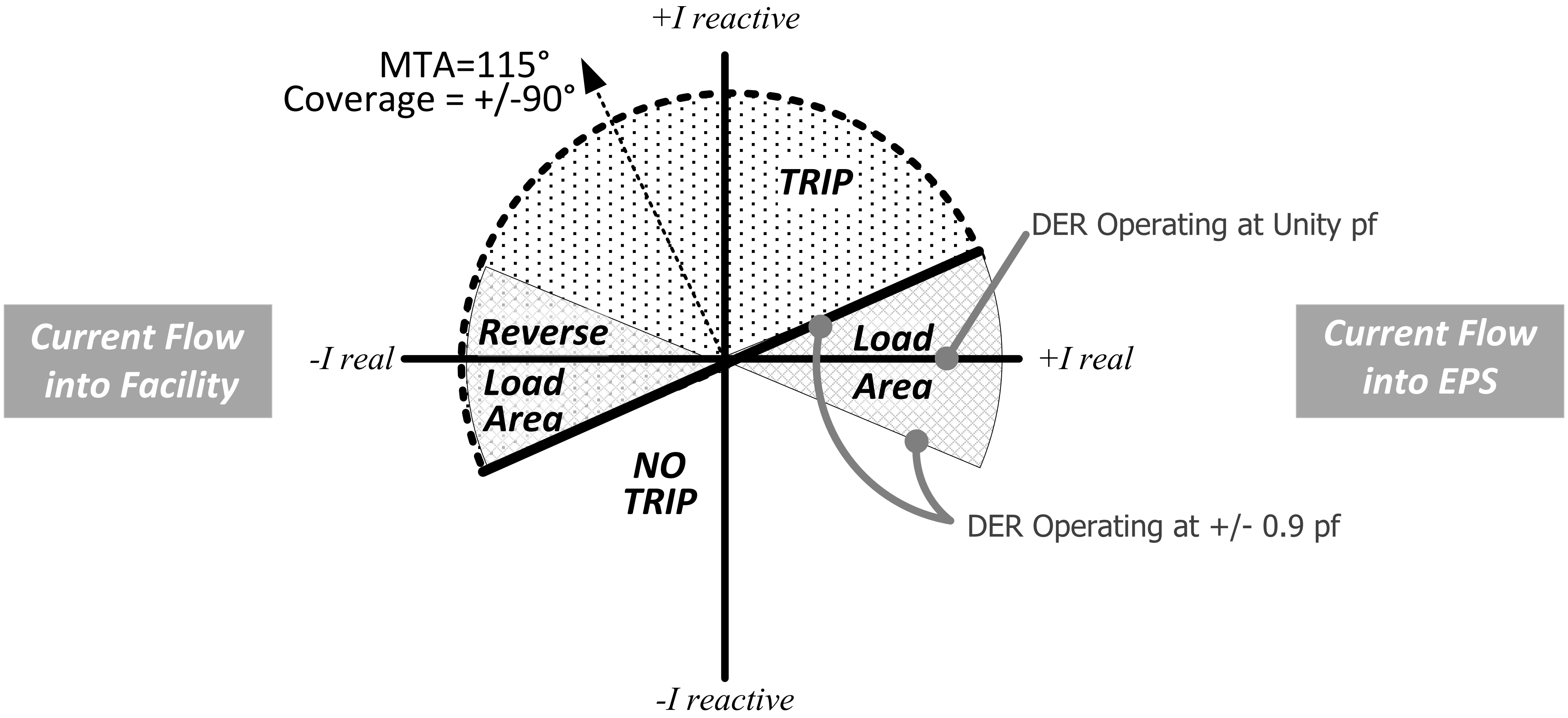
Traditional Directional Element

- For DER IP, directionalization is a reliability and security enhancement to control phase and ground overcurrent elements
- Used at the PCC, directionalization to the *EPS* blinds the overcurrent elements for load and faults in the *DER's facility*, thereby increasing the DER IP security
- In traditional 180° forward/reverse directional control, the overcurrent elements are subject to tripping on the DER's real power output.



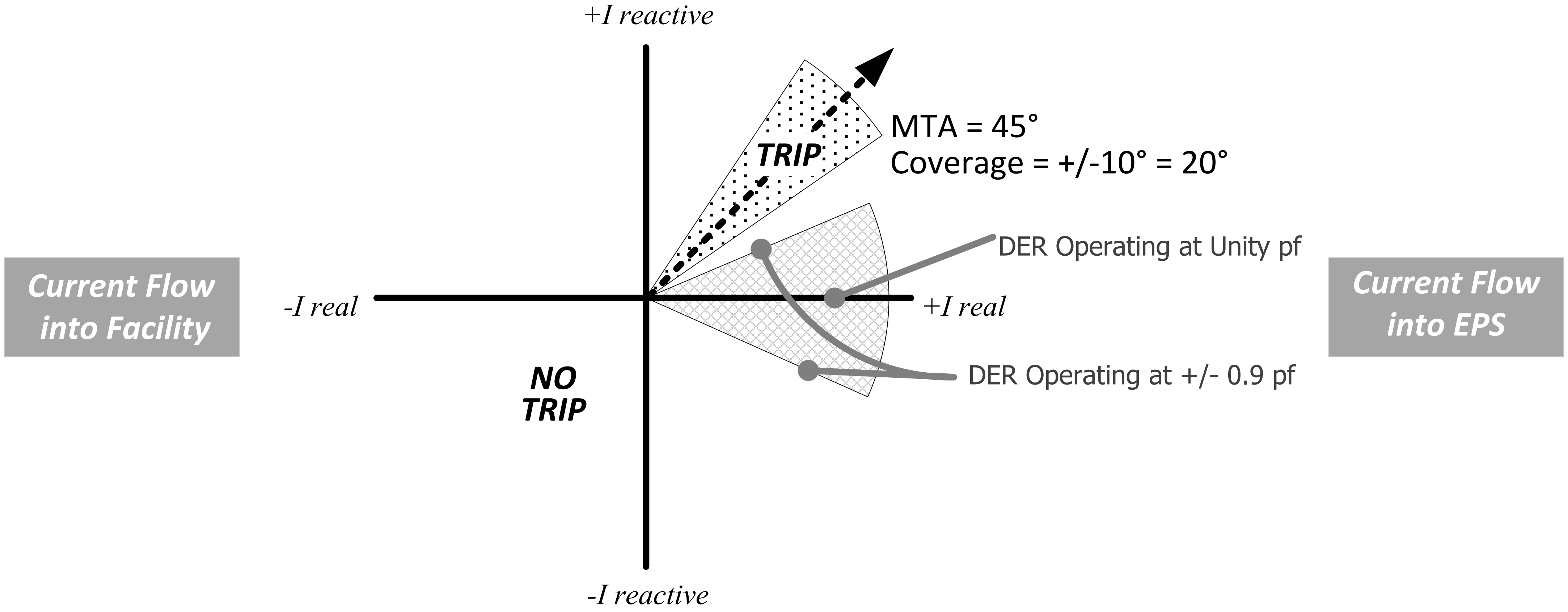
Traditional Directional Element

- Increasing the MTA from 15° to 115° so the forward real power load region is ignored exposes the overcurrent element to trip for load flow and faults in the facility (reverse load area).



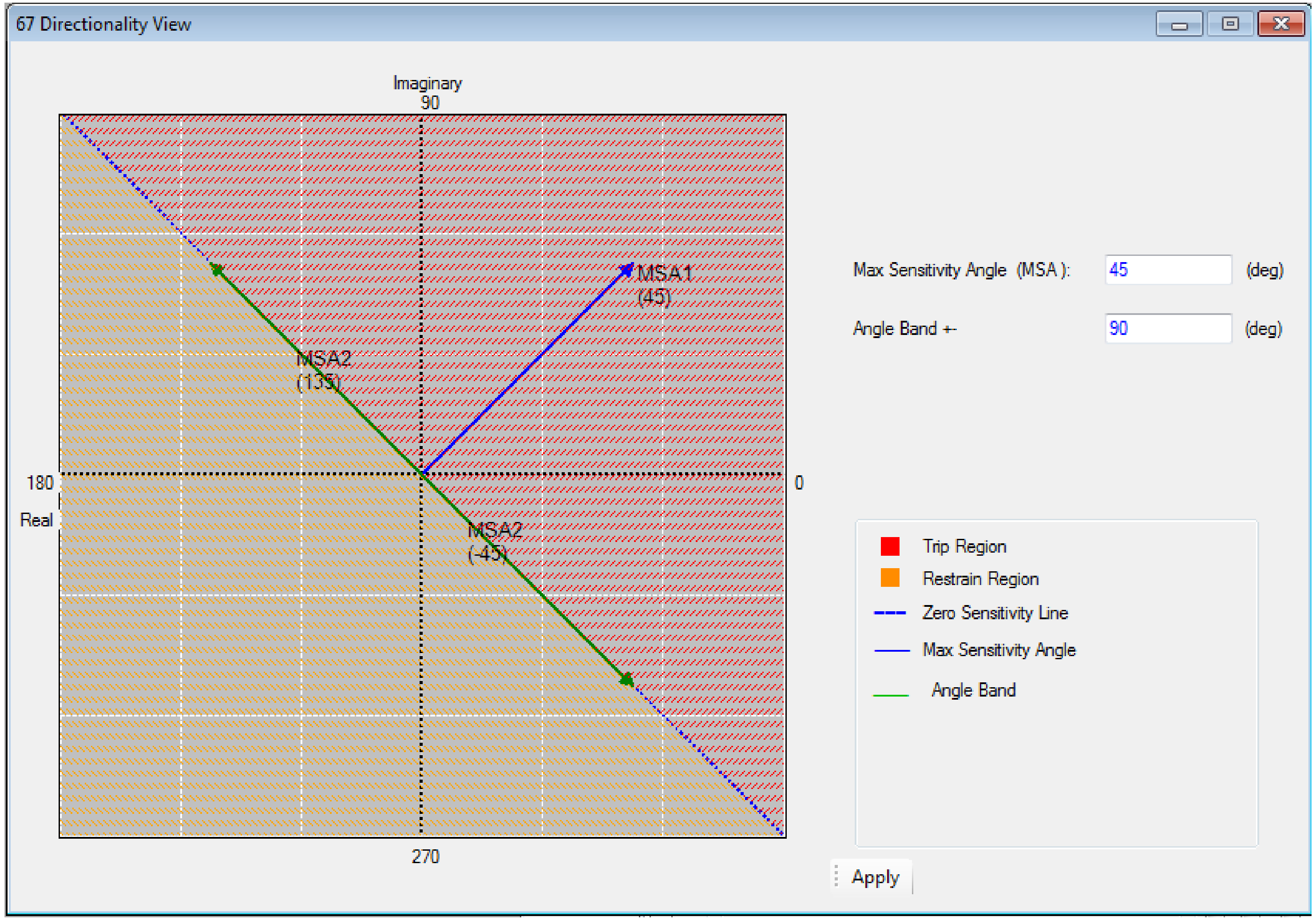
Focused Directionality

- FDO allows the directional characteristic of overcurrent element to be tunable to other than the traditional 180° forward/reverse decision
- Ex., the overcurrent element response angle may be restricted to 45° forward, plus or minus 10°, for an effective response angle of 35° to 55°



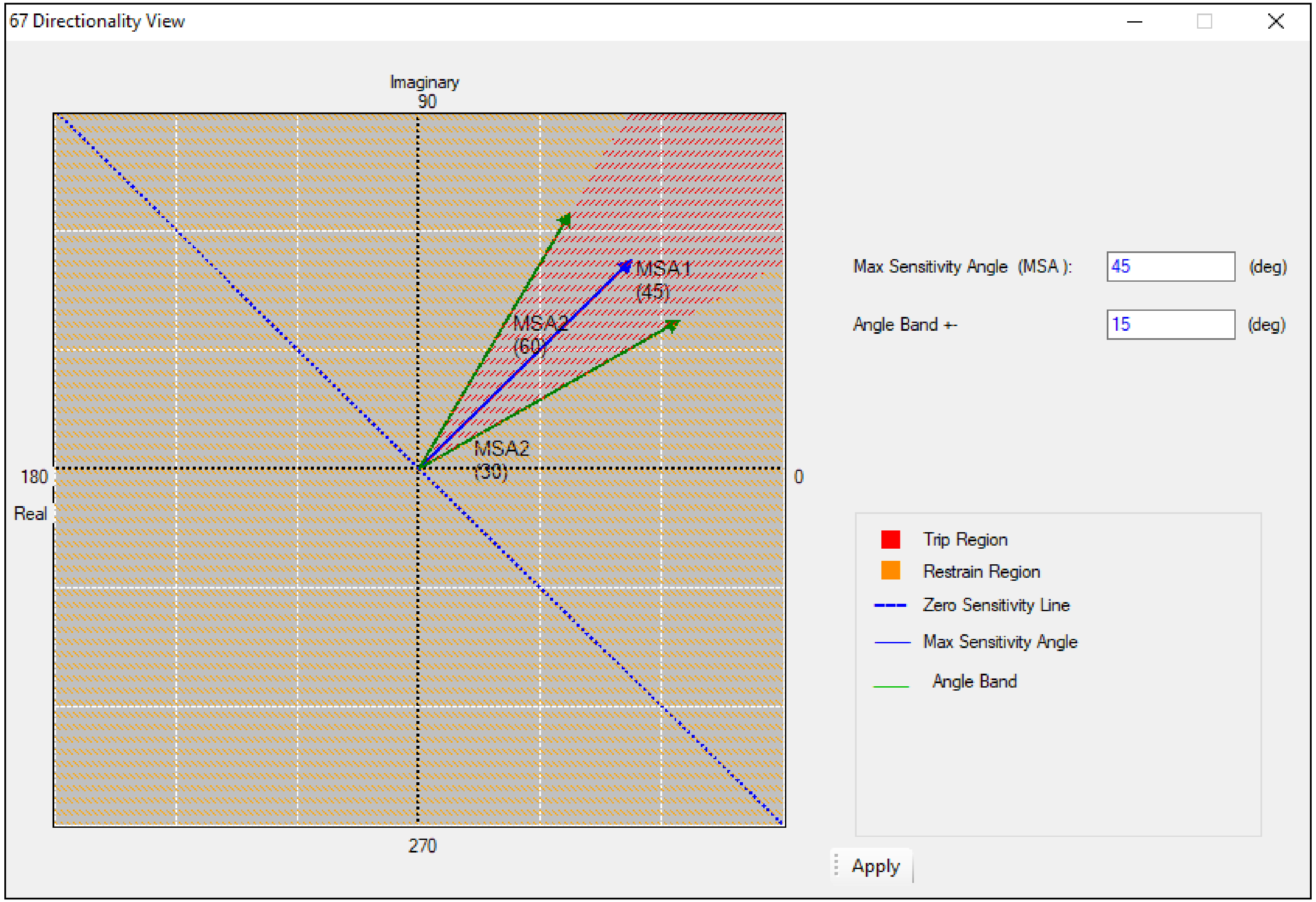
Directional Overcurrent

- 67P, 67Q, 67N (67P shown below)



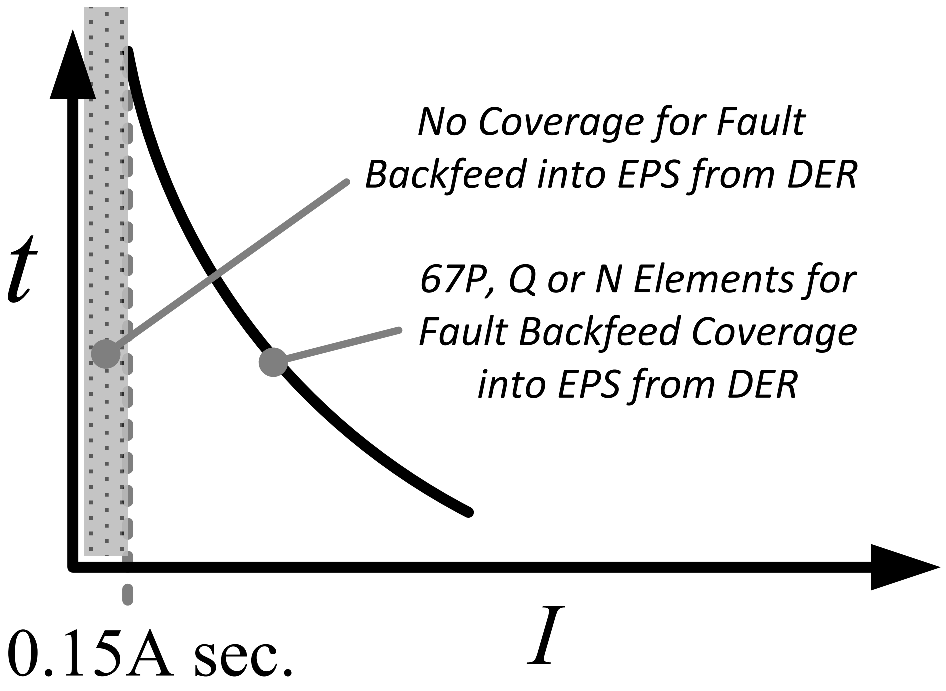
Directional Overcurrent

- 67P, 67Q, 67N (67P shown below)



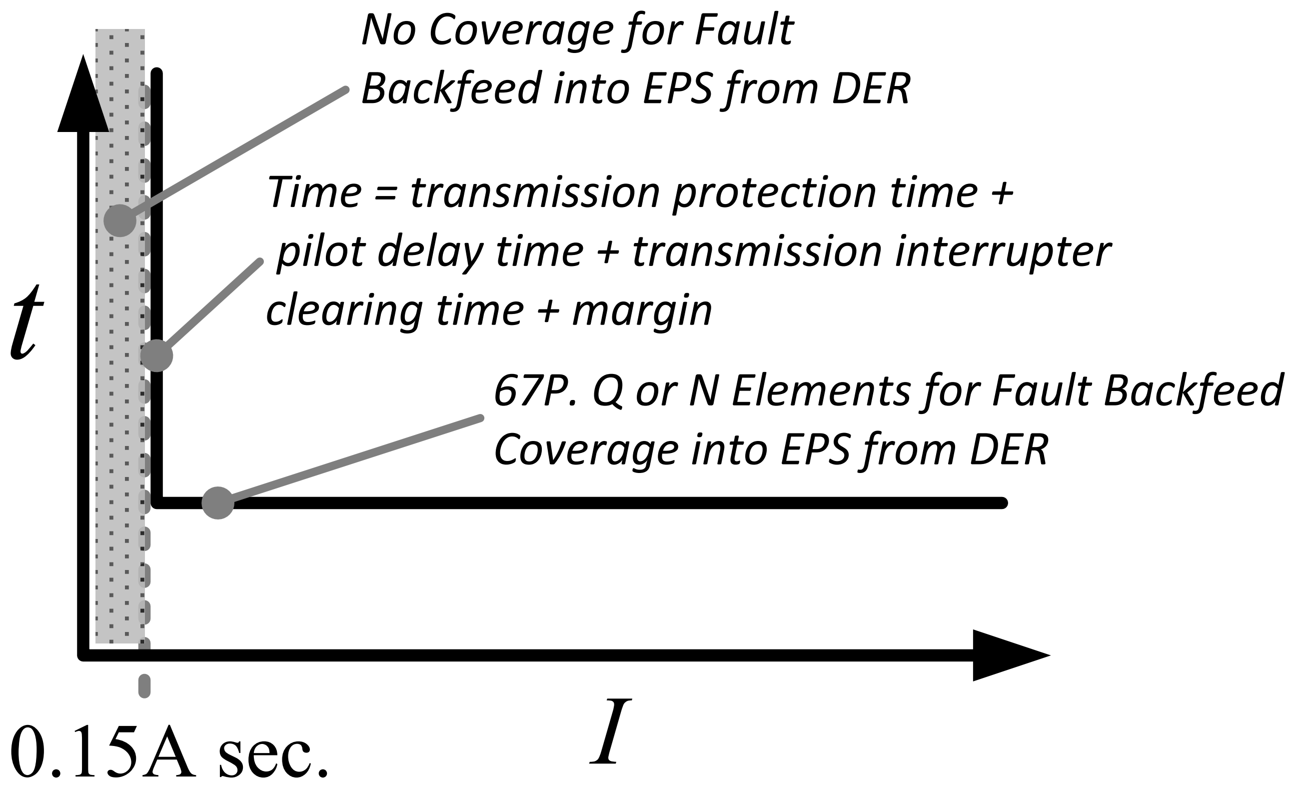
FDO and Current Setting

- FDO elements allow settings as low as 0.15 A secondary which should greatly improve the sensitivity of the overcurrent elements
- The actual minimum primary current level detectable depends on the applied CT ratio
- Ex., DER IP using a 500:5 CT and by employing a setting of 0.15 secondary amps on the FDO element yields a sensitivity of 15 A primary amps



FDO and Current Setting

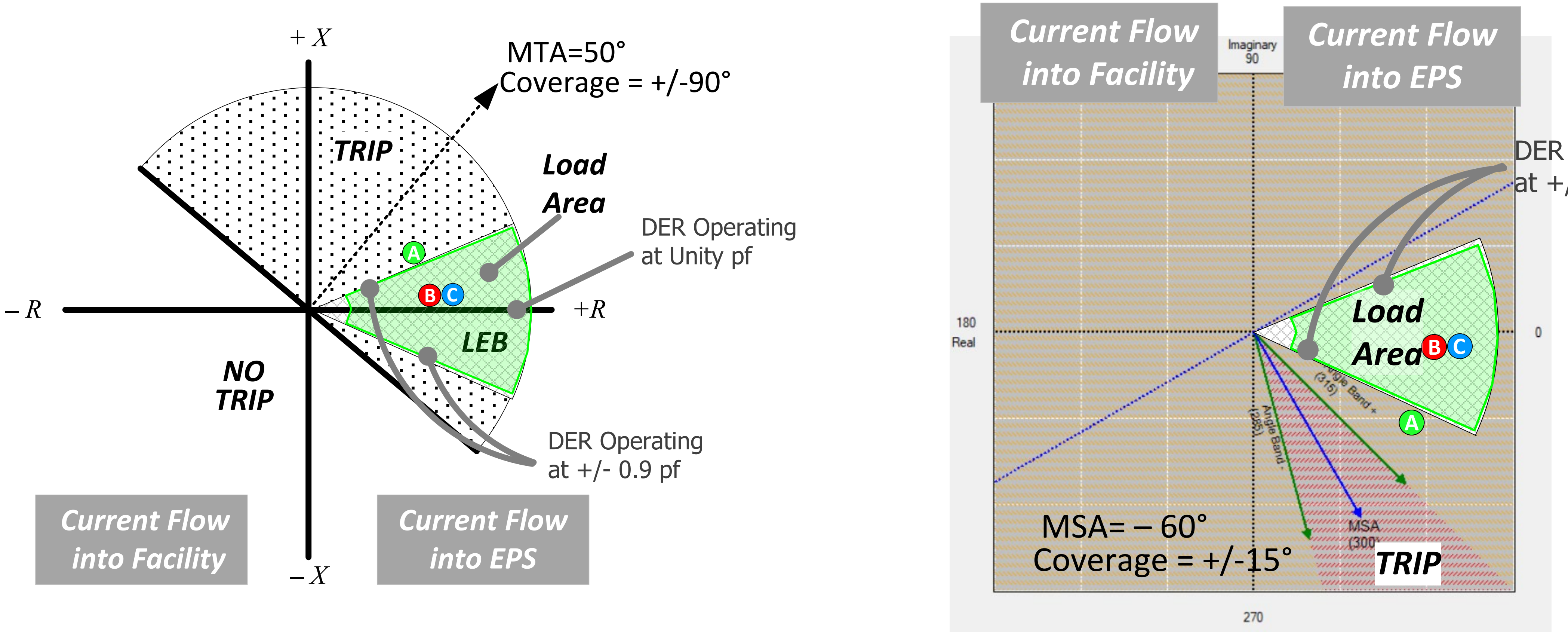
- Sensitive overcurrent element pickup setting with a definite time characteristic will coordinate with transmission protection and allow ride-through.
  - Transmission protection is typically definite time Z with transfer trip aided clearing times of 20-25 with 50BF margin



What about Load Encroachment Blinding (LEB)?

- LEB is effective at ignoring inverter-based DER load current at/near unity power factor.
- LEB typically employs V1/I1 to arrive at Z1 for overcurrent blinding purposes.
- A 3-phase symmetrical load event is assumed.
- In the case of non-3-phase shunt faults (e.g., phase-to-ground, phase-to-phase and phase-to-phase-to-ground faults), LEB is ineffective.
- During a non-three phase shunt fault, LEB will not have any effect on the overcurrent elements, and if the overcurrent elements are set at or below the DER's rated load, and the DER's output current on the unfaulted phase(s) is in the load region (near unity pf) and exceeds the overcurrent setting, an undesired trip will result.
- LEB is not a proxy for FDO.

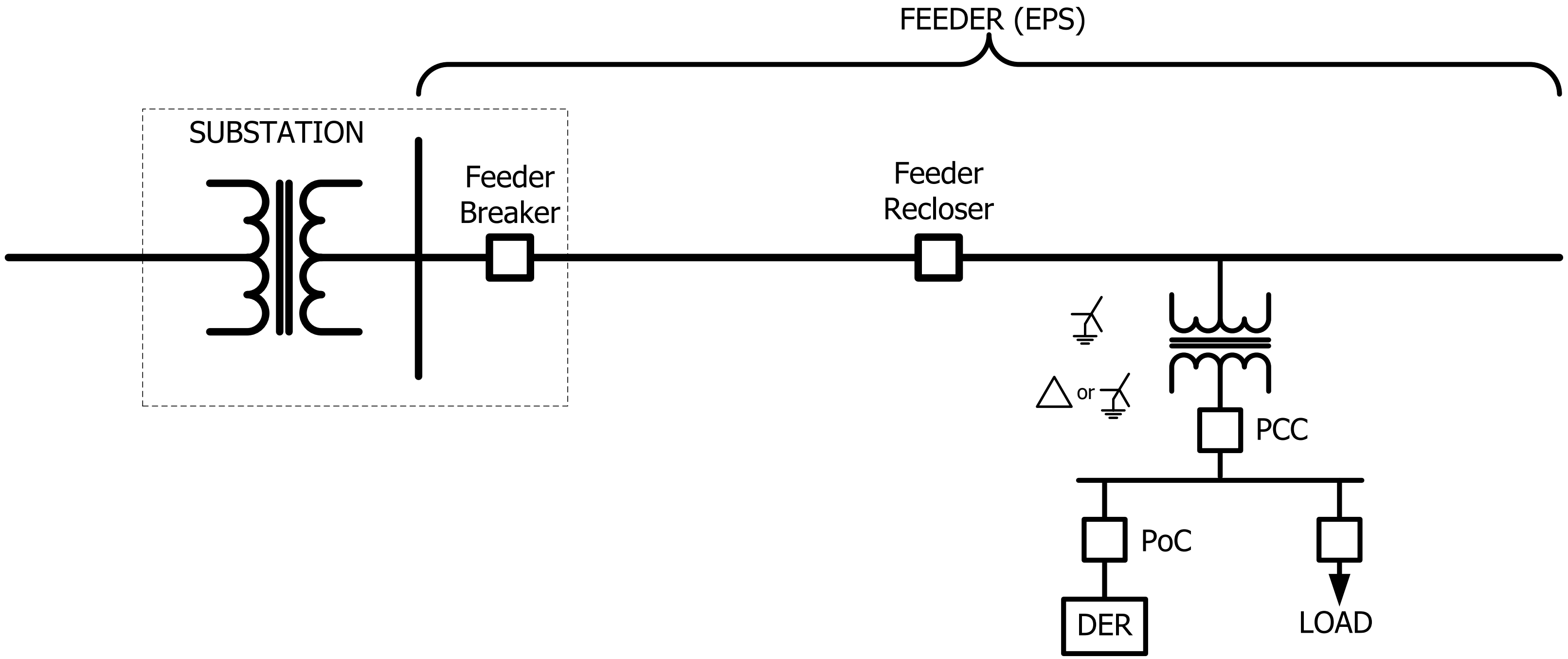
What about LEB?



LEB is **not** a proxy for FDO

Application Considerations

- An inverter, at its terminals, can only provide positive sequence current.
- Transformer winding and grounding at the PCC and EPS energization status at the DER IP play pivotal roles in directionalization and application of FDO.
- **Ground Faults (67N):**
  - In order to apply FDO for ground faults, the interconnection transformer winding at the Utility-side of the point-of-common coupling must be a grounded wye

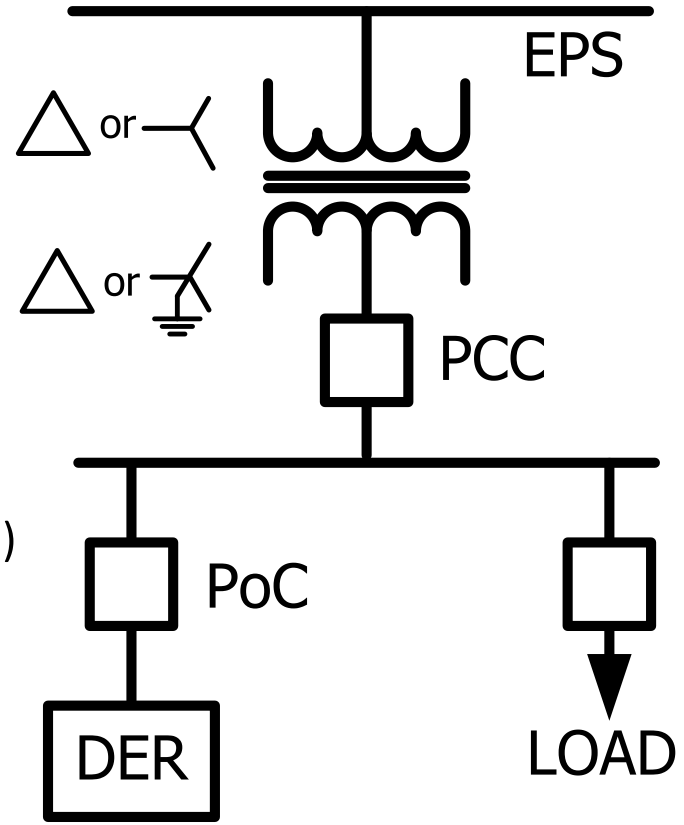


Application Considerations

Ground Faults (67N):

- If the interconnection transformer winding facing the EPS is delta or otherwise ungrounded, with a single phase-to-ground fault on the distribution feeder appreciable ground current is not available to measure.
  - This is not a shortcoming of the FDO approach, but a characteristic of an ungrounded-source supplied system.
  - With ungrounded sources, one would use 3V0 voltage detection.
  - Note that for FDO 67N protection and 3V0 voltage protection both require 3Yg-3Yg VTs on the utility-side of the interconnection transformer (exception: 3Yg-3Yg VT may be on low-side (DER facility side) with 3Yg-3Yg Interconnection Transformer only).

If the 67N cannot element polarize, it will not allow a 67N trip, remaining secure



Phase-to-Phase Faults (67Q):

- A negative sequence polarized directional element is employed for phase-to-phase fault directional determination
- 67Q will work with rotating machine-based DER, or mixtures of rotating machine and inverter-based DER in a given facility
- May not work with inverter-based DER.
- Inverters do not produce negative sequence current and therefore a negative sequence voltage drop does not occur, and negative sequence voltage (V2) may not be available to polarize.
- In most cases, the 67Q will be able to function if the Utility is still connected to the feeder and a phase-to-phase fault is present.
- With FDO 67Q applied at the DER IP, the substation source will allow V2 to be produced by the phase-to-phase faults. The V2 would, in most cases, be measurable at the DER PCC and V2 polarization would be available during the time the feeder was supplied from the substation
- The 67Q used at the DER IP would need to be coordinated to trip slightly faster than the upline feeder relaying or recloser protection.

If the 67Q cannot element polarize, it will not allow a 67Q trip, remaining secure

3-Phase Faults (67P)

- The directional element employs positive sequence voltage polarization, which inverters as well as other DER types produce on a 3-phase fault.

If the 67P cannot element polarize, it will not allow a 67P trip, remaining secure

Other Considerations

- FDO is a method that allows greater dependability and security as the use of the focused angle allows low set overcurrent elements to be applied.
- If the FDO elements cannot polarize for any reason (system conditions prohibit polarizing), the element has the ability to use a threshold in the directional element that will block the overcurrent from picking up and tripping.
  - The FDO approach remains secure if it cannot polarize, yet it offers the opportunity to provide sensitive fault backfeed protection

Other Considerations

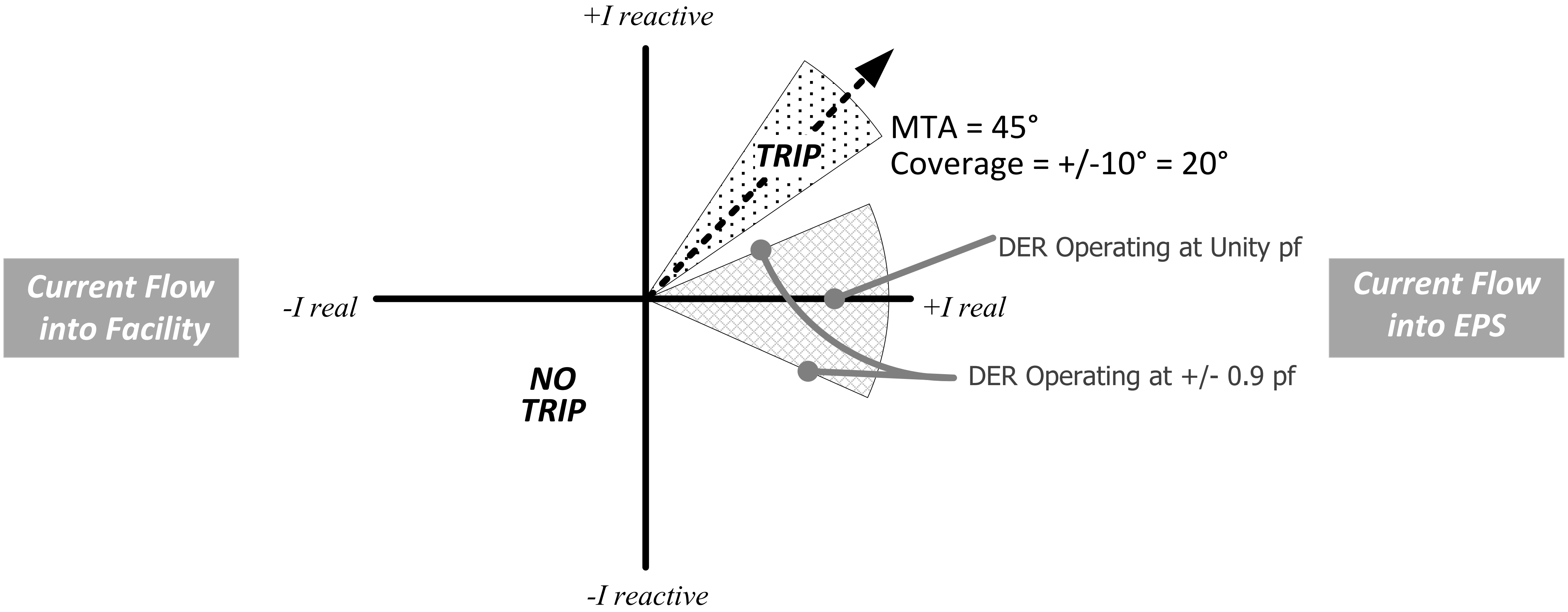
- FDO will always work for rotating-machine based DER, as the rotating machines can produce all sequence quantities for a fault (fault type dependent): positive (for 67P), negative (for 67Q) and zero (for 67N).
- The only limitation is the 67N with ungrounded EPS-facing interconnection transformer windings, similar to the inverter-based DER application discussion
- Note: FDO is not intended for high-impedance fault detection characterized by primary ground faults with a highly resistive component and current values of 10A or less. High-impedance fault detection requires specialized methods.

FDO Summary

- The use of FDO elements allows very low pickup values to be applied for DER supplied EPS fault backfeed protection.
- The use of very low pickup values with FDO improves dependability of the DER IP by greatly increasing the sensitivity of the overcurrent elements below DER rated output level. This allows less dependence on transfer trip for DERs that normally export power to the EPS.
- As very low fault current may be securely detected with FDO elements, the likelihood of an undetectable fault backfeed situation from DER to the EPS decreases.
  – This is because if there is an extremely low current supplying a fault (less than a very low pickup setting), then this low current would typically not be able to hold up the feeder voltage on the islanded feeder. Therefore, the DER IP would typically trip on an undervoltage condition.

FDO Summary

- Load encroachment blinding does not block unfaulted phase(s) with current in the load region from tripping on non-3 phase shunt faults (phase-to-ground, phase-to-phase and phase-to-phase-to ground).
- FDO blocks the unfaulted phase(s) from nuisance tripping and allows tripping of faulted phase(s) on the feeder angle with currents greater, at, or well below rated DER output.



What does FDO offer for DER Interconnection Protection?

- Much more **sensitivity** for fault back-feed protection

- **Security** against load operation, including active DER VAR output
  - Excellent for rotating machine protection too!

- May help **minimize or eliminate** the need for costly transfer trip systems

- **Aid for DER transmission ride-through** for distribution and transmission scale DER application

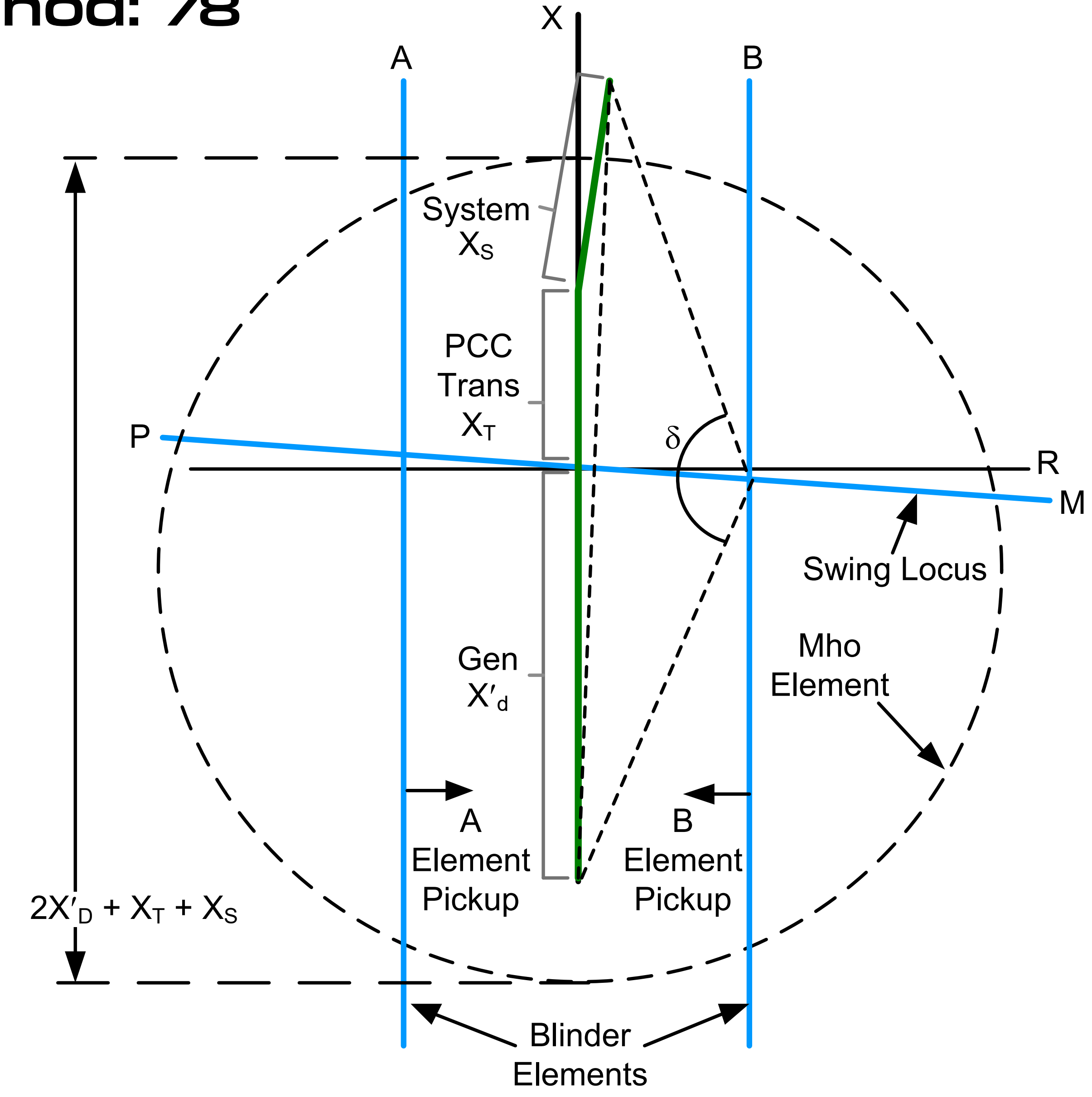
Interconnection Protection

- Damaging System Conditions
  - Loss of synchronism (78)
  - Open phase condition or load imbalance (46, 47), negative sequence current and voltage
  - Phase sequence reversal (47), negative sequence voltage
  - Instantaneous overvoltage (59I)
  - Based on current or voltage imbalance (including reverse phase rotation), power system and DER going out-of-step, or ferroresonance
- Facilitate proper restoration
  - All elements reset, voltage and frequency within limits
  - Reconnect timer (79) (all DER)
  - Sync check (25)
    - Synchronous generators and some self-commutating inverters

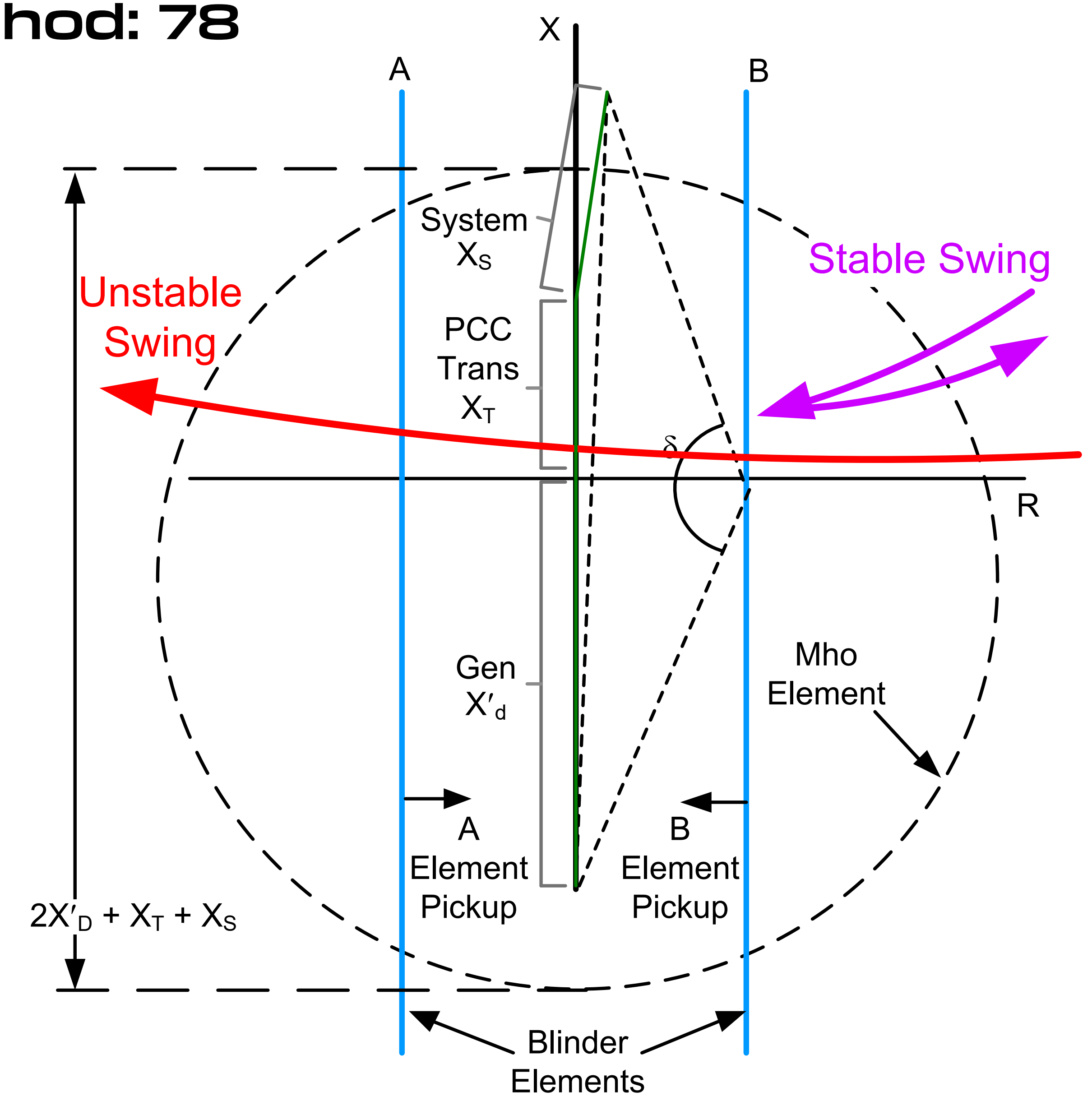
Generator Out-of-Step Protection (78)

- Types of Instability
  - Steady State: Steady Voltage and Impedance (load flow)
  - Transient: Fault, where voltage and impedance change rapidly
  - Dynamic: Oscillations multiple gensets electrically close
- Occurs with unbalance of load and generation
  - Short circuits that are severe and close
  - Loss of lines leaving power plant (raises impedance of loadflow path)
  - Large losses or gains of load
- Generator accelerates or decelerates, changing voltage angle between itself and system
- Designed to cover the situation where electrical center of power system disturbance passes through the PCC transformer or generator itself
- Multiple transformers in generators path to PCC and weak source (long line) are factors encouraging OOS events with DER.

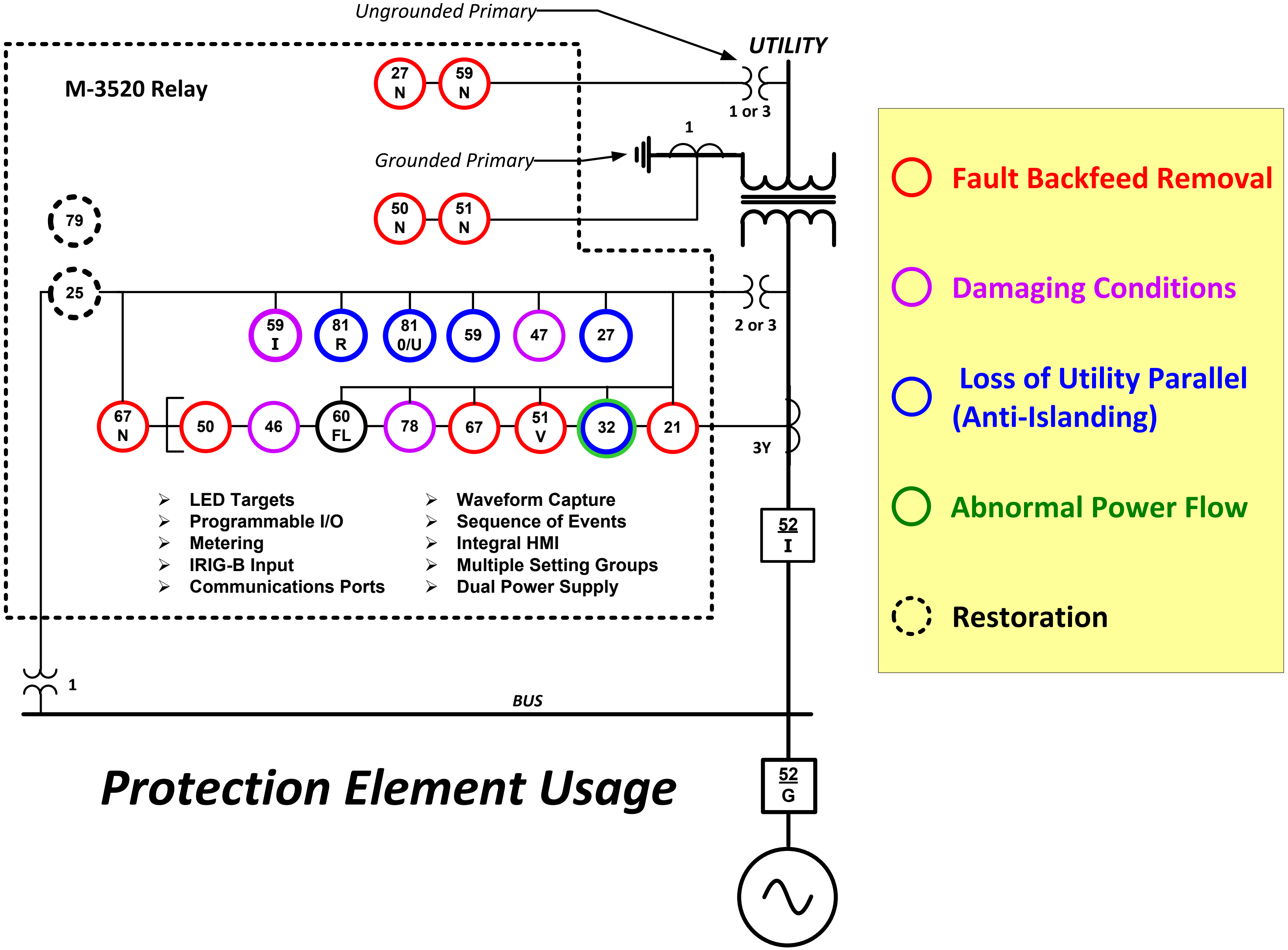
Graphical Method: 78



Graphical Method: 78



Protection Element Usage



Protection Element Usage

Inverter Active Anti-Islanding Protection

- Impedance Measurement
- Similar Methodologies and Other Names
  - Power Shift; Current Notching; Output Variation
- Theory:
  - Amplitude of current changed (increased)
  - With utility connected, little resultant voltage change
  - With utility disconnected, larger resultant change
- Works well with single inverter
- Multiple inverters can swamp each other out as amplitude change is not synced between inverters

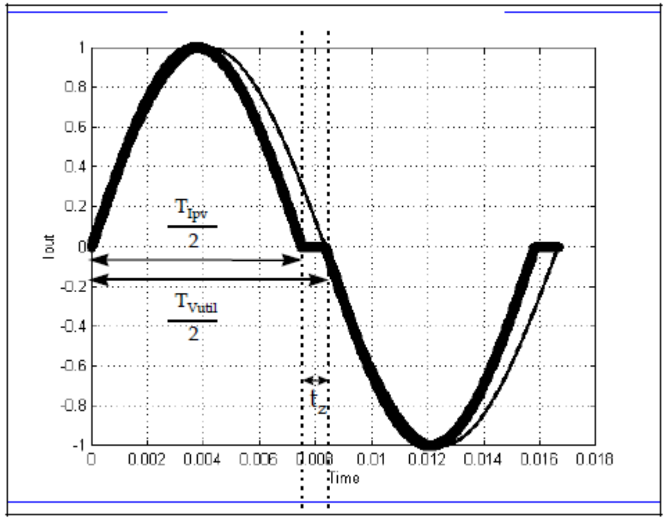
Inverter Active Anti-Islanding Protection

- Detection of Impedance at Specific Frequency
- Similar Methodologies and Other Names
  - Harmonic amplitude jump
- Theory:
  - Inject a current harmonic of a specific frequency
  - At the harmonic frequency injected, the Utility impedance is much lower than the load impedance
  - The harmonic current flows into the grid, and no abnormal voltage is seen
  - With utility disconnected, a harmonic voltage is seen at the inverter
- Works well with multiple inverters
- May be difficult to obtain secure yet dependable settings

Inverter Active Anti-Islanding Protection

- Slip Mode Frequency Shift (SFS)
- Similar Methodologies and Other Names
  - Slide Mode Frequency Shift; Phase Lock Loop Slip; "Follow the Herd"
- Theory:
  - Moves phase angle of voltage dependent on frequency measured, thereby causing changes in frequency
  - With utility connected, frequency does not change
  - With utility disconnected, frequency change is detected
- Highly effective in the multiple inverter applications and provides a good compromise between islanding detection effectiveness, output power quality, and impact on transient response of overall power system.
- May be difficult to obtain secure yet dependable settings

Inverter Active Anti-Islanding Protection



- Frequency Bias
- Similar Methodologies and Other Names
  - Frequency Shift Up/Down; Active Frequency Drift
- Theory:
  – Current waveform of inverter is slightly distorted such that there is a continuous trend to change frequency
  – When connected to utility, it is impossible to change frequency
  – When disconnected from utility, frequency forced to drift up or down
- Frequency bias requires small degradation of PV inverter output power quality
- In order to maintain effectiveness in multiple-inverter case, there would have to be agreement between all inverters on direction of the frequency bias.

Inverter Active Anti-Islanding Protection

- Sandia Frequency Shift (SFS)
- Similar Methodologies and Other Names
  - Accelerated Frequency Drift; Active Frequency Drift with Positive Feedback; “Follow the Herd”
- Theory:
  - Frequency is changed up or down depending on if higher or lower than rated
  - When connected to the utility grid, minor grid frequency changes are detected, and the method attempts to increase the change in frequency
  - The stability of the grid prevents change
  - When disconnected from the utility, the frequency is forced to up or down.

Inverter Active Anti-Islanding Protection

Sandia Frequency Shift (SFS) (con’t)

- Provides a good compromise between islanding detection effectiveness, output power quality, and system transient response effects
- Requires that the output power quality be reduced slightly when it is connected to the grid because the positive feedback amplifies changes that take place on the grid

Inverter Active Anti-Islanding Protection

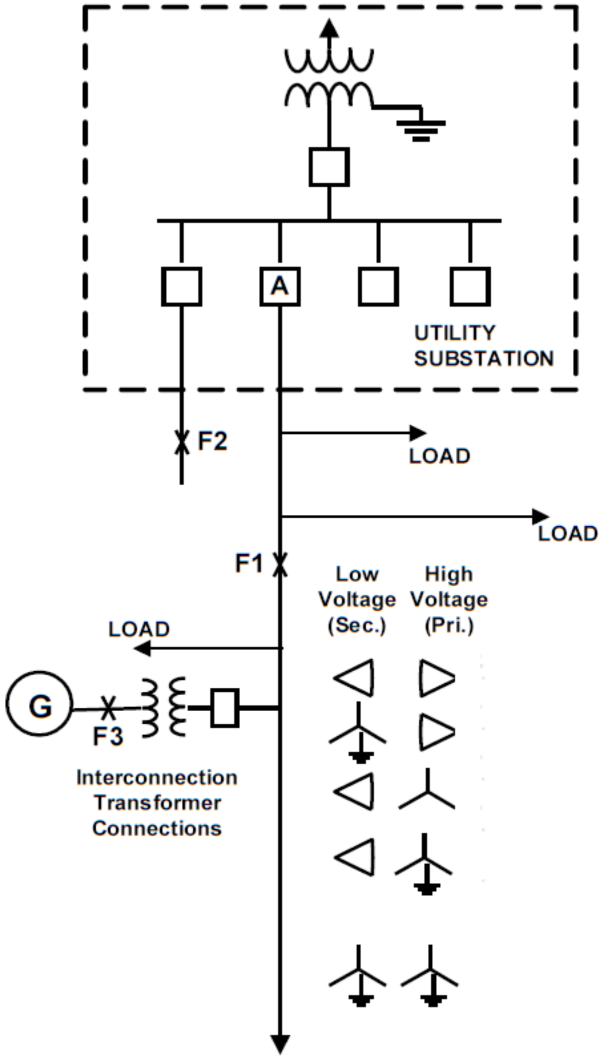
- Sandia Voltage Shift (SVS)
- Similar Methodologies and Other Names
  - Voltage shift, positive feedback on voltage; “Follow the Herd”
- Theory:
  - Voltage is increased or decreased according to if utility voltage is above or below rated
  - When connected to the utility grid, there is no change in voltage
  - When disconnected from the utility, there is a change in voltage
- Effective islanding prevention
- Method may have small impacts on the utility system transient response and power quality
- Penetration levels of inverters using SVS may have to be kept low on weaker grids in order to avoid system-level problems

Inverter Active Anti-Islanding Protection

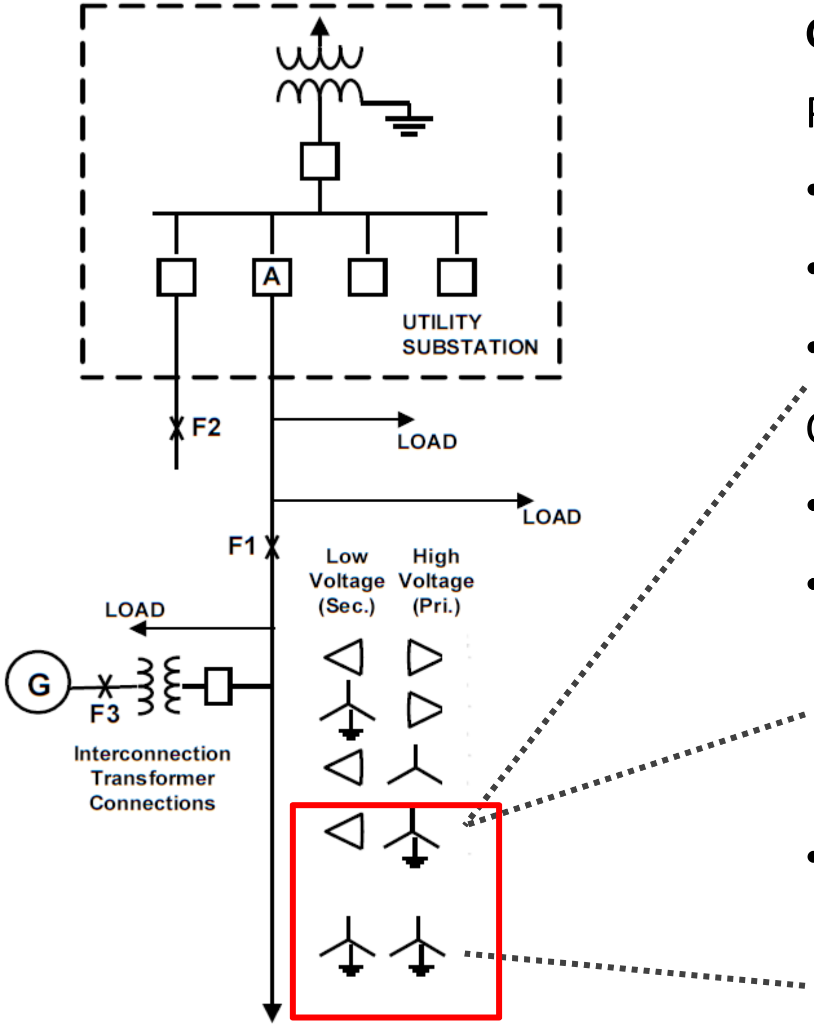
- Frequency Jump
- Similar Methodologies and Other Names
  - Zebra Method
- Theory:
  - Dead zones are inserted into the output current waveform at some interval of cycles
  - When connected to the utility grid, the dead zone is not detected
  - When disconnected from the utility grid, the dead zone is detected
- Not useful on multiple inverter applications

Interconnection Transformer Winding Arrangements Impact Protection

- The winding arrangements facing the utility and the facility have an impact on protection
- Interconnection Transformer convention:
  - Utility = Primary
  - Facility = Secondary



Interconnection Transformers Primary (Utility) Grounding Impacts



Grounded Primary:

Pros:

- No overvoltage for ground fault at F1
- No overvoltage for ground fault at F2
- No ground current from feeder for faults at F3 (delta sec. only)

Cons:

- Provides an unwanted ground current for feeder faults at F1 and F2
- Creates a ground source even when delta secondary circuit is disconnected
  - May cause coordination problems within facility, as well as increased ground fault current to Utility
- Allows feeder relaying at A to respond to a secondary ground fault at F3 (Ygnd-Ygnd only)

Interconnection Transformers Primary (Utility) Grounding Impacts

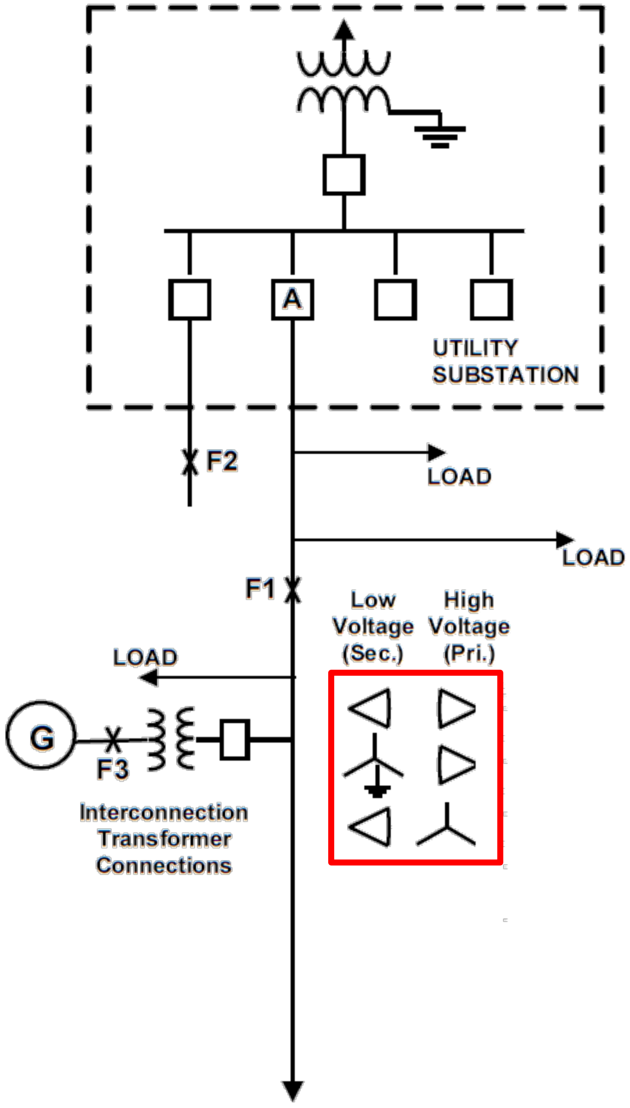
Ungrounded Primary:

Pros:

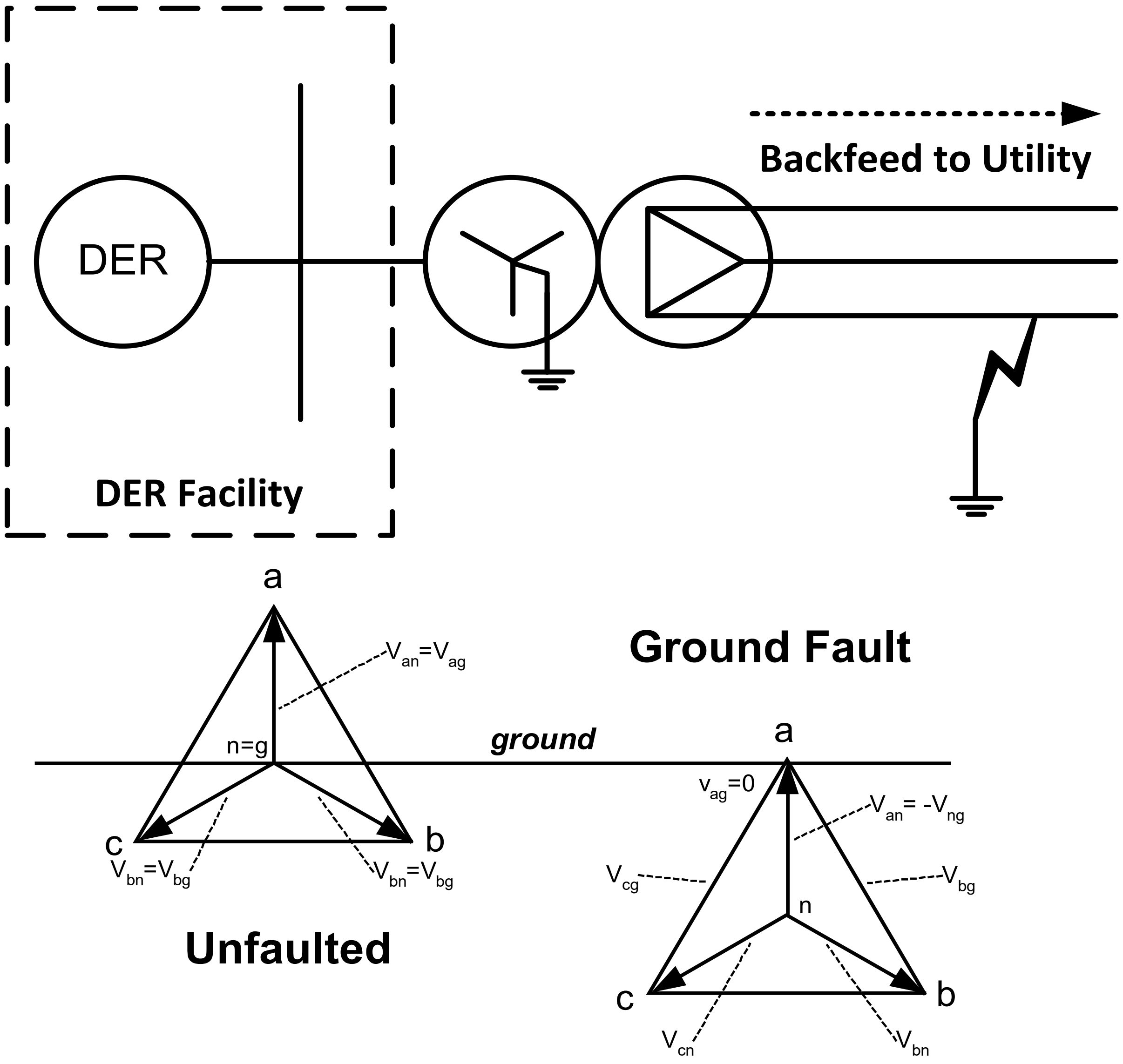
- No ground fault backfeed for fault at F1 & F2
- No ground current from breaker A for a fault at F3

Cons:

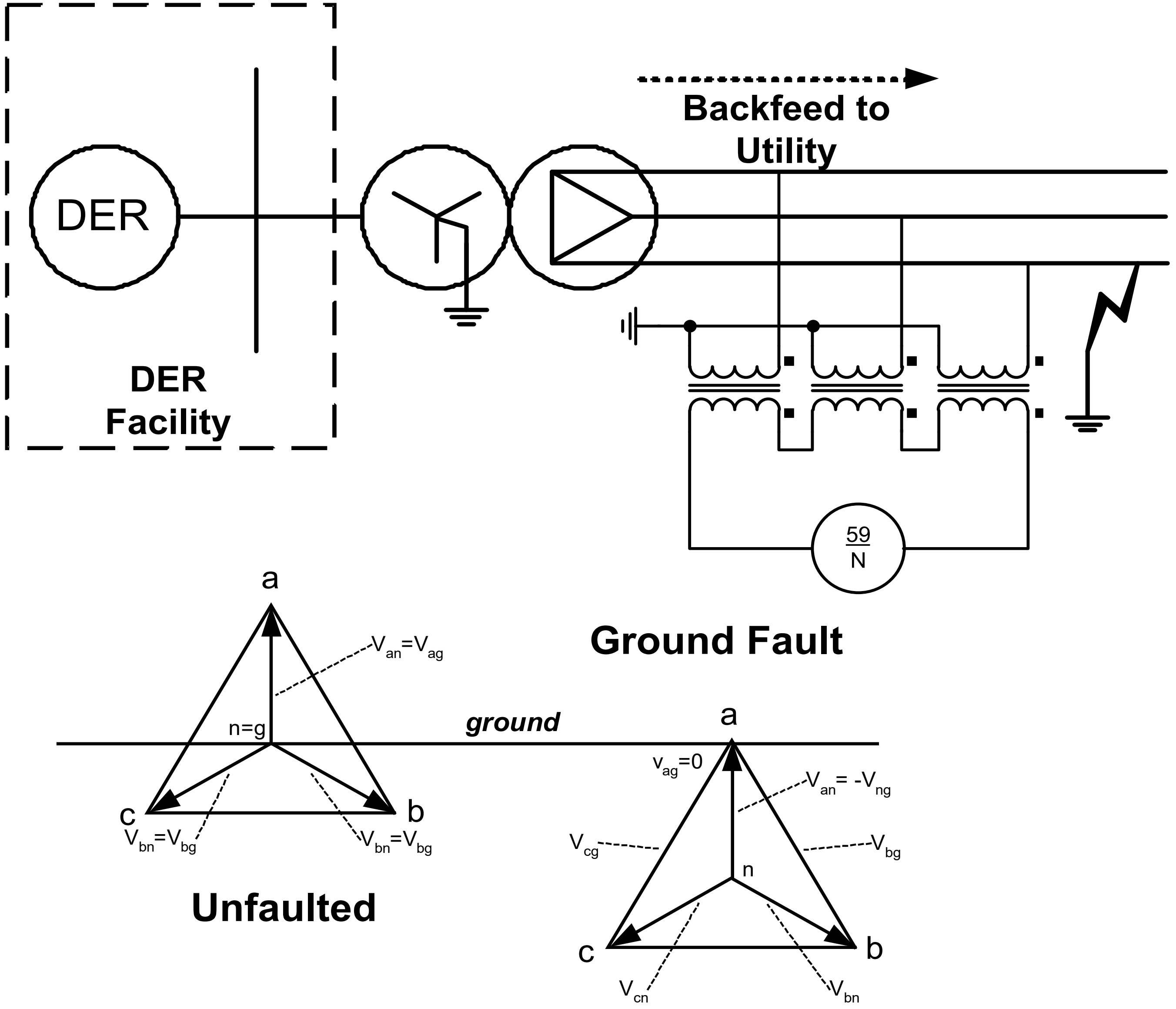
- Supplies the feeder from an ungrounded source after substation breaker A trips causing overvoltage



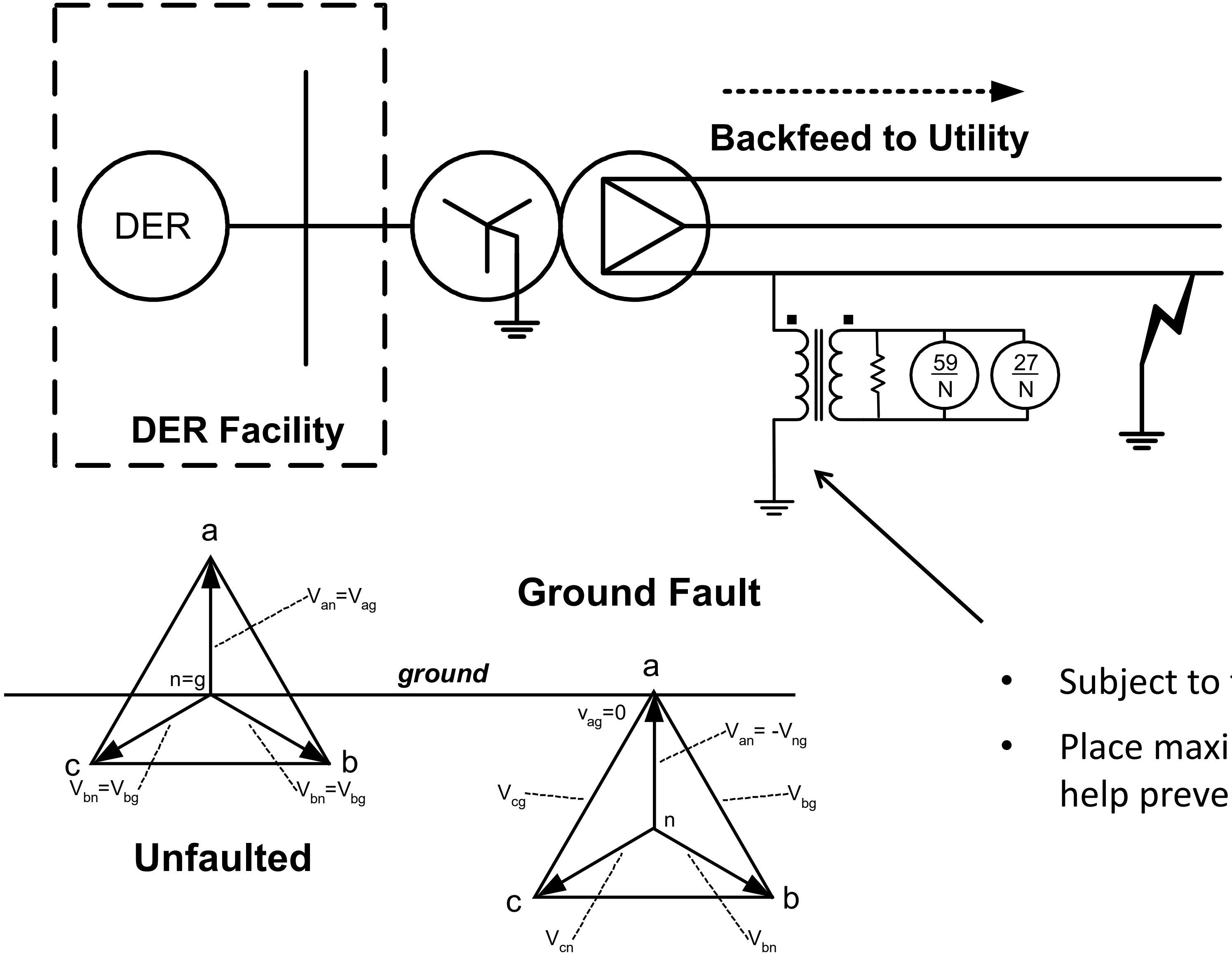
Ungrounded Primary: Faulted System Backfeed Overvoltage



Sensing Ungrounded System Ground Faults with 3 Voltage Transformers

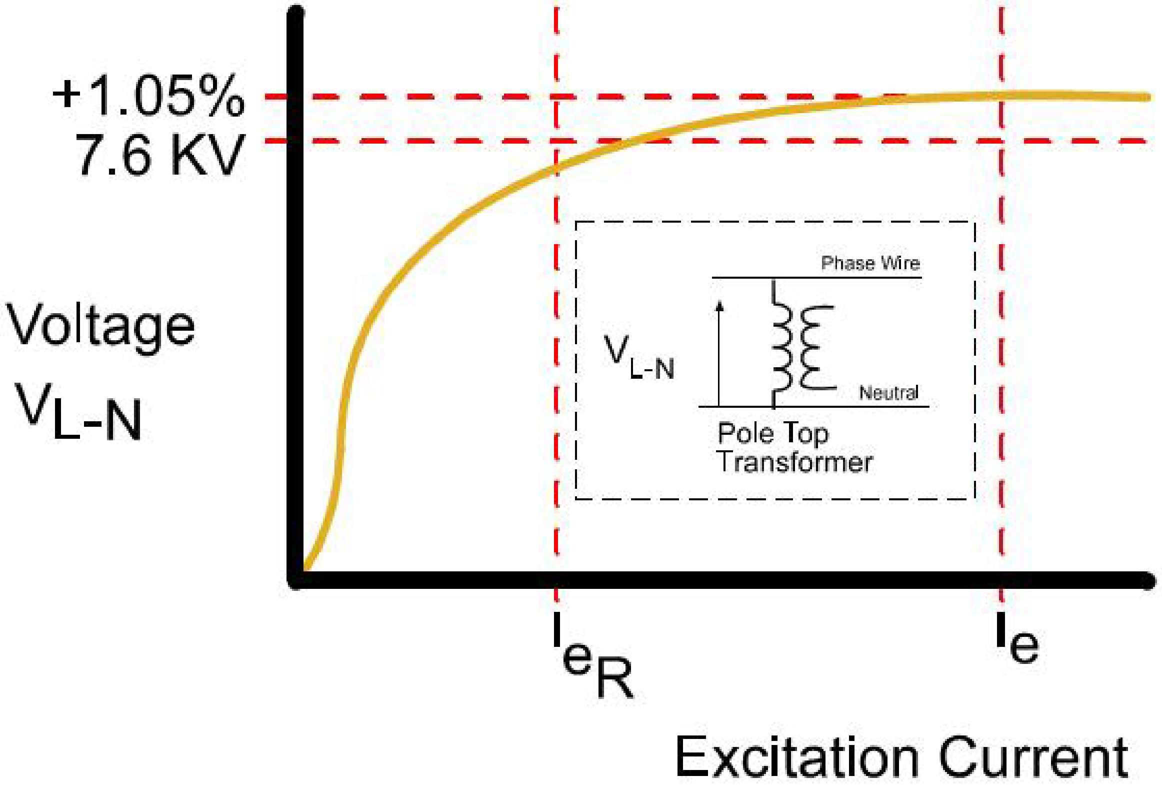


Sensing Ungrounded System Ground Faults with 1 Voltage Transformer



- Subject to ferroresonance
- Place maximum resistive burden of VT to help prevent ferroresonance

Impact of Overvoltage: Saturation Curve of Pole-Top Transformer



- Many utilities only allow use of ungrounded primary windings only if the DER sustains at least a 200% overload on islanding
- The overload prevents the overvoltage from occurring

Types of Power Sources

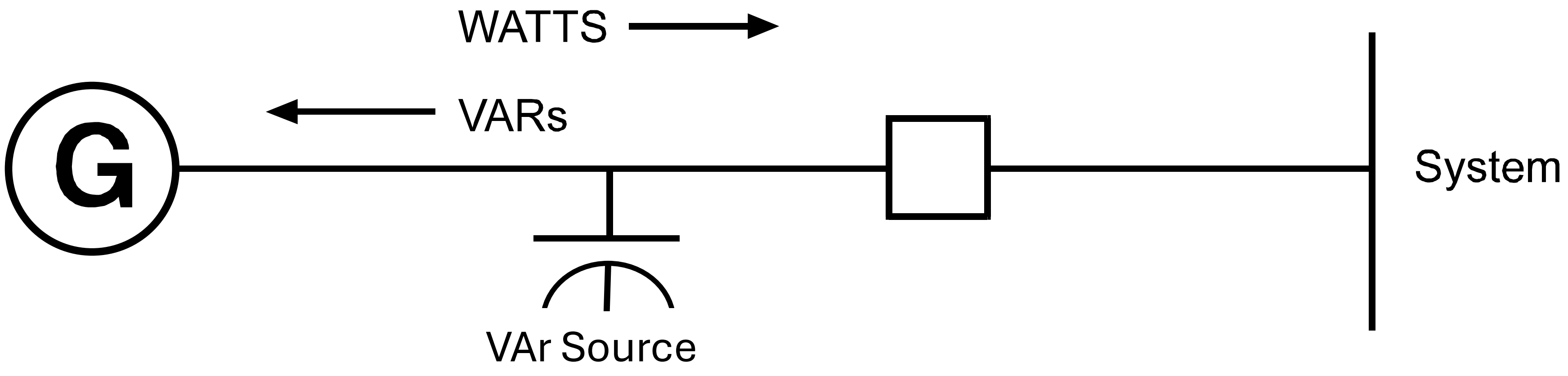
Induction

- Contributes fault current
- Usually not capable of fault backfeed
  - VARs from system required to operate
  - Fault contribution characteristics same as induction motor
- Sync equipment not needed

Synchronous

- Contributes fault current
- Capable of short time sustained fault backfeed due to presence of an exciter
- Sync equipment needed

Induction Generator



Induction

- Excitation provided externally by system
  - VAR drain
- Less costly than synchronous machines
  - No excitation system or control
  - No sync equipment needed
- Limited in size to <=500 K VA
- May cause ferroresonance after disconnection from utility (self-excitation from nearby caps)

Types of Generators

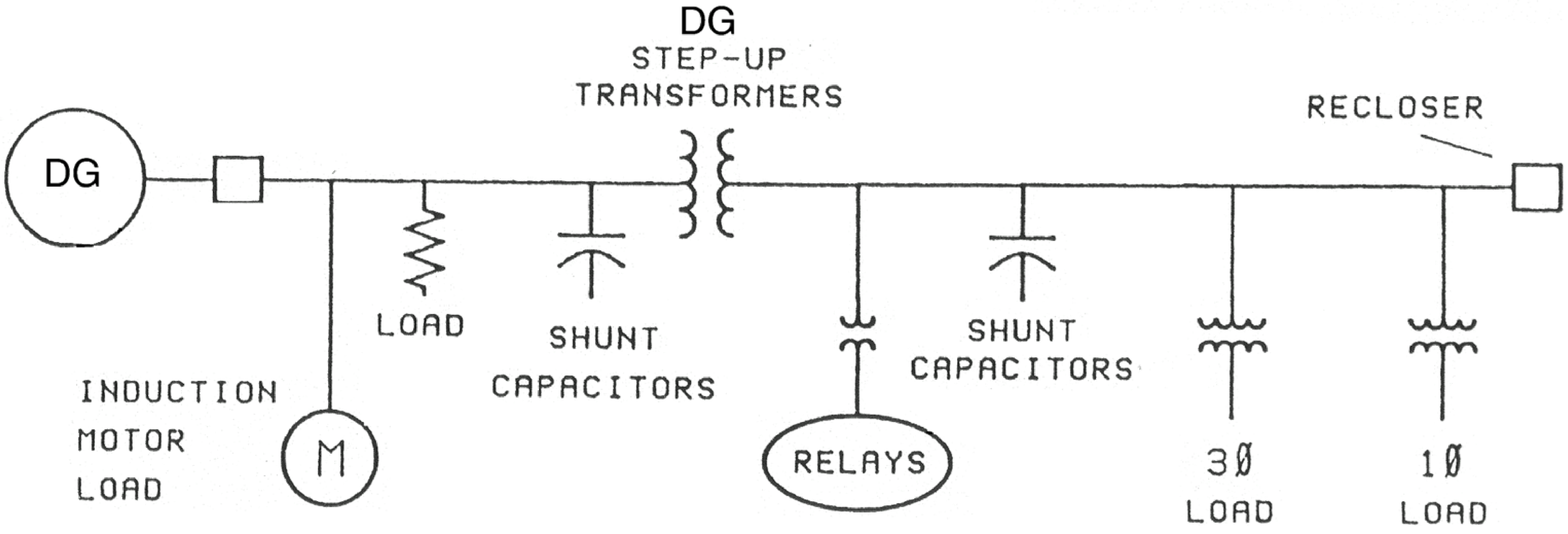
- Some Wind Power
- Some Small Hydro
- Some small prime mover driven

Ferroresonance

- Ferroresonance can take place between an induction generator and capacitors after utility disconnection from feeder
  - Ferroresonance can also occur on Synchronous Generators!
- Generator is excited by capacitors if the reactive components of the generator (X_G) and aggregated capacitors (X_C) are close in value
- This interplay produces non-sinusoidal waveforms with high voltage peaks. This causes transformers to saturate, causing non-linearities that exacerbate the problem.

Test Circuit Setup

- New York Field Tests- 1989
- Field Test Circuit



Schematic of Test Circuit.

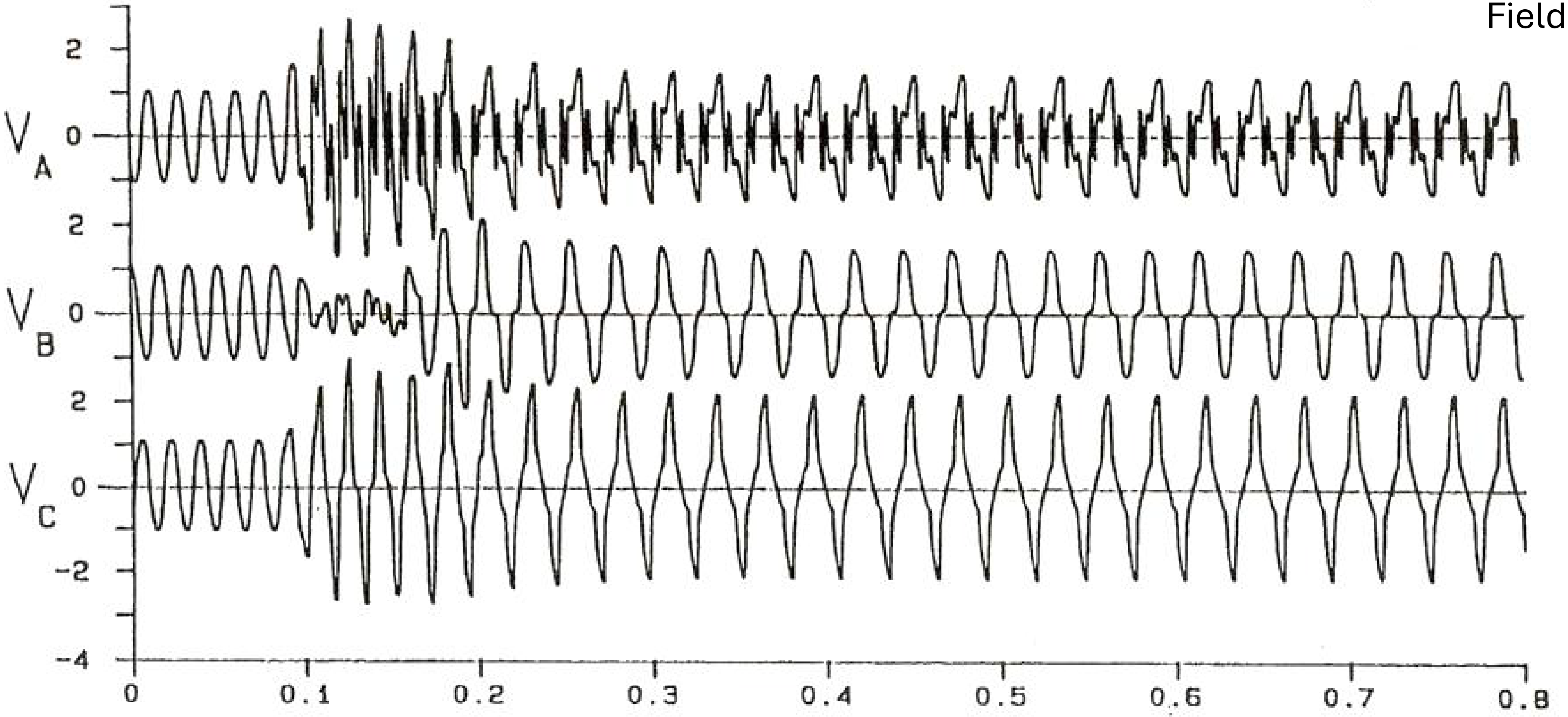
Conditions for Ferroresonance

- Feeder that DER is connected to must be isolated from the utility
  - (Islanded condition)
- KW load in the island must be less than 3 times DER rating
- Capacitance must be greater than 25% and less than 500% of DER rating
- There must be a transformer in the circuit to provide nonlinearity

Ferroresonance: Test Circuit Setup

New York Field Tests- 1989

Field Test Circuit



Conditions:

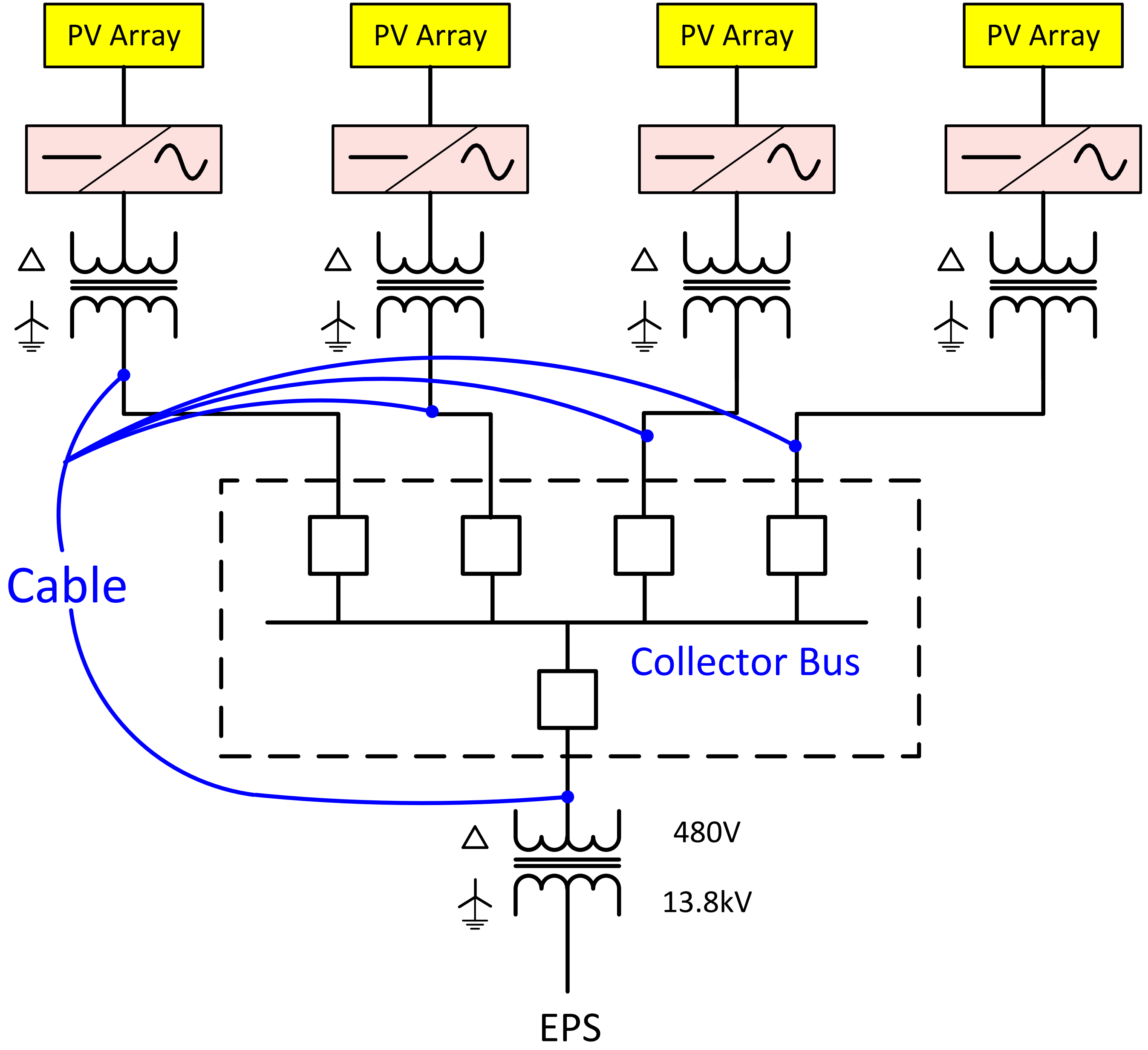
Wye-Wye Transformers, 100 kVAr capacitance, 60 kW generator, 12 kW load

Inverter-Cable Ferroresonance

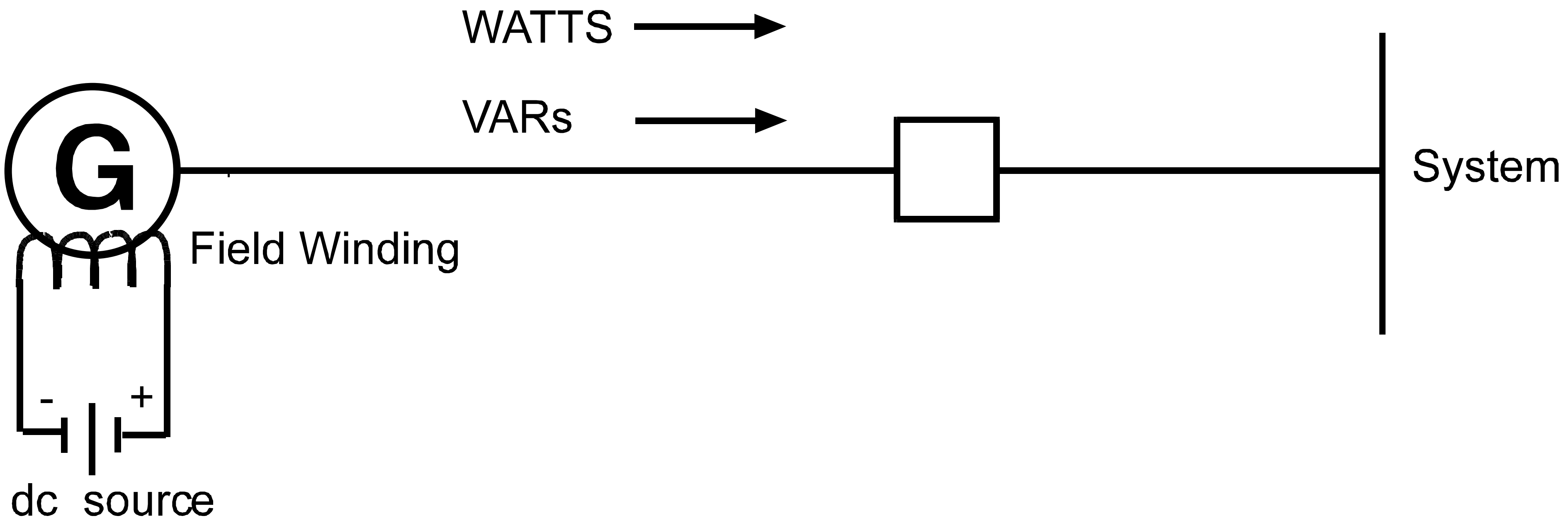
- Medium voltage PV facilities are often comprised of 500 kW-1 MW PV arrays feeding inverters
- The inverters are then connected to a transformer to produce 480 V AC
- The output of the 480 V transformers is input to collector bus switchgear by cables
- The output of the collector bus switchgear is brought to a 480 to MV step up transformer by cables
- The MV terminals of the 480 V:MV transformer is connected to the EPS

Inverter-Cable Ferroresonance

- When operating to supply the EPS, the inverters are in *current controlled mode*
- Upon sudden loss of EPS, the inverters now lack a *voltage reference*
- The cables are *capacitive*, and hold up voltage
- The inverters do not control voltage, but rather produce current when voltage is sensed
- The voltage produced may go high under these circumstances
- High voltage saturates the transformers (starting at 1.1pu), which are non-linear when saturated
- You now have set the stage for ferroresonance of the islanded PV facility


PV Array
PV Array
PV Array
PV Array
Cable
Collector Bus
480V
13.8kV
EPS

Synchronous Generator



Synchronous

- Excitation provided by field
  - May be a VAR source
  - Requires excitation system and control
- Sync equipment needed
- Sized 10 kW and up

Types of Generators

- Prime mover driven
- Some wind
- Some hydro (larger)

Small Generator: Fault Current Contribution

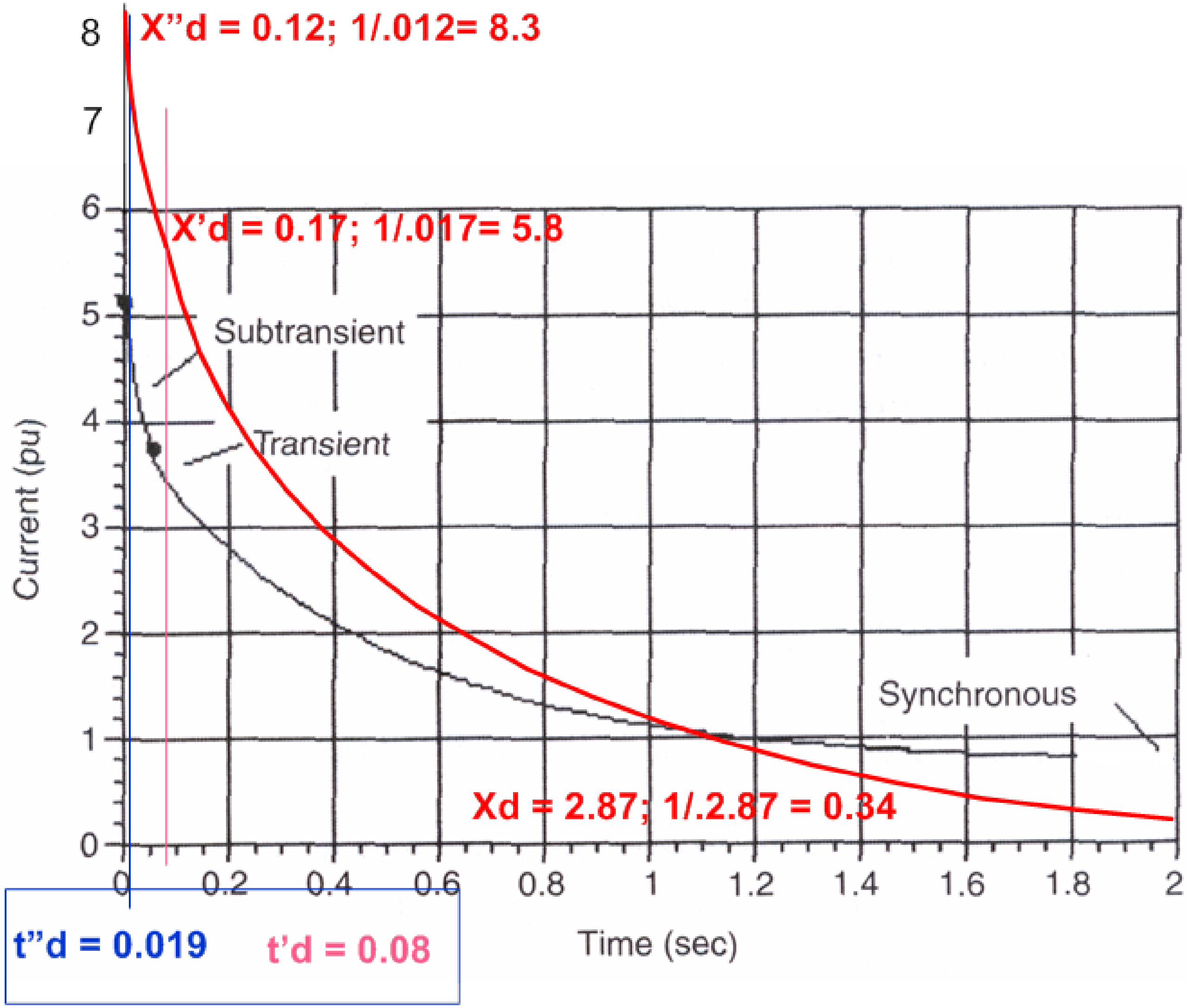
- It's all about x''_d - t''_d, x'_d - t'_d, and x_d, plus how excited (self or Permanent Magnetic Generator (PMG))
- X_d steady state reactance
  - x''_d used for initial fault level determination
    - x''_d sub-transient reactance and t''_d is sub-transient current time
- X'_d used for next interval of fault level determination
  - x'_d transient reactance and t'_d is transient current time
- Consult genset manufacturer for alternator data sheets!

≈400 kVA Generator

	50 Hz				60 Hz			
TELEPHONE INTERFERENCE	THF<2%				TIF<50			
COOLING AIR	0.8 m^3/sec 1700 cfm				0.99 m^3/sec 2100 cfm			
VOLTAGE SERIES STAR	380/220	400/231	415/240	440/254	416/240	440/254	460/266	480/277
VOLTAGE PARALLEL STAR	190/110	200/115	208/120	220/127	208/120	220/127	230/133	240/138
VOLTAGE SERIES DELTA	220/110	230/115	240/120	254/127	240/120	254/127	266/133	277/138
kVA BASE RATING FOR REACTANCE VALUES	350	350	350	350	400	420	440	440
Xd DIR. AXIS SYNCHRONOUS	3.01	2.71	2.52	2.24	3.47	3.26	3.12	2.87
X'd DIR. AXIS TRANSIENT	0.20	0.18	0.17	0.15	0.21	0.20	0.19	0.17
X"d DIR. AXIS SUBTRANSIENT	0.14	0.13	0.12	0.11	0.15	0.14	0.13	0.12
Xq QUAD. AXIS REACTANCE	2.58	2.33	2.16	1.92	2.92	2.74	2.63	2.41
X"q QUAD. AXIS SUBTRANSIENT	0.36	0.32	0.30	0.27	0.41	0.38	0.37	0.34
X_L LEAKAGE REACTANCE	0.07	0.06	0.06	0.05	0.08	0.08	0.07	0.07
X_2 NEGATIVE SEQUENCE	0.24	0.22	0.20	0.18	0.28	0.26	0.25	0.23
X_0 ZERO SEQUENCE	0.10	0.09	0.08	0.07	0.10	0.09	0.09	0.08
REACTANCES ARE SATURATED	VALUES ARE PER UNIT AT RATING AND VOLTAGE INDICATED							
T'd TRANSIENT TIME CONST.	0.08s							
T"d SUB-TRANSTIME CONST.	0.019s							
T'do O.C. FIELD TIME CONST.	1.7s							
Ta ARMATURE TIME CONST.	0.018s							
SHORT CIRCUIT RATIO	1/Xd							

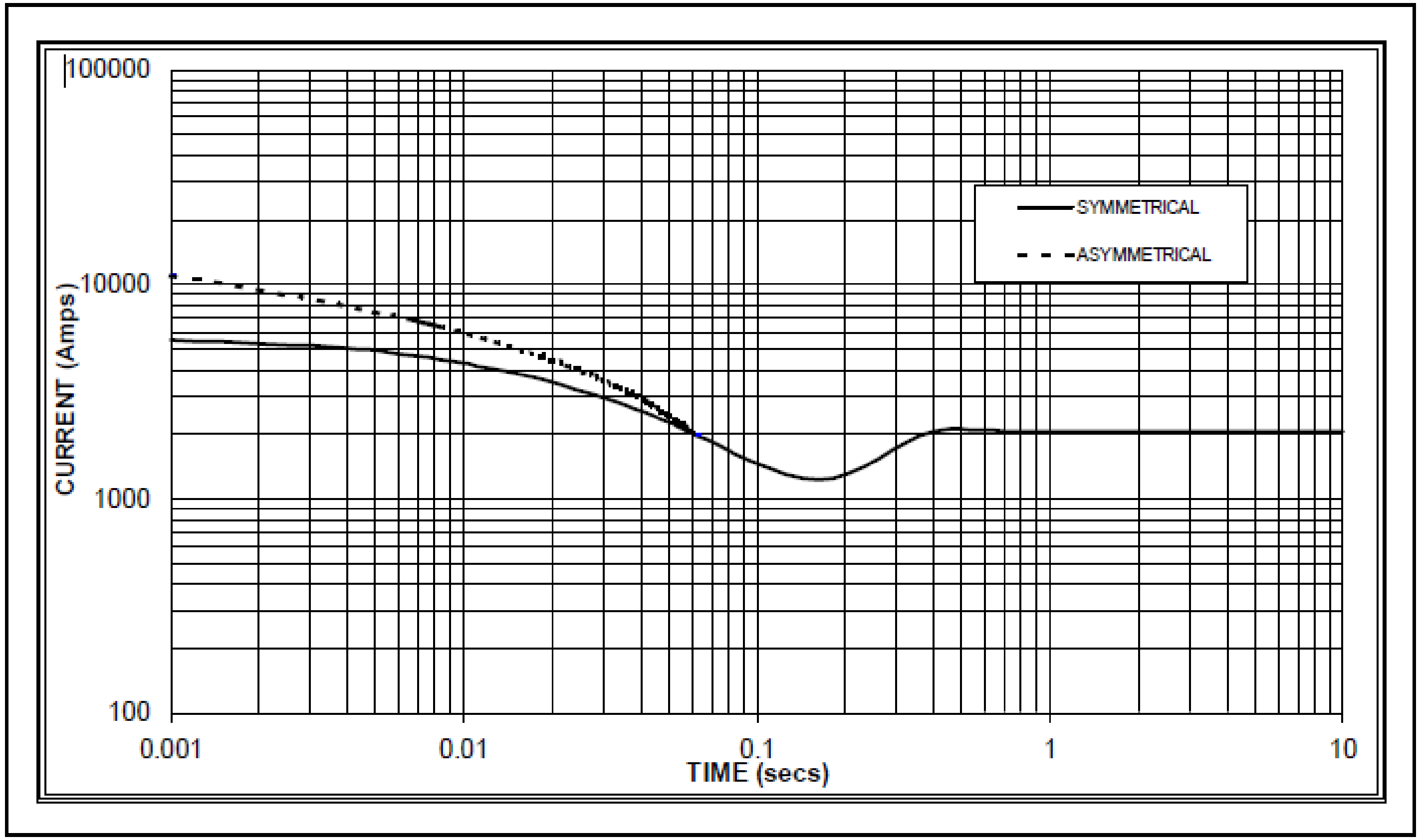
Rated Amps = 482 A

Fault Current for ≈400 kVA Generator



400kVA @ 480V = 482A

Small Genset Current Decrement for PMG



	3 Phase	2 Phase L–L	1 Phase L–N
Instantaneous	x 1.0	x 0.87	x 1.3
Minimum	x 1.0	x 1.80	x 3.20
Sustained	x 1.0	x 1.50	x 2.50
Max Sustained Duration	10 sec	5 sec	2 sec

- PMG = Permanent Magnet Generator
- Uses PM Excitation that does not fully collapse fault current
- This example is from a small genset, about 600 A rated current

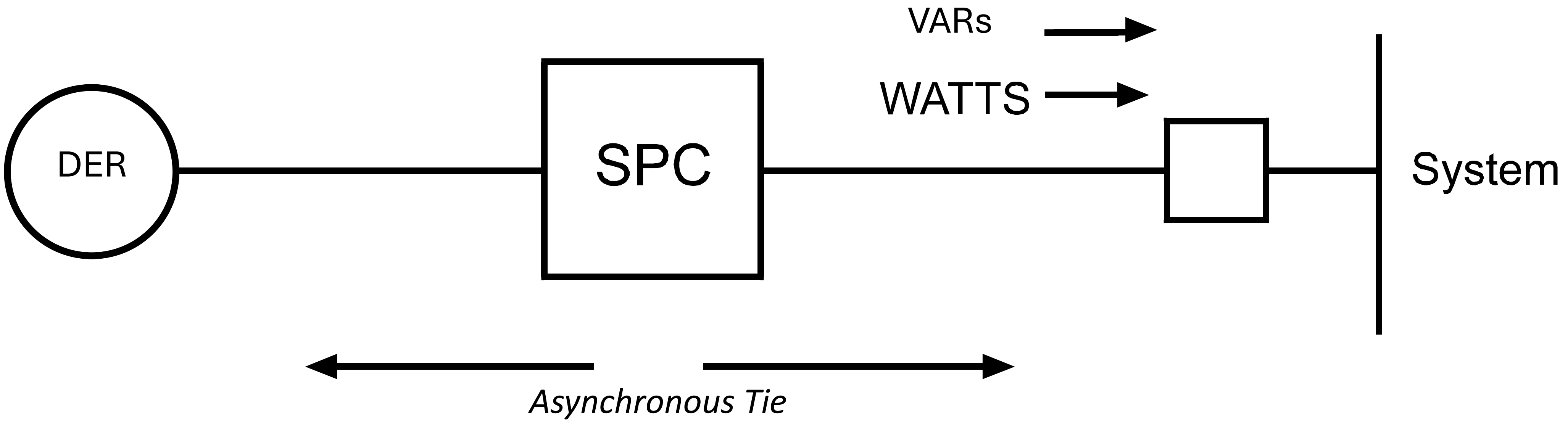
Cummins Power Generation: Application Manual -- Liquid Cooled Generator Sets” -- Ver.G.EN

Types of Power Sources

Asynchronous (Static Power Converters)

- Capable of limited fault current
- Grid Paralleled and Grid Isolation Variants and Operational Modes
  - Grid Isolated Mode uses Voltage Control and may be capable of fault backfeed and fault ride-through
  - Grid Isolated Mode may require sync check for connected loads if rotating machinery

Asynchronous Generator: Static Power Converter or Inverter



Asynchronous

- Static Power Converter (SPC) converts generator frequency to system frequency (dc-ac or ac-dc-ac)

Types of Generators

- Solar, PV
- Fuel Cells
- Wind
- Microturbine
- Storage

Non-Grid Parallel Inverters

- Voltage Controlled
- Can provide limited fault current to the grid
- Fault current is in the order of 1.1-1.3 pu rated load current
- Can provide fault ride-through
  - Fault current will be maintained as long as trip settings allow
    - *Operating in Voltage Control Mode:* Fault current reactive component will increase as the inverter contributes to a fault
- Can cause system transient overvoltages if power output to connected load ratio suddenly decreases (transient control issue)

Grid Paralleled Inverters

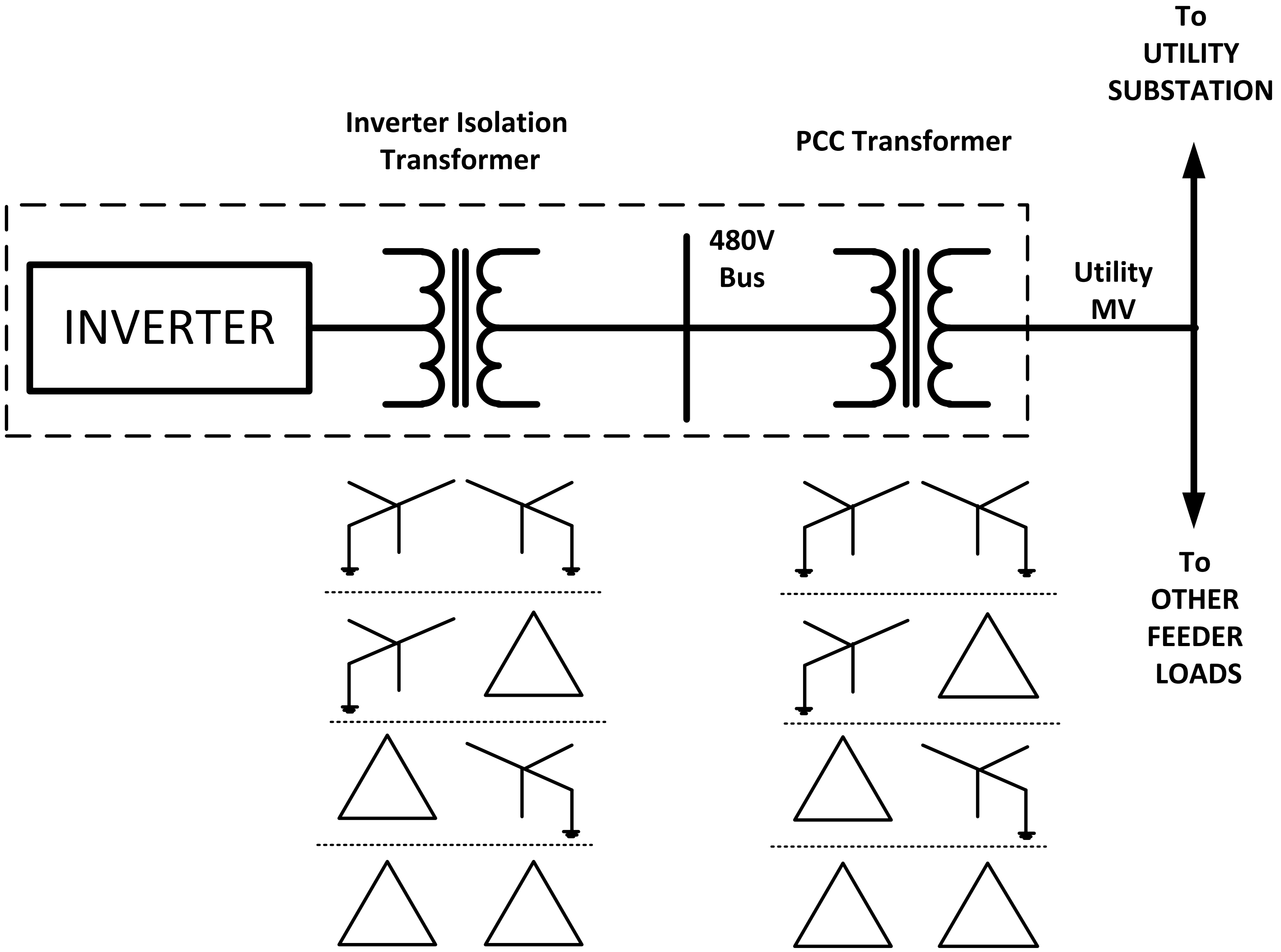
- *Current* Controlled
- Can provide limited fault current
  - Fault current is in the order of 1.1-1.3 pu rated load current
  - Fault current will decay when utility disconnects
  - If overloaded, current will diminish even faster
- Can cause system transient overvoltages if power output to connected load ratio suddenly decreases (transient control issue)

Grid Paralleled Inverters

Most grid paralleled inverters have built-in anti-islanding protection (if UL 1741 compliant)

- Inverter tries to periodically change output (f, V or I)
  - If grid is hot, inverter cannot make noticeable change
  - If grid has tripped, the f, V, or I moves and the controller trips the machine
- Difficult to test; some utilities do not trust and require other protection

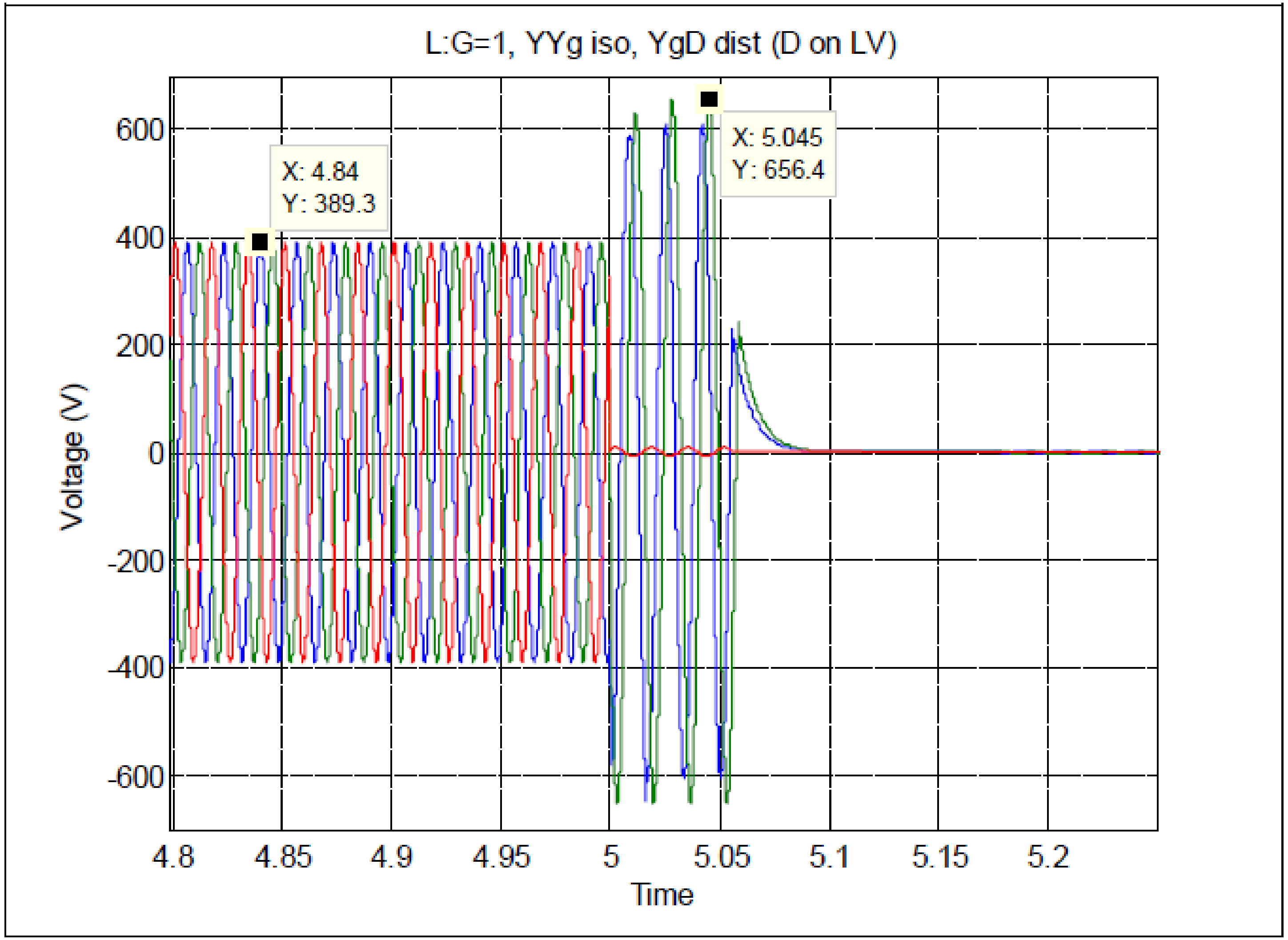
Inverters, Sudden Load Rejection and Overvoltage



- Tests run on inverter to connected to 480 V Bus, then connected to utility MV feeder
- Used different ISOLATION transformer winding arrangements and PCC transformer winding arrangements
- Varied the level of load rejection (load:gen) to see transient voltage response effects

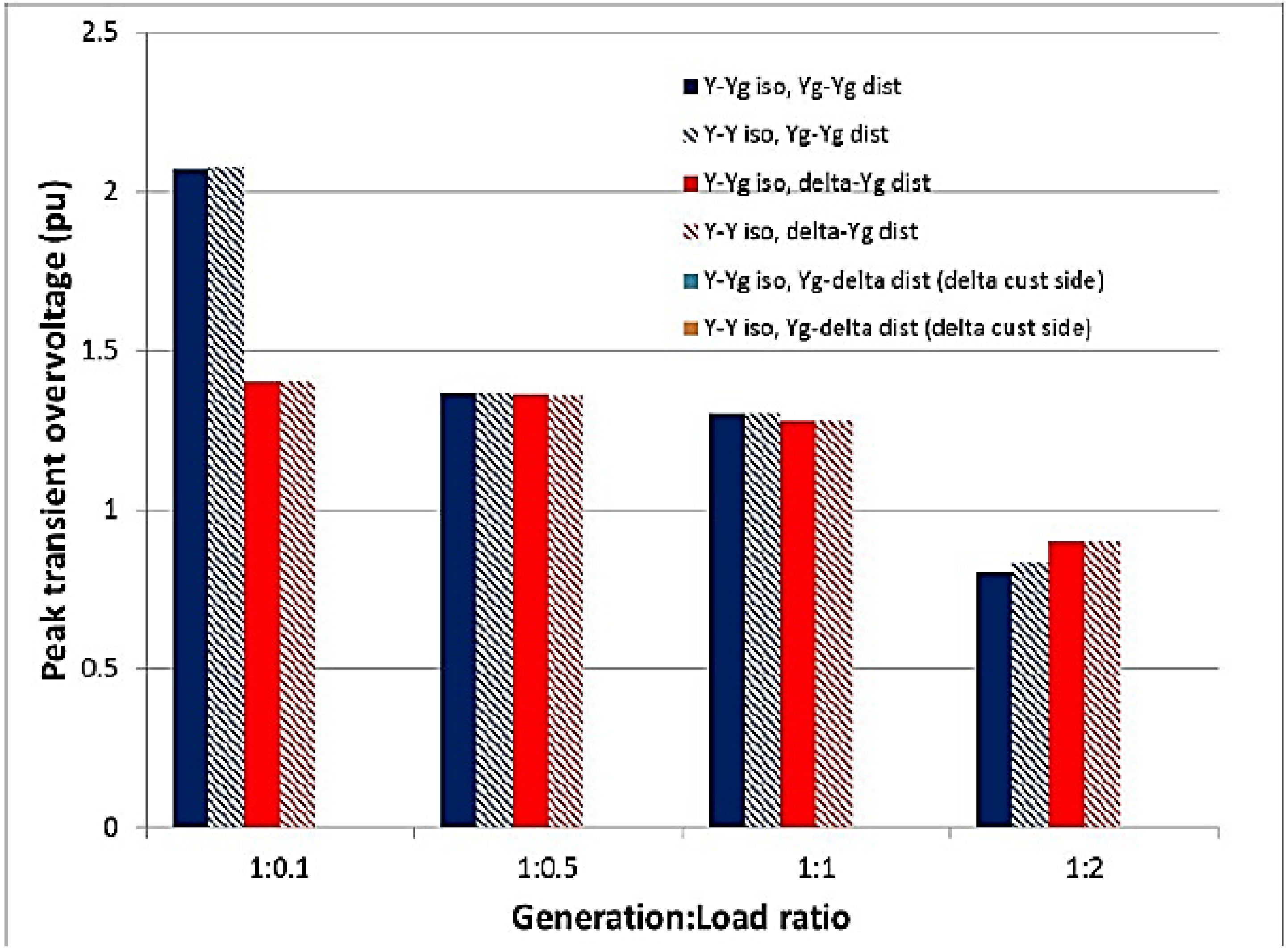
"Effective grounding of distributed generation inverters may not mitigate transient and temporary overvoltage"; WPRC Conference 2012; M. E. Ropp, Member, IEEE, M. Johnson, Member, IEEE, D. Schutz, Member, IEEE, S. Cozine, Member, IEEE

Inverters, Sudden Load Rejection and Overvoltage



Typical response seen when load is suddenly rejected and load:gen ratio changes

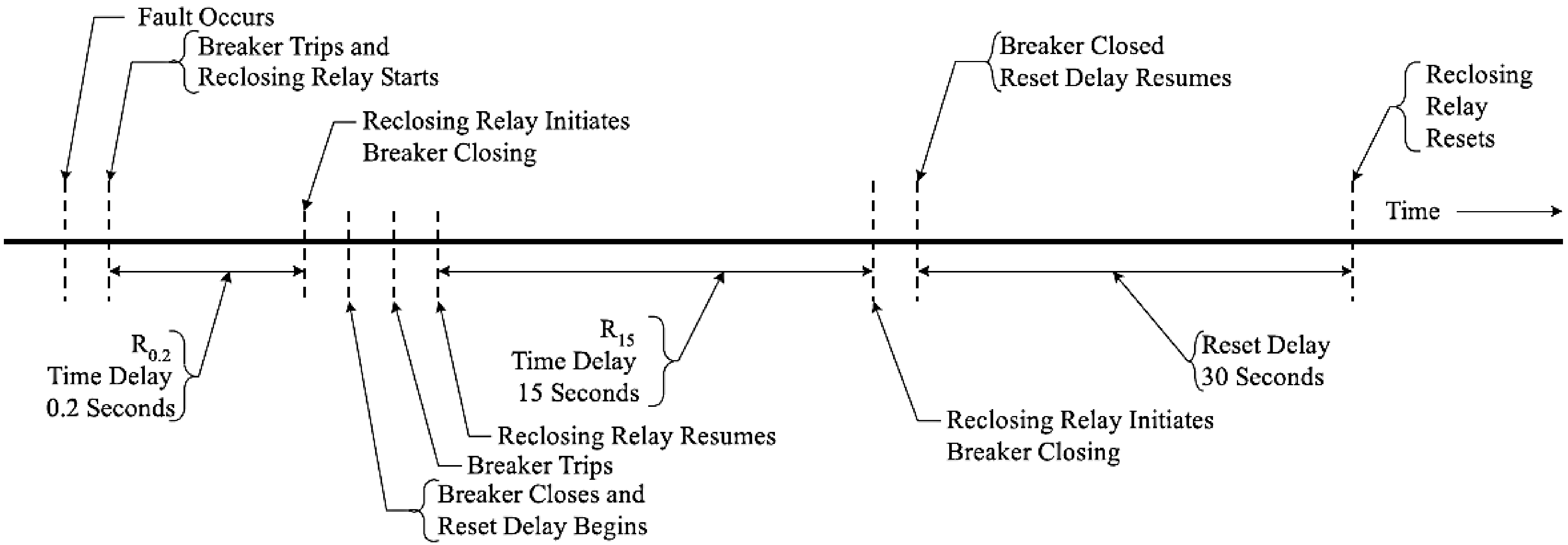
Inverters, Sudden Load Rejection and Overvoltage



Transient overvoltage an inverter control issue, not a grounding issue

Used to assure utility has gone through successful reclose cycle

- Set longer than total reclose cycle
  - All clearing and shot time, plus longest possible reclaim time
  - Typically set in minutes

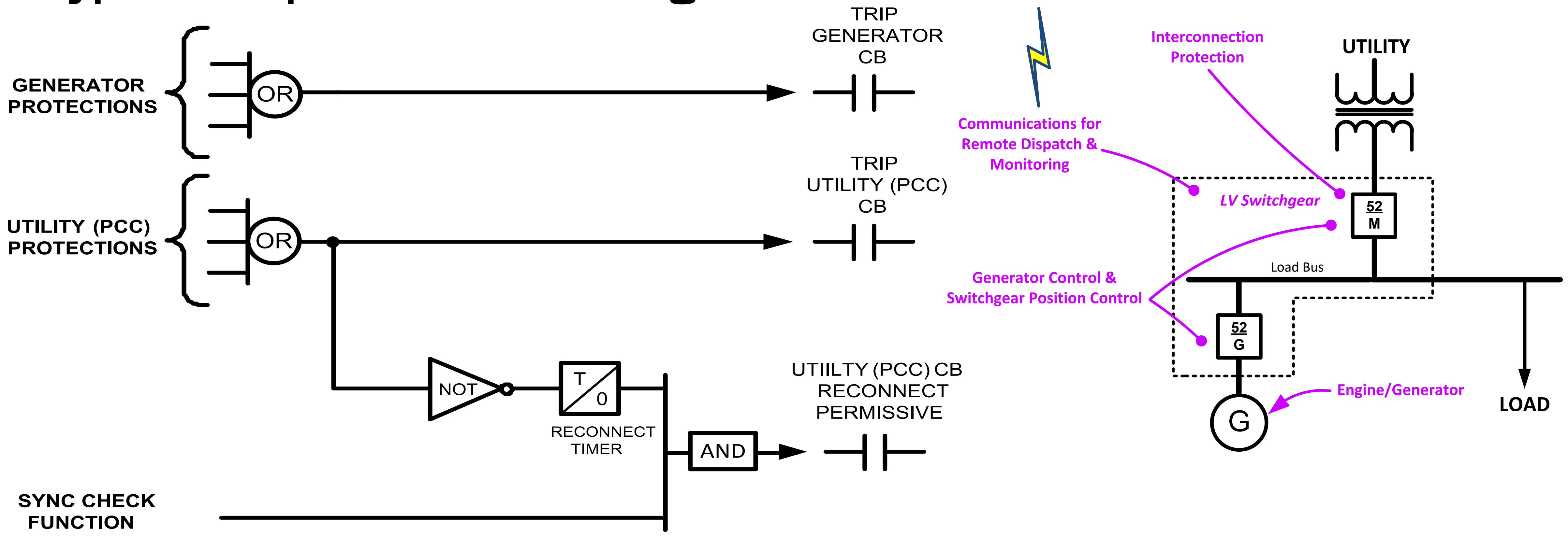


Uses permissive from voltage and frequency functions to assure utility source is back and viable

DER Protection Coordination

- Tripping Order
  - Utility
  - DER Interconnect
  - DER Generator
- Restoration Order
  - Utility Substation Breaker (or Recloser)
  - DER Interconnection Breaker
  - DER Generator Breaker (if tripped)

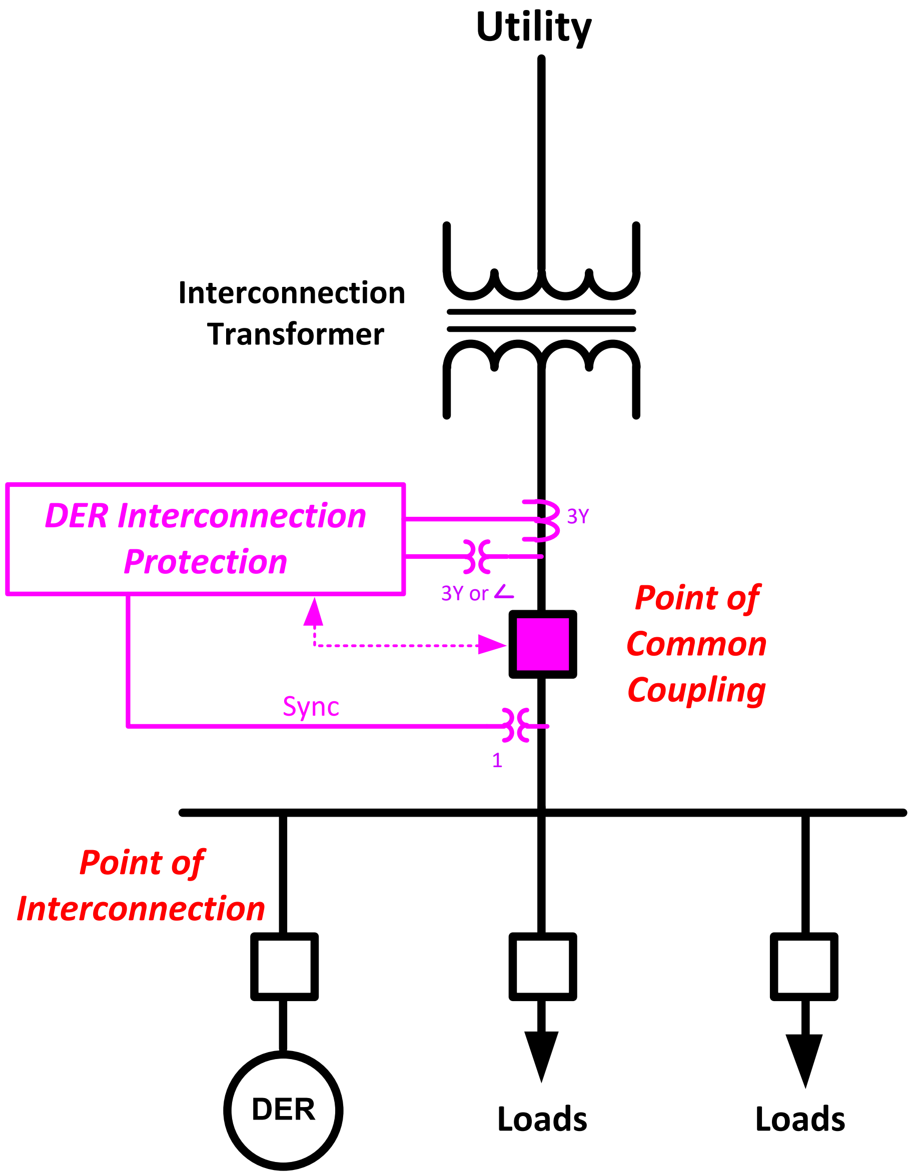
Typical Trip/Reconnect Logic



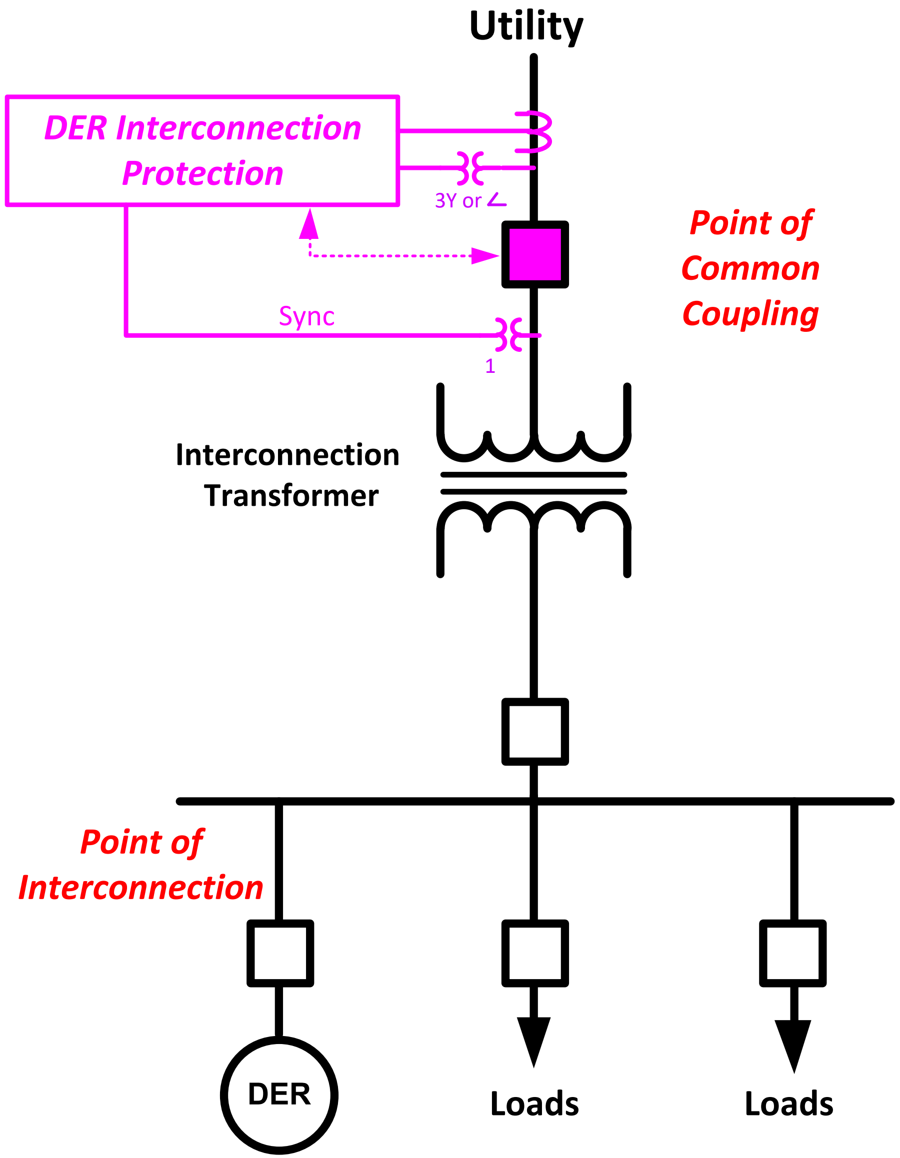
NOTES:

- "T" in the timer function is the preset time delay. Timer is time delay on pickup type.
- Generator protections sourced from generator CTs and PTs
- Utility (PCC) protections sourced from Utility CTs and PTs
- Sync check function(s) sourced from PTs from the load bus and the Utility (PCC)

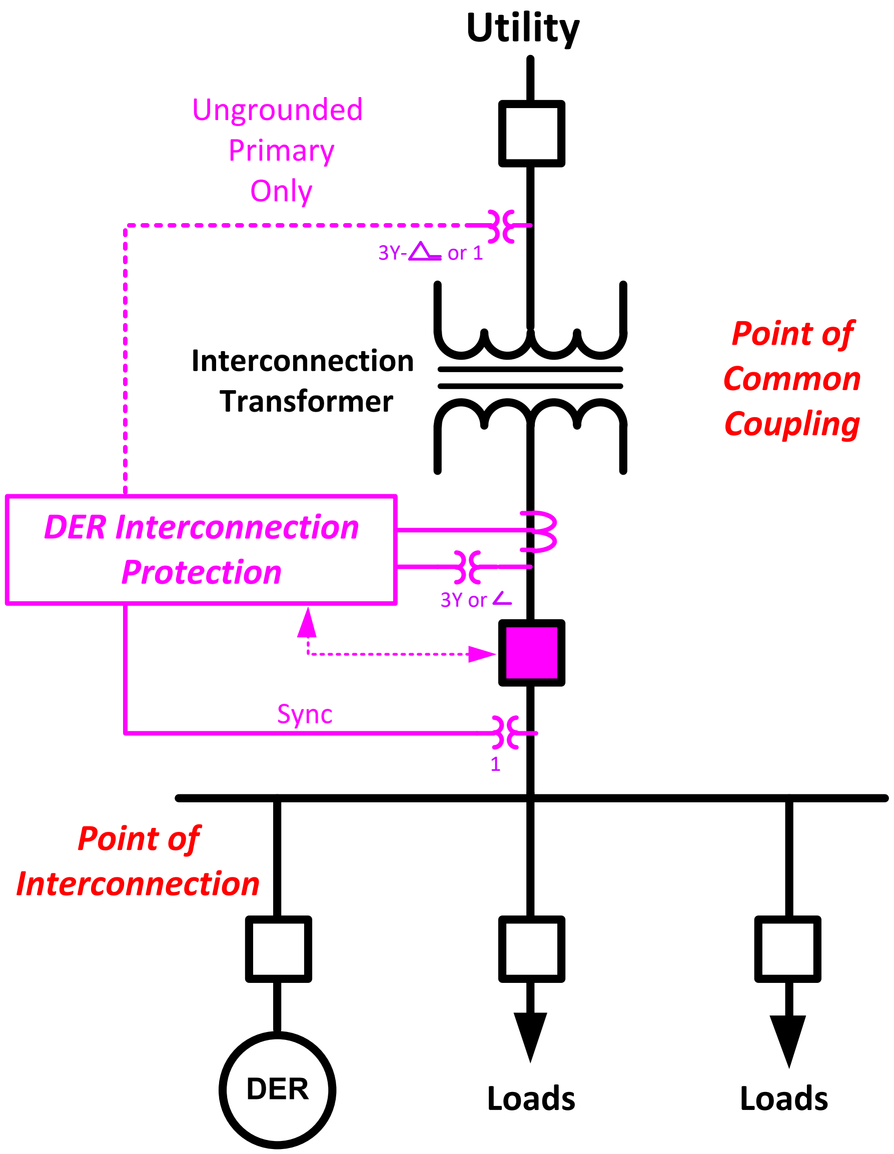
Interconnection Protection Placement



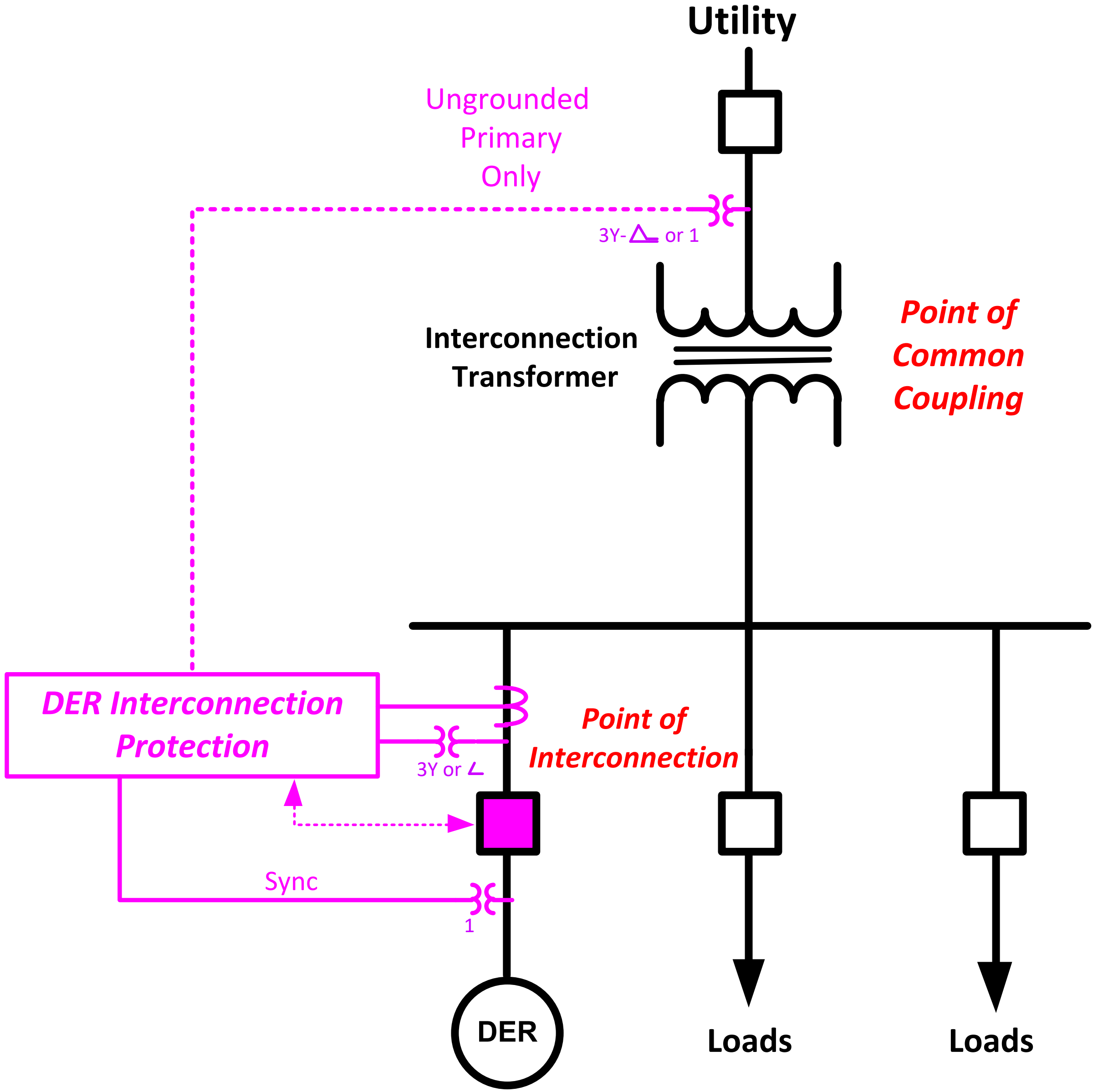
Interconnection Protection Placement



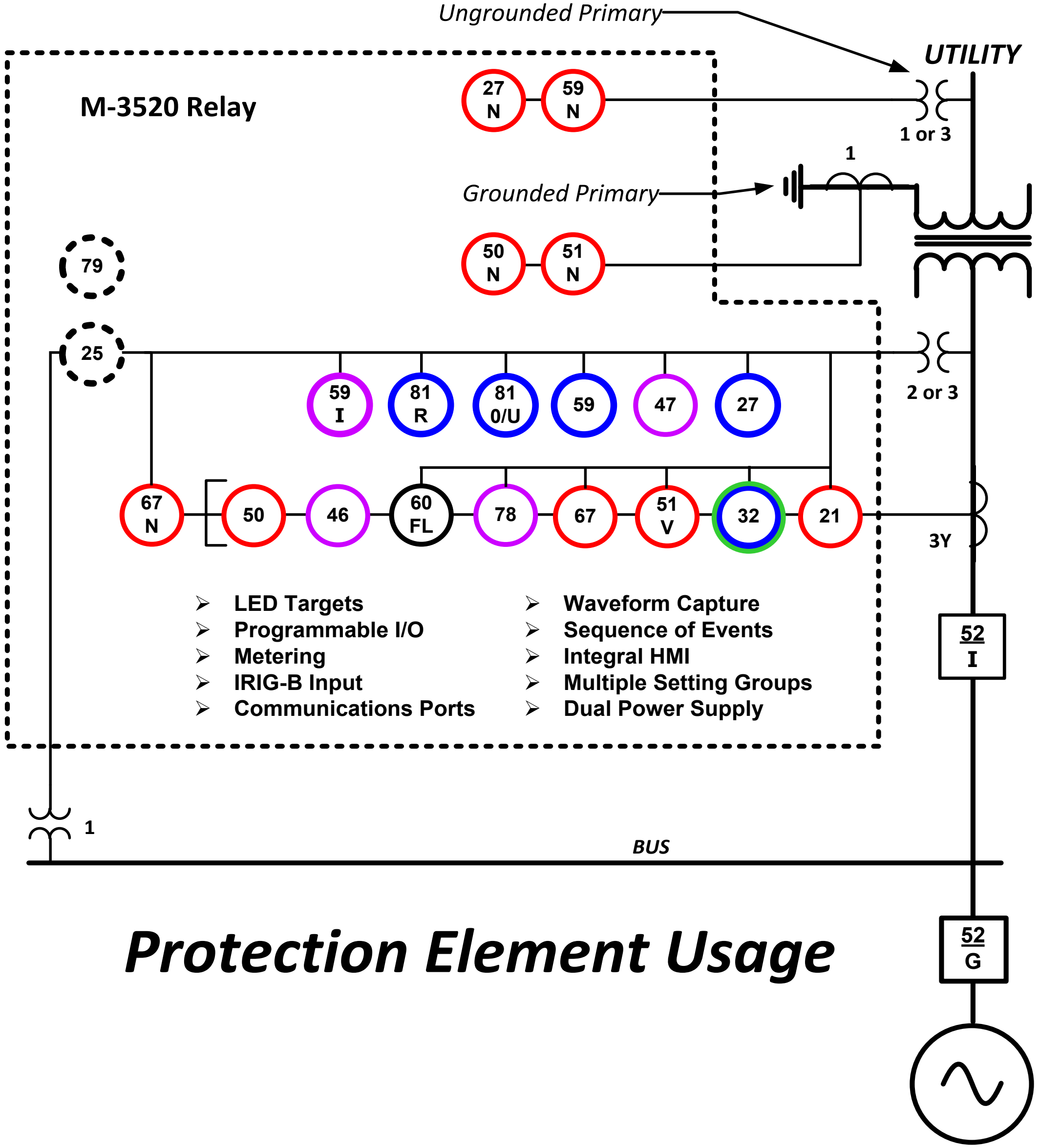
Interconnection Protection Placement



Interconnection Protection Placement



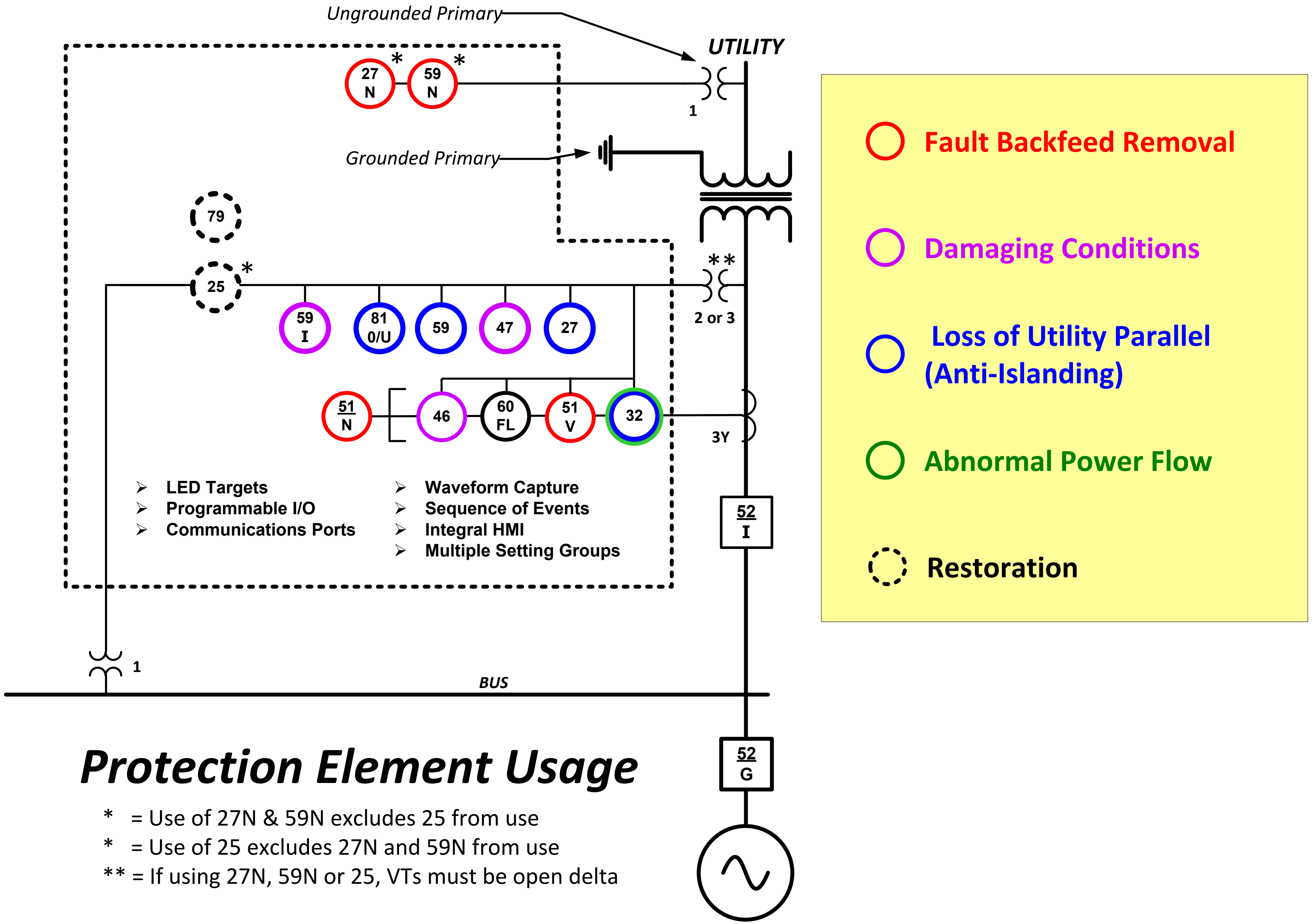
Comprehensive Protection Application



Protection Element Usage

- Fault Backfeed Removal
- Damaging Conditions
- Loss of Utility Parallel (Anti-Islanding)
- Abnormal Power Flow
- Restoration

Small DER or Inverter Protection Application



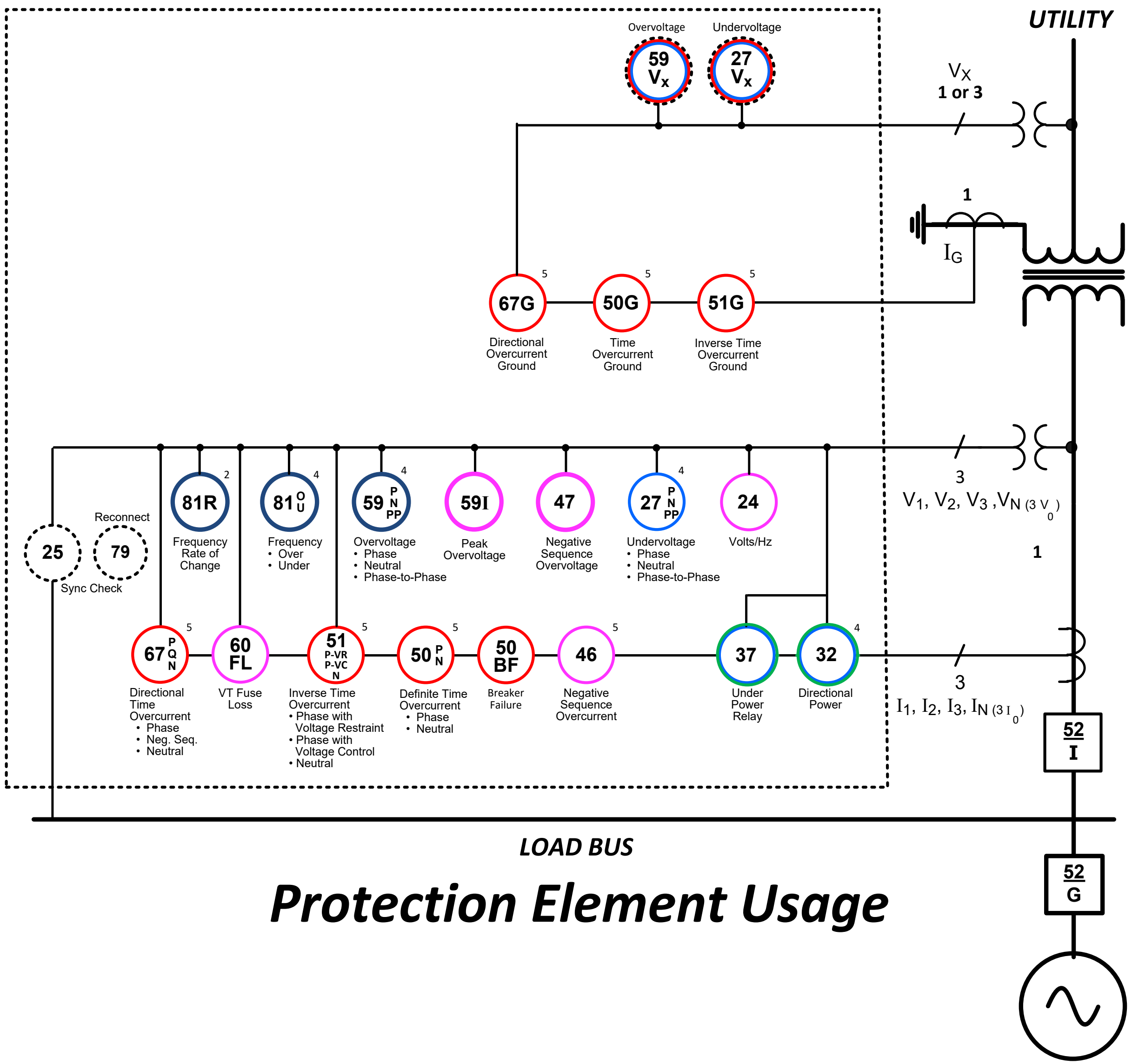
Protection Element Usage

* = Use of 27N & 59N excludes 25 from use

* = Use of 25 excludes 27N and 59N from use

** = If using 27N, 59N or 25, VTs must be open delta

Advanced Convergent Protection Application



Protection Element Usage

- Fault Backfeed Removal
- Damaging Conditions
- Loss of Utility Parallel (Anti-Islanding)
- Abnormal Power Flow
- Restoration

Convergent Attributes for Smart Grid

- Ethernet
  - 7 Concurrent Sessions
- Protocols
  - DNP 3.0
  - IEC 61850
- Cyber Security
  - NERC CIPS
  - FIPS
  - Radius
  - IEEE Complaint Passwords
- Extended Logging
  - Distributed Data Storage at PCC
- Power Quality Monitoring
  - 128 samples per cycle
  - Harmonics to the 63rd
  - THD, TDD
  - Sag/Swell/Flicker
- DME Oscillography Capture

DIFFICULT TO MAKE OTHER DEVICES A RELAY
POSSIBLE TO MAKE A RELAY PERFORM OTHER ROLES

Generator vs. Interconnection Protection

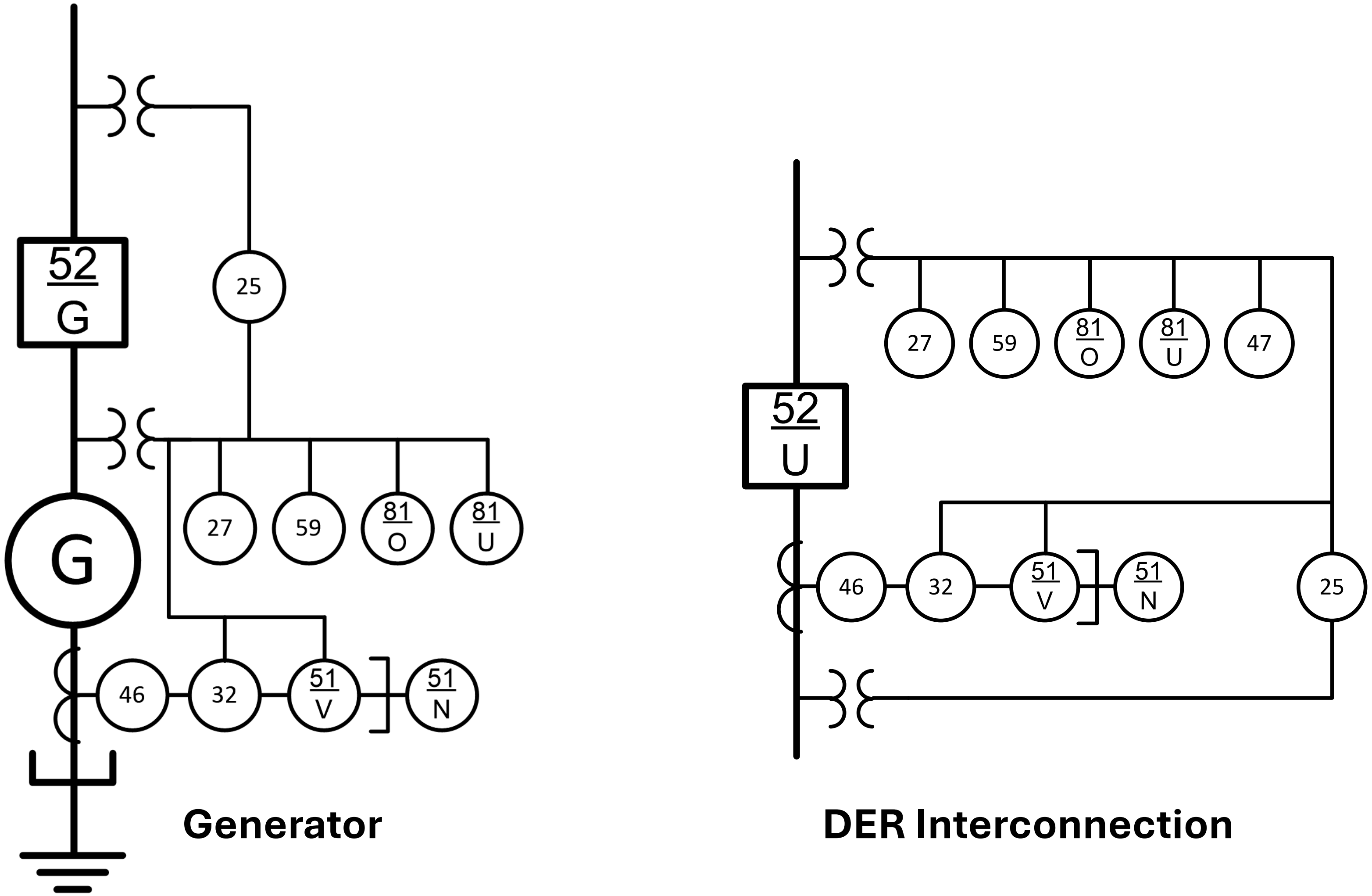
Generator

- Protect a Generator from
  - Internal Faults
  - Abnormal operating conditions
    - From generator support systems
    - From the grid
  - System faults and disturbances

Interconnection

- Protect utility personnel from feeders that should be deenergized
- Protect the utility and DER from
  - Abnormal operating conditions
  - Fault backfeed
  - Damaging distribution assets
- Protect other utility customers from poor power quality

Generator vs Interconnection Protection



Generator

DER Interconnection

Although using similar elements, it is **where they are sensing, how they are set and coordinated**, and **what they trip** that determines the service.

IEEE Distribution Practices Survey – 1/02

Interconnection Transformer

- 2002 Survey
  - Grounded wye primary – 58%
  - Delta primary – 9%
  - Other – 33%
- 1995 Survey
  - Grounded wye primary – 33%
  - Delta primary – 33%
  - Other – 33%

IEEE Distribution Practices Survey – 1/02

Impact on Utility Protection

- No effect – 22%
- Revised feeder coordination – 39%
- Added directional ground relays – 25%
- Added direction phase relays – 22%
- Added supervisory control – 22%
- Revised switching procedures – 19%

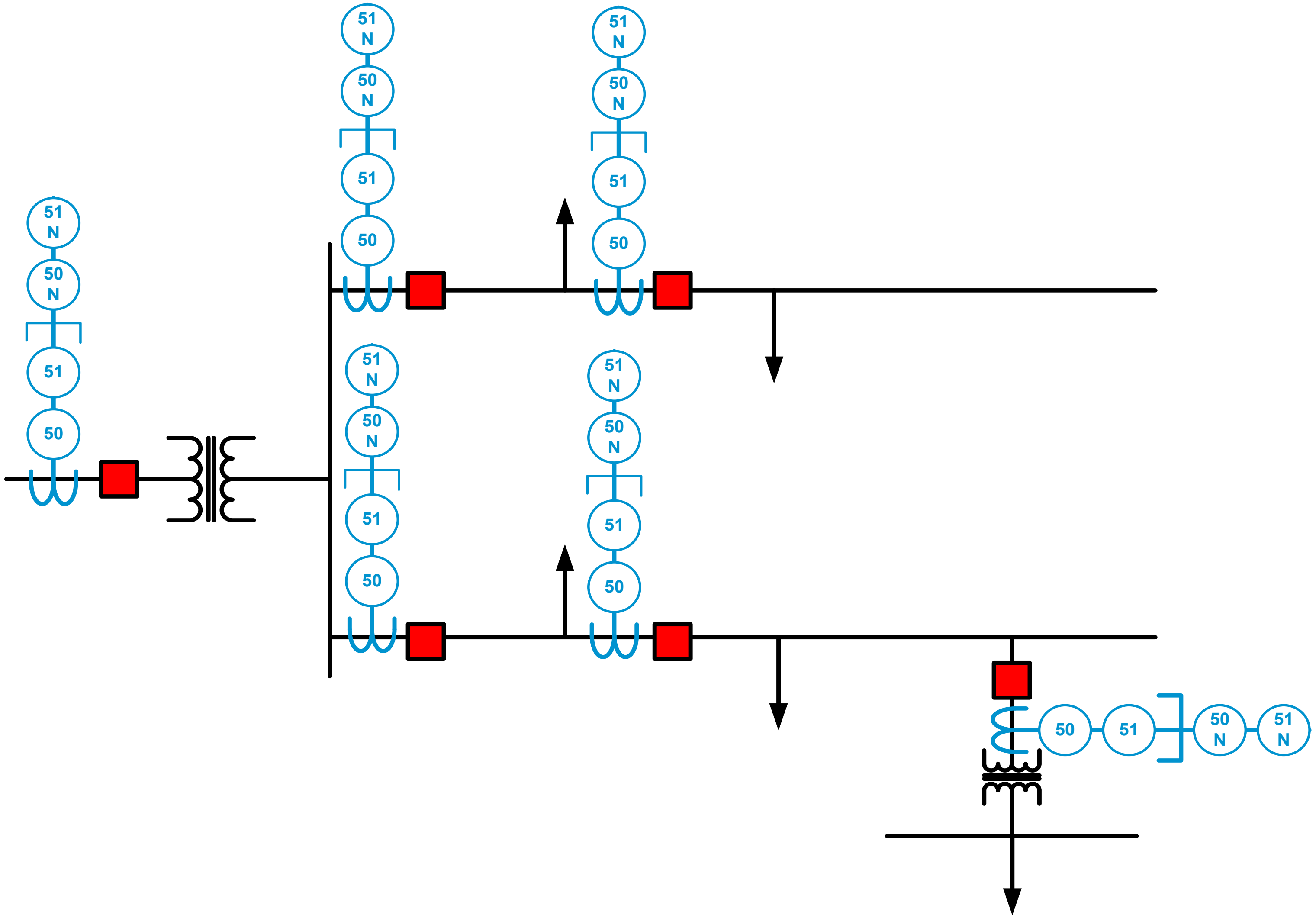
Bidirectional Fault Currents: Coordination

Impact on Utility Protection

- Use directional elements in substation protection, mid-line reclosers and DER
- Substation
  - Directionalize using 67 and 67N (instead of 50/51 and 50/51N)
  - Trip toward DER (downstream) to avoid sympathy trips for out-of-section faults
  - Trip toward Substation for remote breaker failure
- Reclosers
  - Directionalize using 67 and 67N (instead of 50/51 and 50/51N)
  - Trip toward Substation for remote breaker failure
- DER
  - Directionalize using 67 and 67N (instead of 50/51 and 50/51N)
  - Trip direction away from DER (upstream)

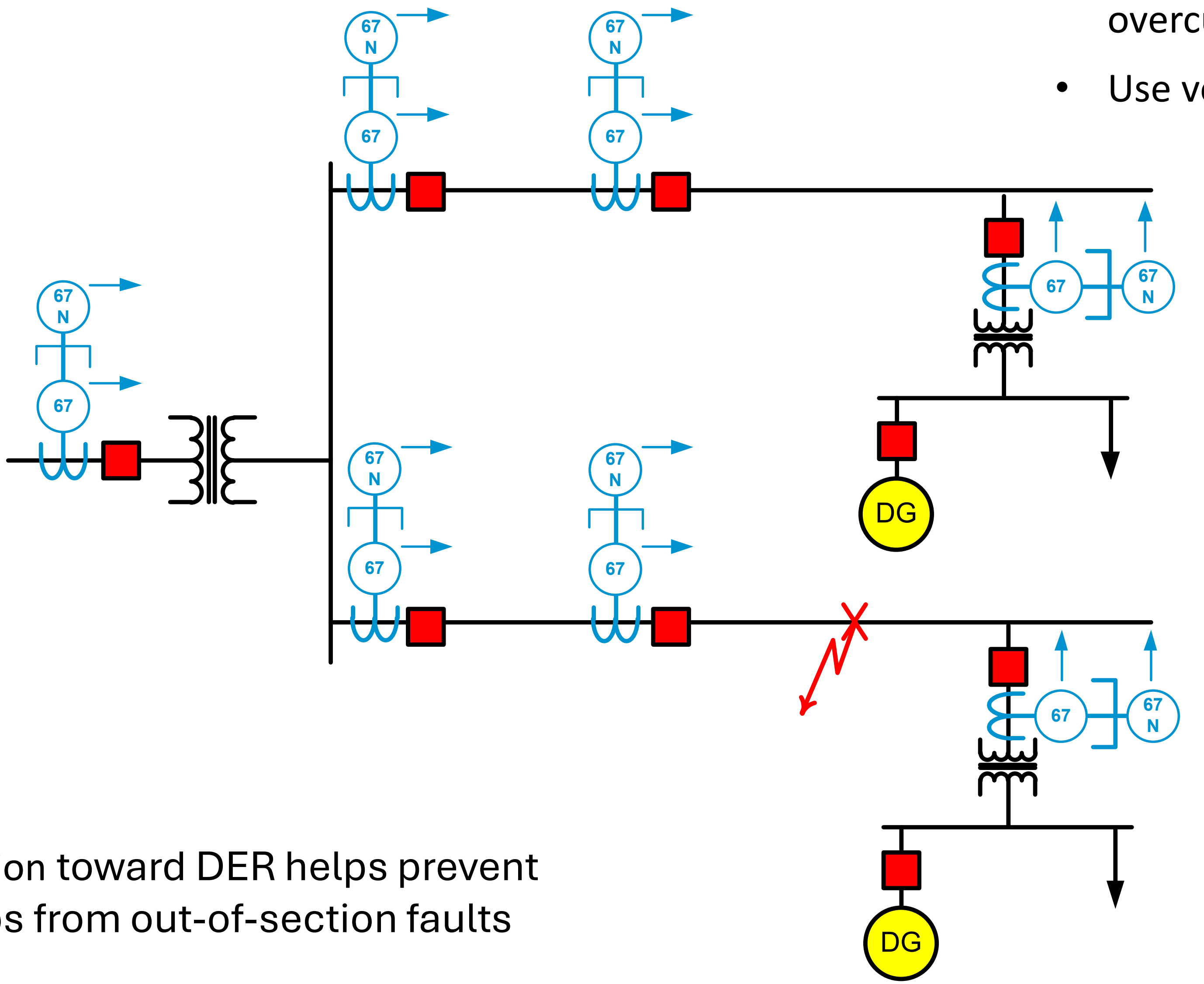
Radial Distribution

- Non-directional phase and ground overcurrent elements



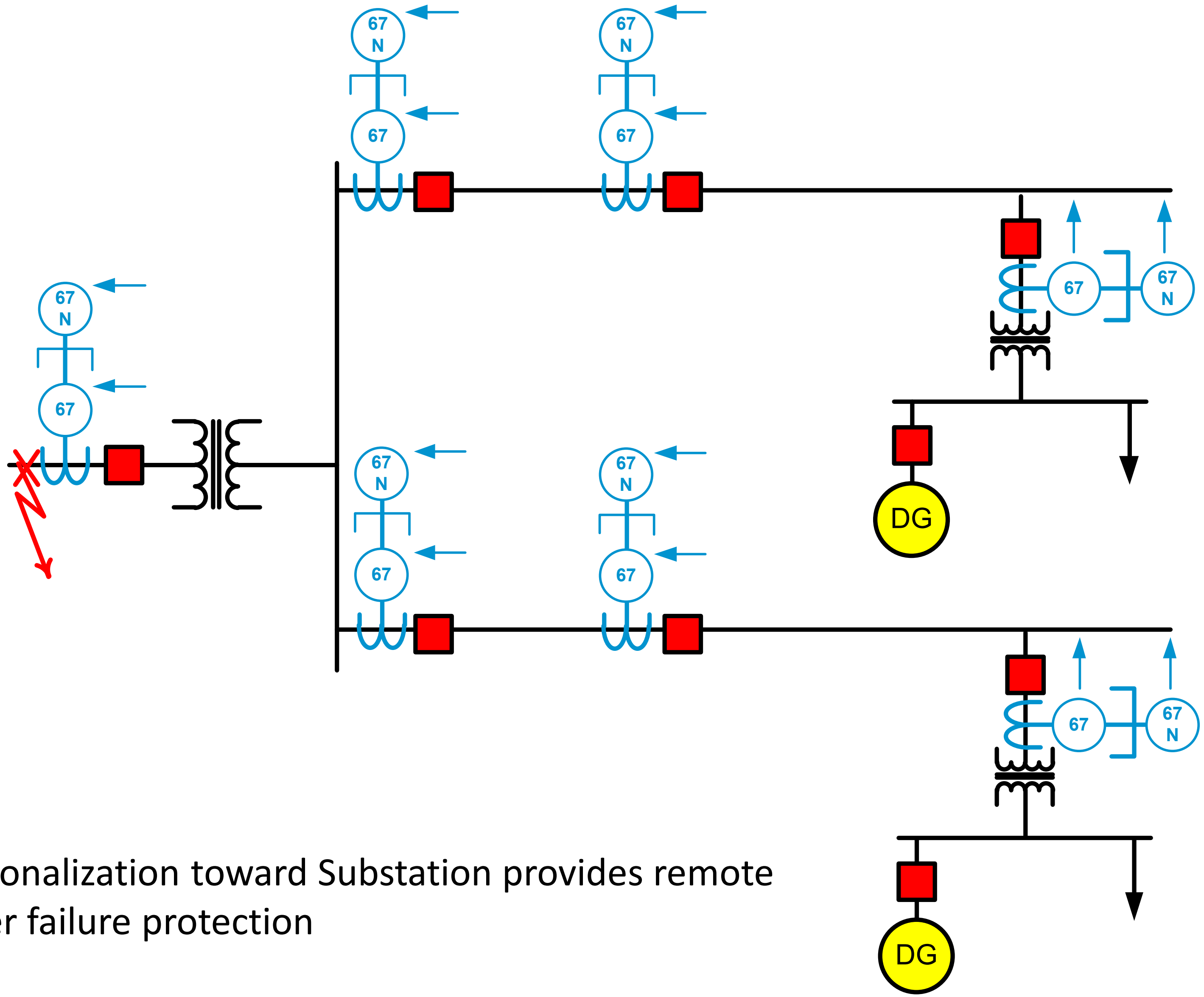
DER on System

- Directional phase and ground overcurrent elements
- Use voltage polarization



- Directionalization toward DER helps prevent sympathy trips from out-of-section faults

DER on System



- Directional phase and ground overcurrent elements
- Use voltage polarization
- All reverse looking elements trip slower than all forward looking elements

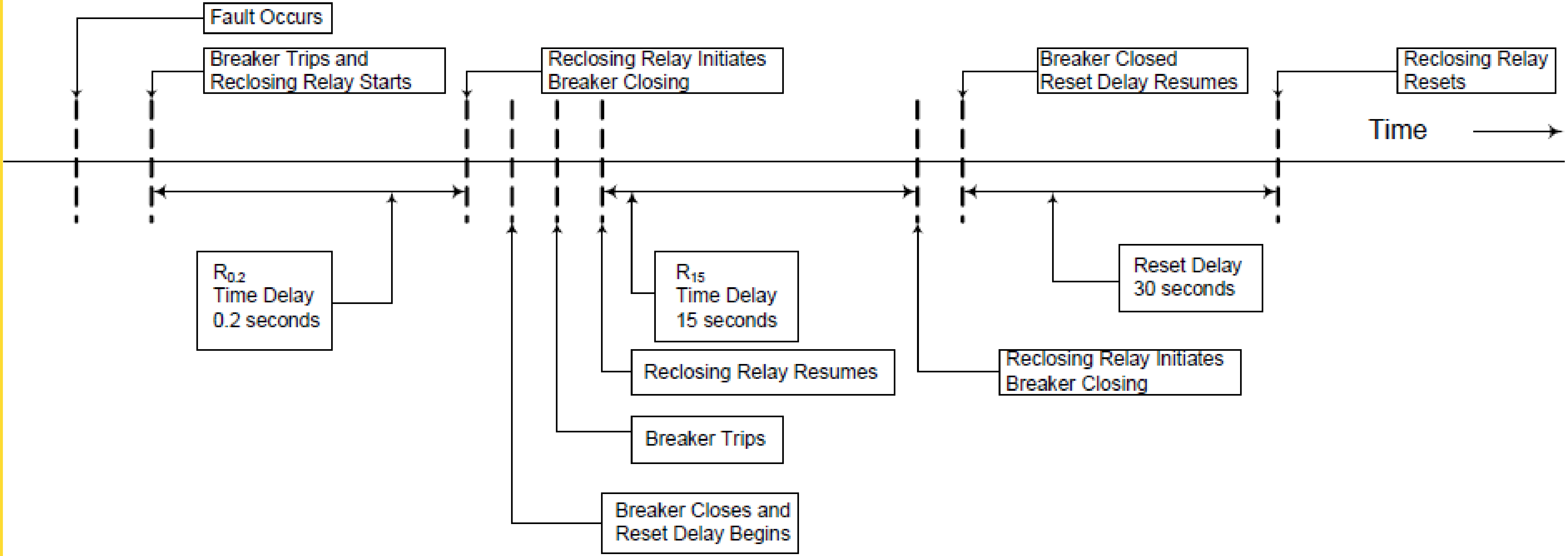
- Directionalization toward Substation provides remote breaker failure protection

IEEE Distribution Practices Survey – 1/02

DER Impact on Utility Reclosing

- Revise reclosing practices – 50%
- Added voltage relays to supervise reclosing – 36%
- Extend 1st shot reclose time – 26%
- Added transfer trip – 20%
- Eliminate reclosing – 14%
- Added sync check – 6%
- Reduce reclose attempts – 6%

Utility Reclosing Issues: It is All About Time…



- If high-speed reclosing is employed, the DER interconnection protection must be faster!
- Clearing time includes protection operation and breaker opening

Impact of IEEE 1547-2018

It’s all about “Ride-Through” and Reactive Support

IEEE 1547-2018

It's all about "Ride-Through" and Reactive Support

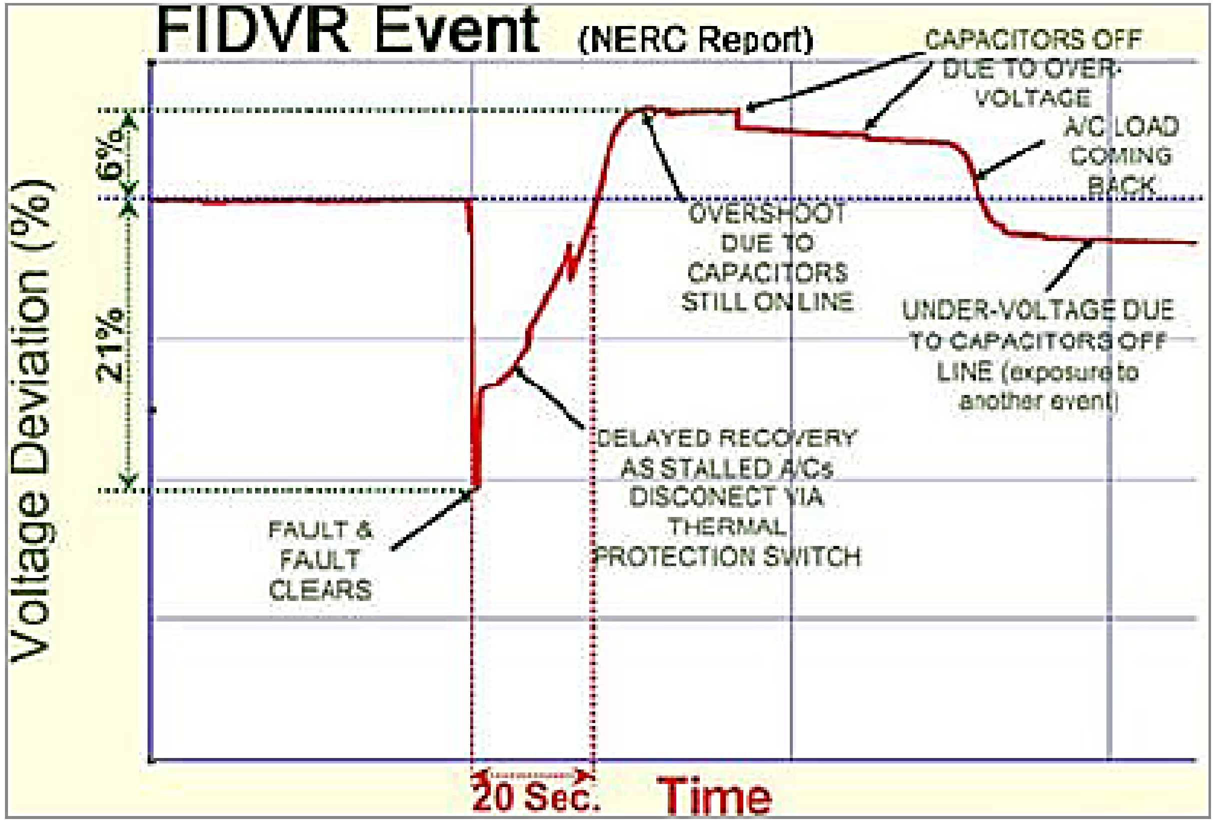
- As DER penetration increases, the ability to "ride-though" transient faults on adjacent feeders and transmission is becoming more important
- IEEE 1547 had to be modified:
  - **Voltage and frequency limits "loosened"** to allow fault "ride-through"
  - DER may actively control their **reactive** power output
- IEEE 1547 addresses ride-through by making it the utility's choice to allow or disallow it
- Off-nominal voltage and frequency limits may be greatly widened, offering ride-through capability
- Impact: Changes for protection setpoints for all types of DER

IEEE 1547-2018

- If large amounts of DER are easily “shaken off” for transient out-of-section faults, voltage and power flow upset can occur in:
  - Feeders
  - Substations
  - Transmission
- Fault ride-through capability makes the system more stable
- Distribution: Having large amounts of DER “shaken off” for transient events suddenly upsets load flow and attendant voltage drops.
  - Impacts include unnecessary LTC, regulator and capacitor control switching
  - If amount of DER shaken off is large enough, voltage limits may be violated
- Transmission: Having large amounts of DER “shaken off” for transient events may upset load flow into transmission impacting voltage, VAR flow and stability

FIDVR Event

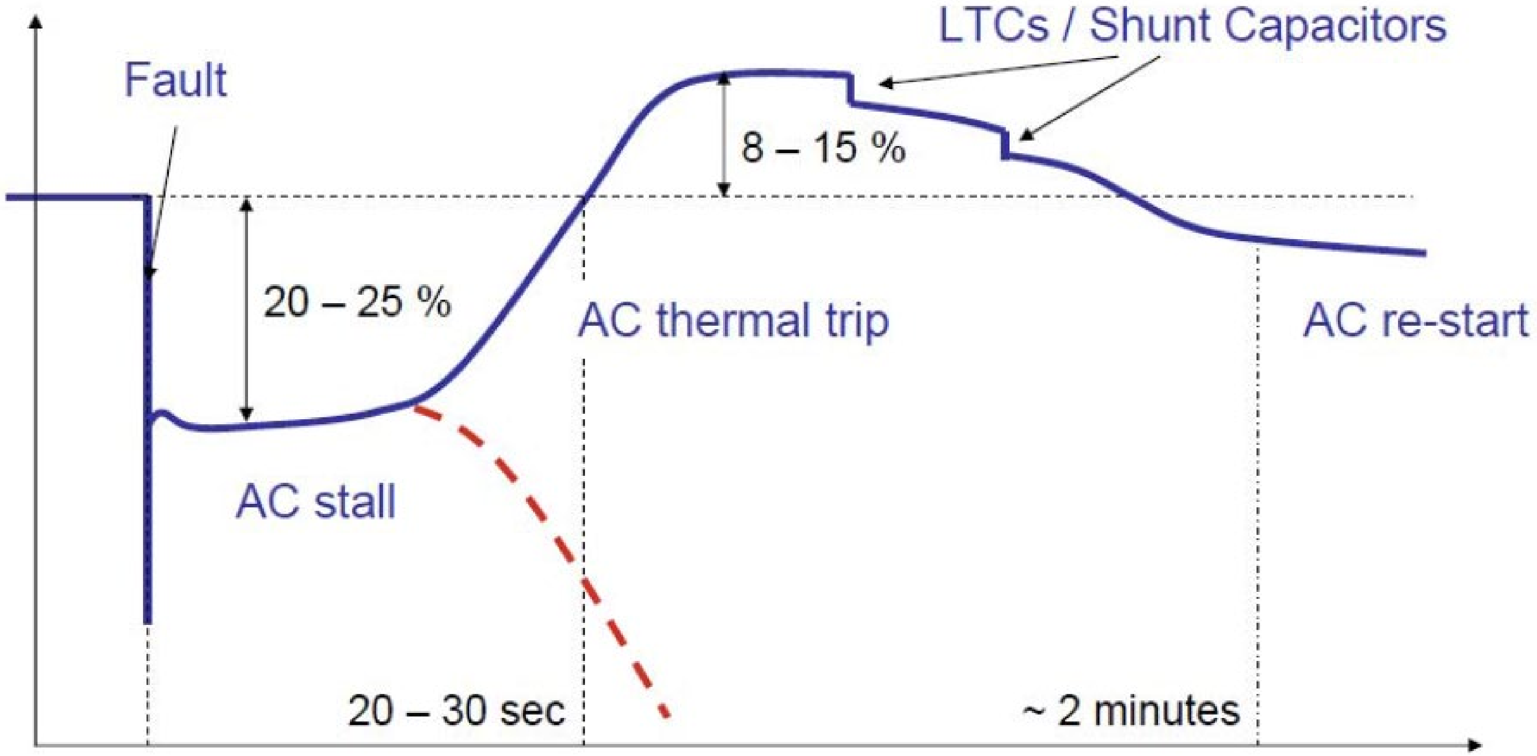
Fault Induced Delayed Voltage Recovery



- Power system event in which the voltage remains at low levels for several seconds after a transmission, sub-transmission, or distribution fault has been cleared
- FIDVR is caused by the stalling of induction motors driving constant torque loads

FIDVR Event

Fault Induced Delayed Voltage Recovery



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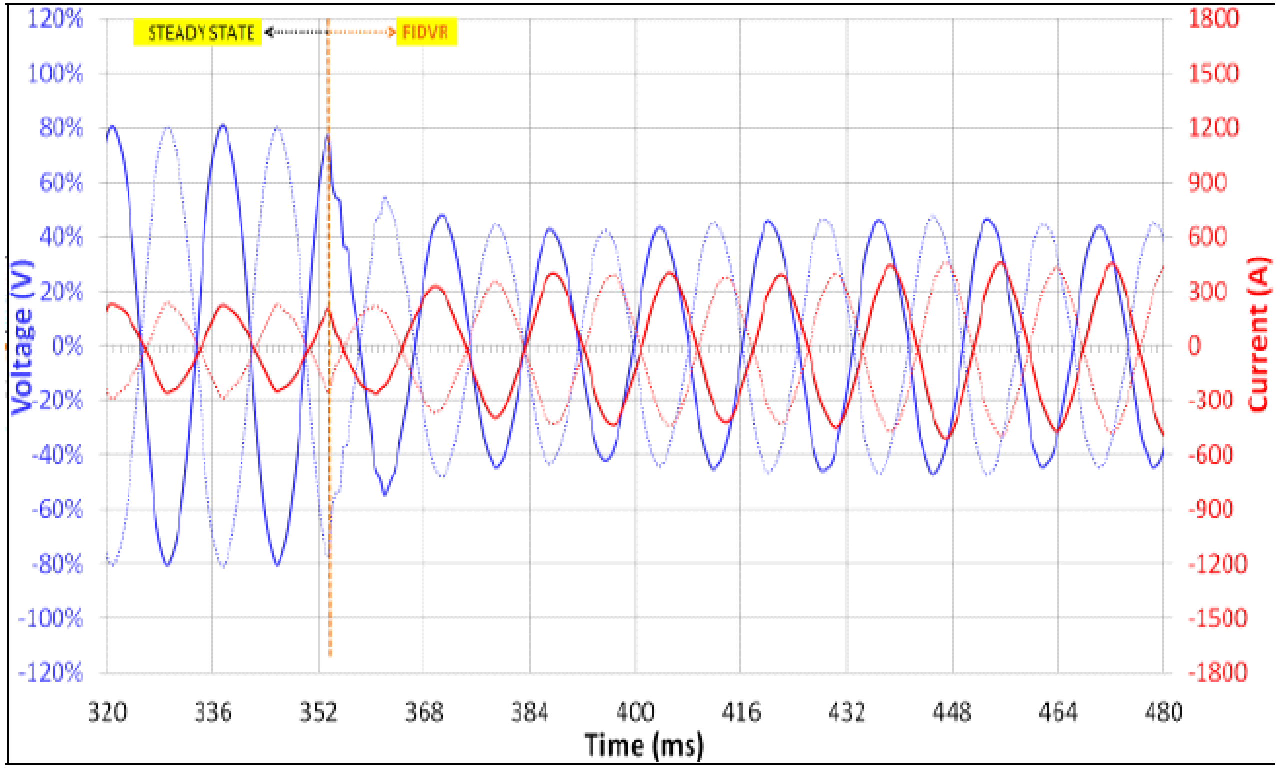
FIDVR Event

Fault Induced Delayed Voltage Recovery



- Power system event in which the voltage remains at low levels for several seconds after a transmission, sub-transmission, or distribution fault has been cleared
- FIDVR is caused by the stalling of induction motors driving constant torque loads

1547-2018: Active Voltage/VAR Control

- “On coordination with and approval of, the area EPS and DR operators, shall be required for the DR to **actively participate to regulate the voltage by changes of real and reactive power. “**

- The DR shall not cause the Area EPS service voltage at other Local EPSs to go outside the requirements of ANSI C84.1-2006 1 1995, Range A.

Old IEEE 1547 Trip values for Voltage (59, 27)

Voltage range (% of base voltage[a])	Clearing time(s)[b]
V< 50	0.16
50 ≤ V< 88	2.00
110 < V < 120	1.00
V ≥ 120	0.16

[a]Base voltages are the nominal system voltages stated in ANSI C84.1-1995, Table 1.

[b]DR ≤ 30 kW, maximum clearing times; DR > 30kW, default clearing times.

Old IEEE 1547 Trip values for Frequency (81-U, 81-O)

DR size	Frequency range (Hz)	Clearing time(s)[a]
≤ 30 kW	> 60.5	0.16
	< 59.3	0.16
> 30 kW	> 60.5	0.16
	< {59.8 – 57.0} (adjustable set point)	Adjustable 0.16 to 300
	< 57.0	0.16

[a]DR ≤ 30 kW, maximum clearing times; DR > 30 kW, default clearing times.

IEEE 1547-2018 Trip values for Frequency (81-O, 81-U)

Frequency range (Hz)	Operating mode	Minimum time (s) (design criteria)
$f > 62.0$	No ride-through requirements apply to this range	
$61.2 < f \leq 61.8$	Mandatory Operation[a]	299
$58.8 \leq f \leq 61.2$	Continuous Operation[a,b]	Infinite[c]
$57.0 \leq f < 58.8$	Mandatory Operation[b]	299
$f < 57.0$	No ride-through requirements apply to this range	

IEEE 1547-2018

Fault Ride-Through

- Categories I, II, III
  - Category I: based on essential bulk electric system (BES) stability/reliability needs and reasonably attainable by all DER technologies that are in common usage today
  - Category II: covers all BES stability/reliability needs and coordinated with existing reliability standards to avoid tripping for a wider range of faults
  - Category III: based on both BES stability/reliability and distribution system reliability/power quality needs and coordinated with existing interconnection requirements for very high DER penetration

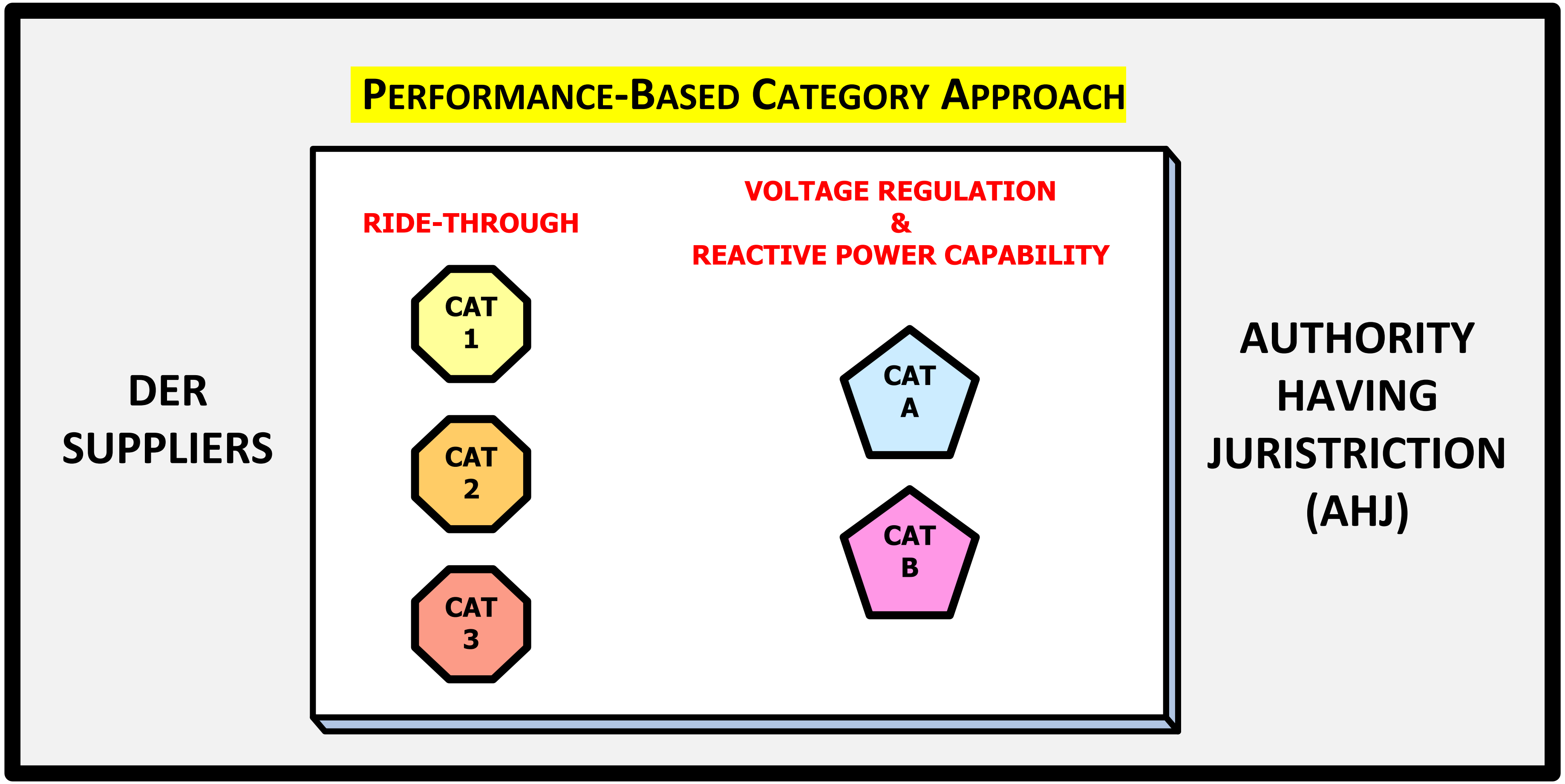
IEEE 1547-2018

- Voltage Regulation Performance
- Reactive Power Capability
  - Categories A, B
  - **Category A**
    - Covers minimum performance capabilities needed for Area EPS voltage regulation that are reasonably attainable by all state-of-the-art DER technologies
    - Performance is deemed adequate for applications where the DER penetration in the distribution system is lower, and where the DER power output is not subject to frequent large variations

IEEE 1547-2018

- Voltage Regulation Performance
- Reactive Power Capability
  - Categories A, B
  - **Category B**
    - Covers all requirements within Category A and specifies supplemental capabilities needed to adequately integrate the DER in local Area EPS, where the DER penetration is higher or where the DER power output is subject to frequent large variations.

IEEE 1547-2018



Recommended:

- Use CATS I and A together
- Use CATS II, III and B together

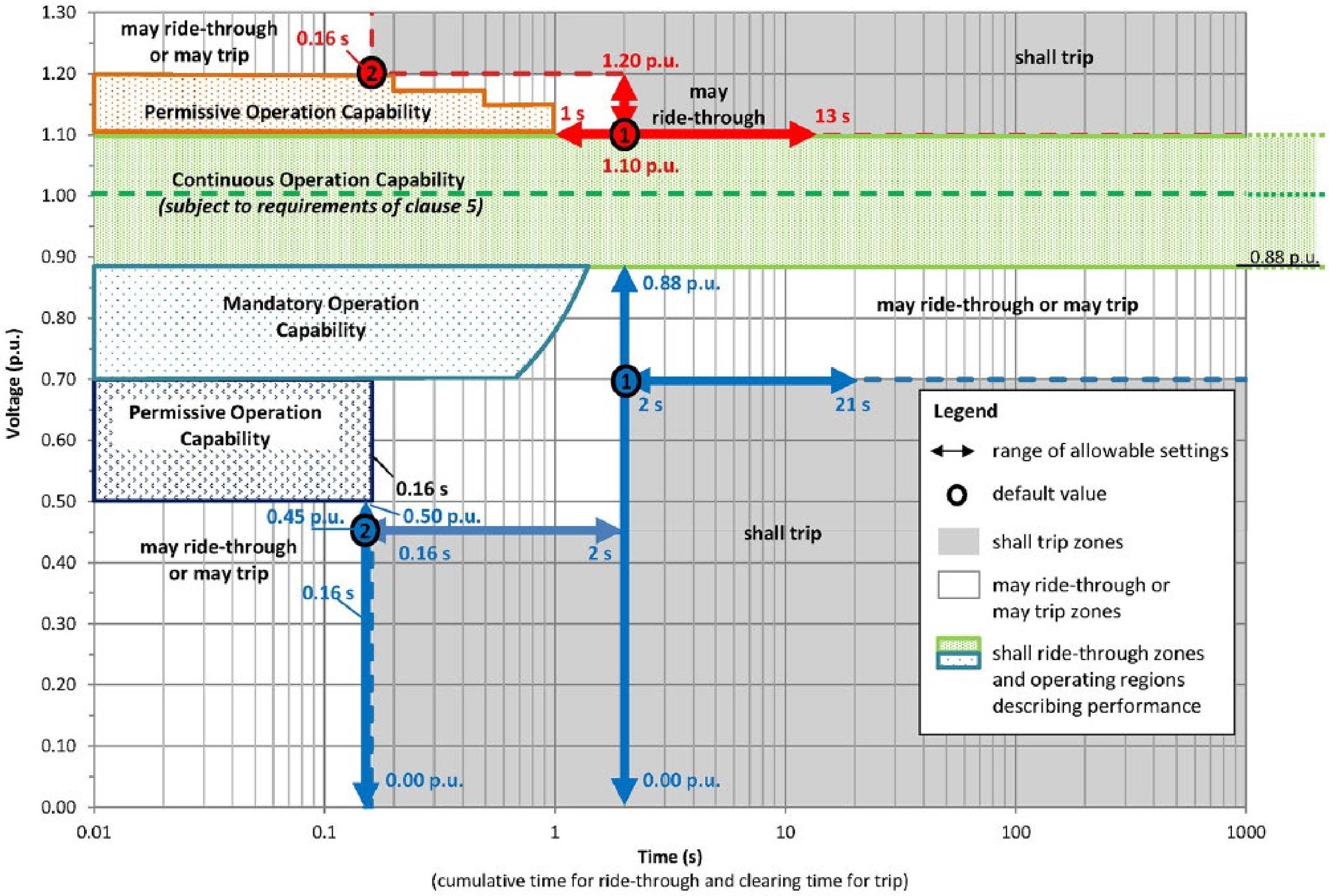
IEEE 1547-2018

Voltage Trip Limits: CAT I

Shall trip—Category I				
Shall trip function	Default settings[a]		Ranges of allowable settings[b]	
	Voltage (p.u. of nominal voltage)	Clearing time (s)	Voltage (p.u. of nominal voltage)	Clearing time (s)
OV2	1.20	0.16	fixed at 1.20	fixed at 0.16
OV1	1.10	2.0	1.10–1.20	1.0–13.0
UV1	0.70	2.0	0.0–0.88	2.0–21.0
UV2	0.45	0.16	0.0–0.50	0.16–2.0

IEEE 1547-2018

Voltage Trip Limits: CAT I



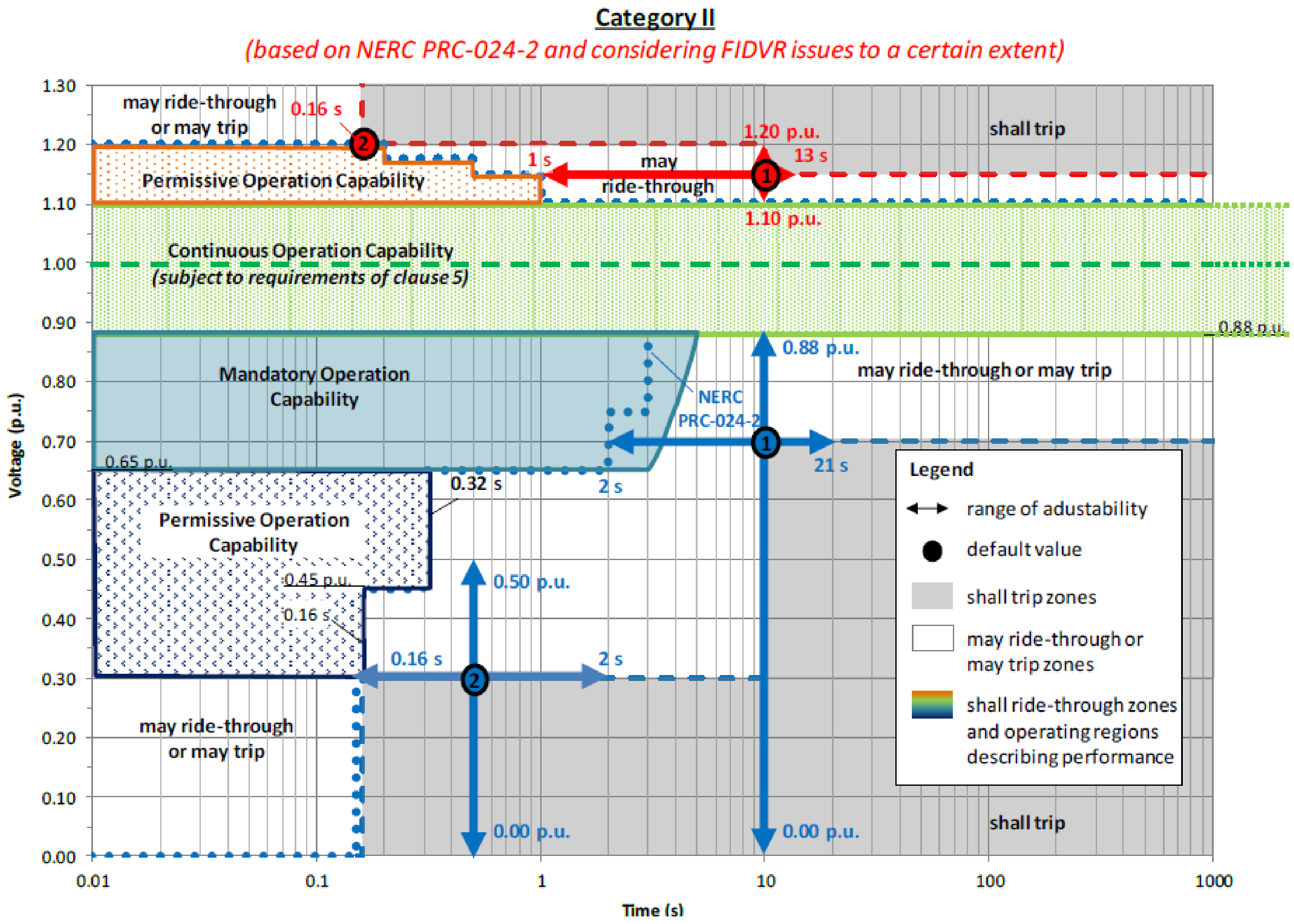
IEEE 1547-2018

Voltage Trip Limits: CAT II

Shall trip—Category II				
Shall trip function	Default settings[a]		Ranges of allowable settings[b]	
	Voltage (p.u. of nominal voltage)	Clearing time (s)	Voltage (p.u. of nominal voltage)	Clearing time (s)
OV2	1.20	0.16	fixed at 1.20	fixed at 0.16
OV1	1.10	2.0	1.10–1.20	1.0–13.0
UV1	0.70	10.0	0.0–0.88	2.0–21.0
UV2	0.45	0.16	0.0–0.50	0.16–2.0

IEEE 1547-2018

Voltage Trip Limits: CAT II



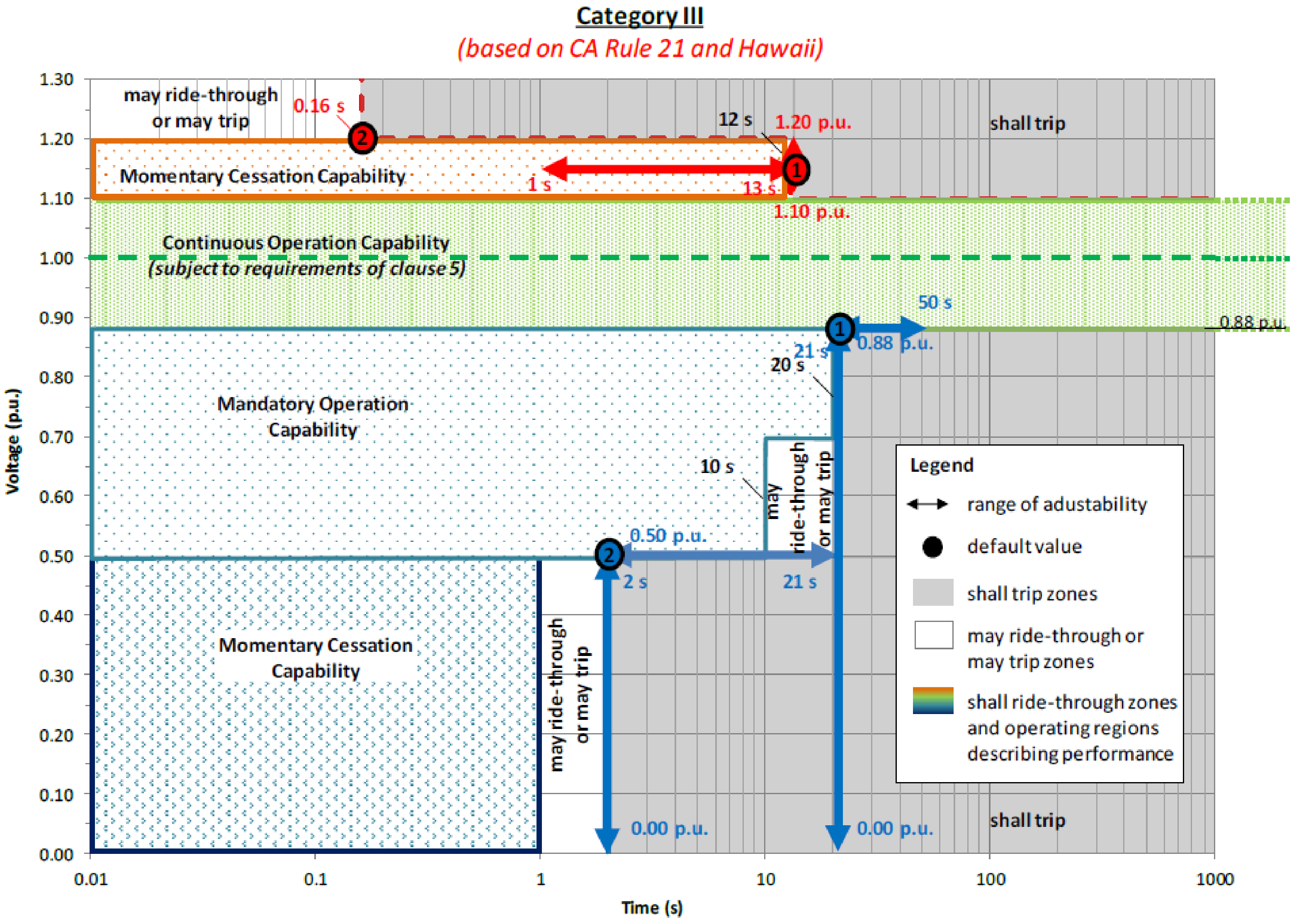
IEEE 1547-2018

Voltage Trip Limits: CAT III

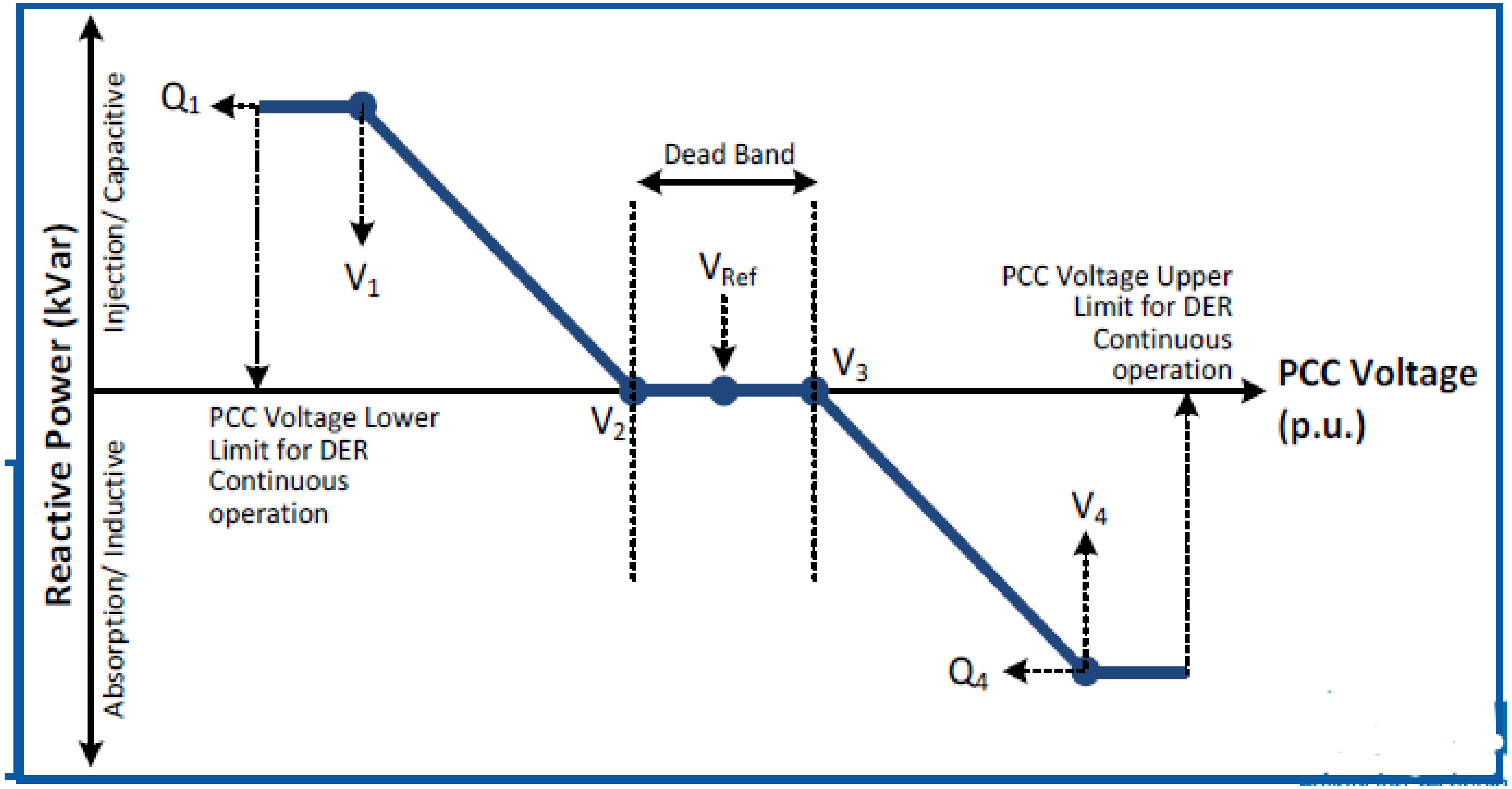
Shall trip—Category III				
Shall trip function	Default settings[a]		Ranges of allowable settings[b]	
	Voltage (p.u. of nominal voltage)	Clearing time (s)	Voltage (p.u. of nominal voltage)	Clearing time (s)
OV2	1.20	0.16	fixed at 1.20	fixed at 0.16
OV1	1.10	13.0	1.10–1.20	1.0–13.0
UV1	0.88	21.0	0.0–0.88	21.0–50.0
UV2	0.50	2.0	0.0–0.50	2.0–21.0

IEEE 1547-2018

Voltage Trip Limits: CAT III

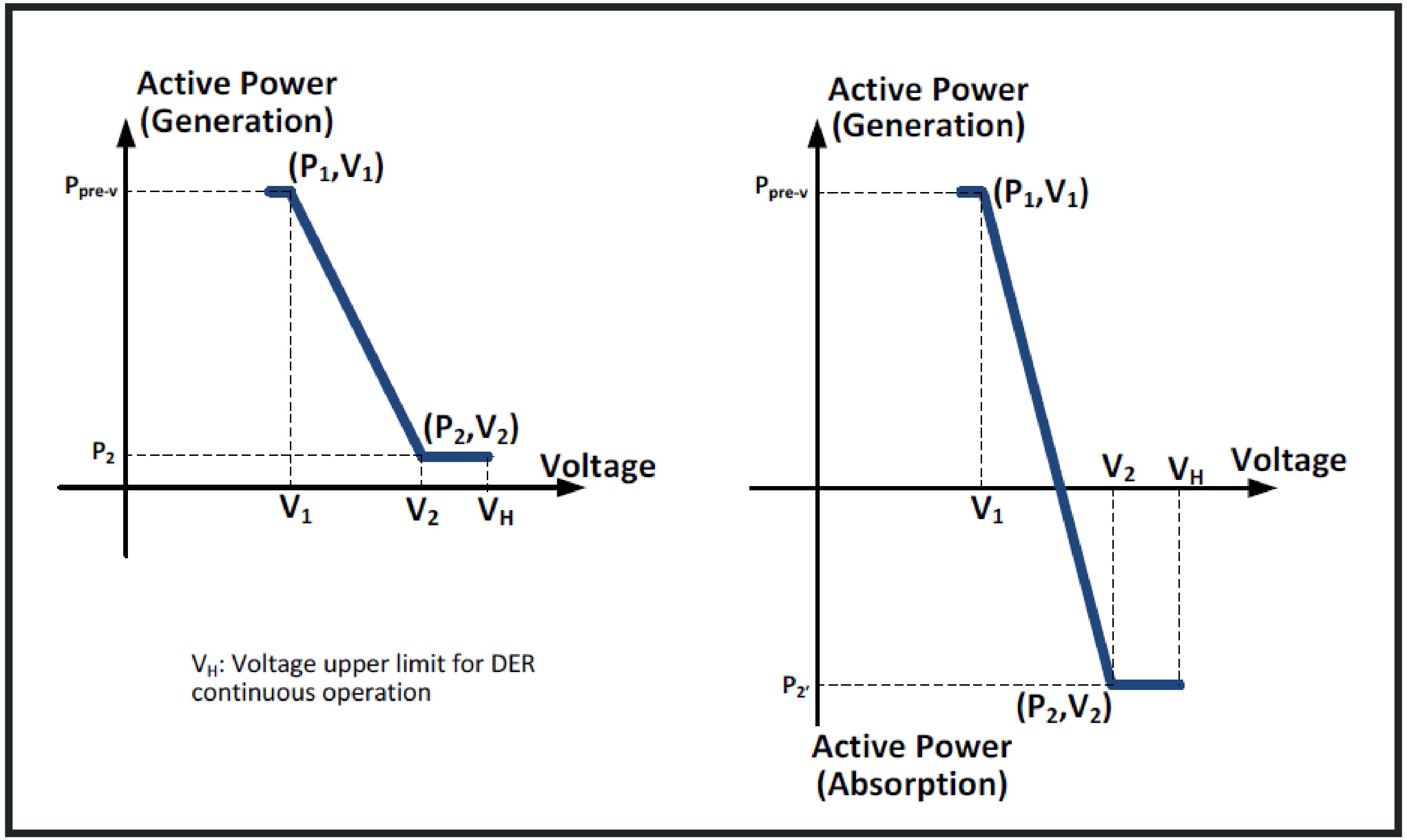


DER Actively Controlling VAR



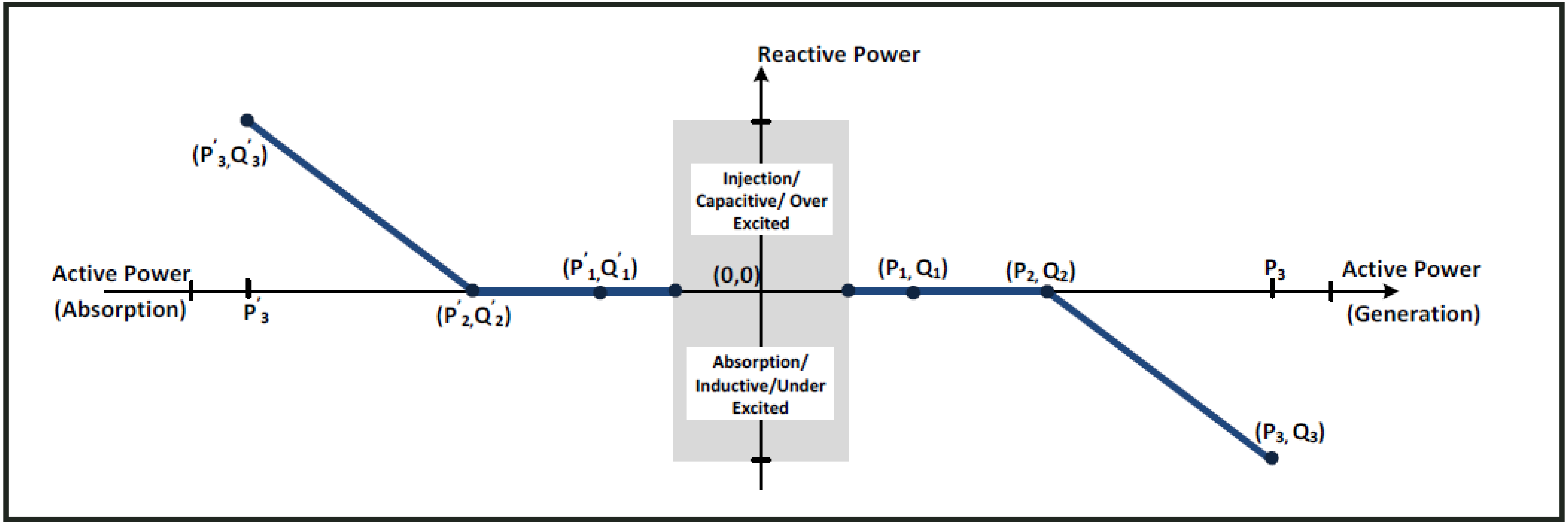
- Uses droop characteristic
- Based on voltage sensing at PCC or PI
- If inverter based, a “Smart” Inverter

DER Actively Controlling VAR: Volt-Watt (Volt Droop)



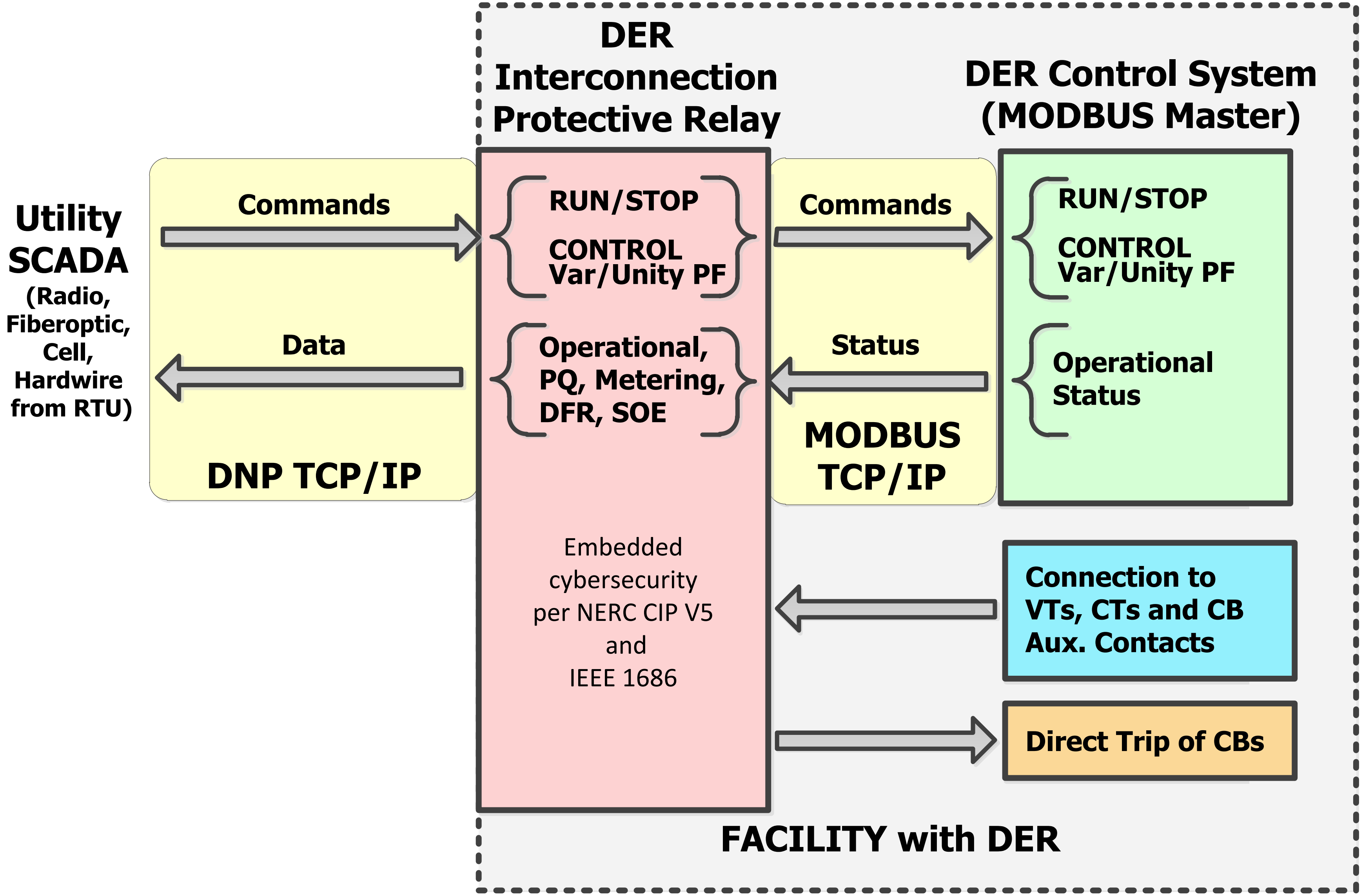
- Uses droop characteristic
- Based on **power and voltage sensing** at PCC
- If inverter based, a “Smart” Inverter

DER Actively Controlling VAR: Watt-VAr (Watt Droop)



- Uses droop characteristic
- Based on **power and voltage sensing** at PCC
- If inverter based, a "Smart" Inverter

DER Interconnection Relay as the Utility Interface Point



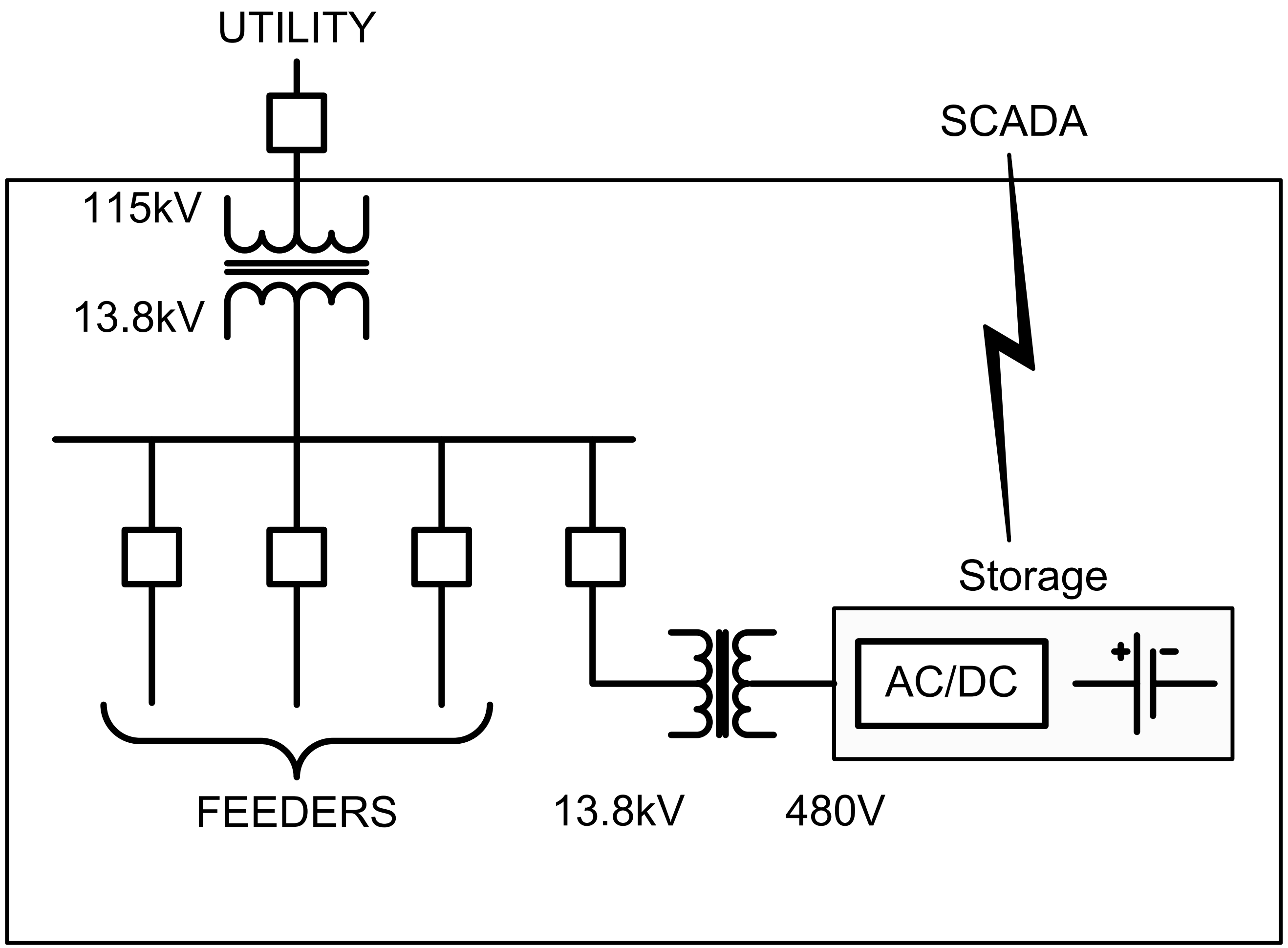
DER Variability: V/VAR Issues

Coping Methods for Fast DER Variability:

Using DMS and Controllable Assets

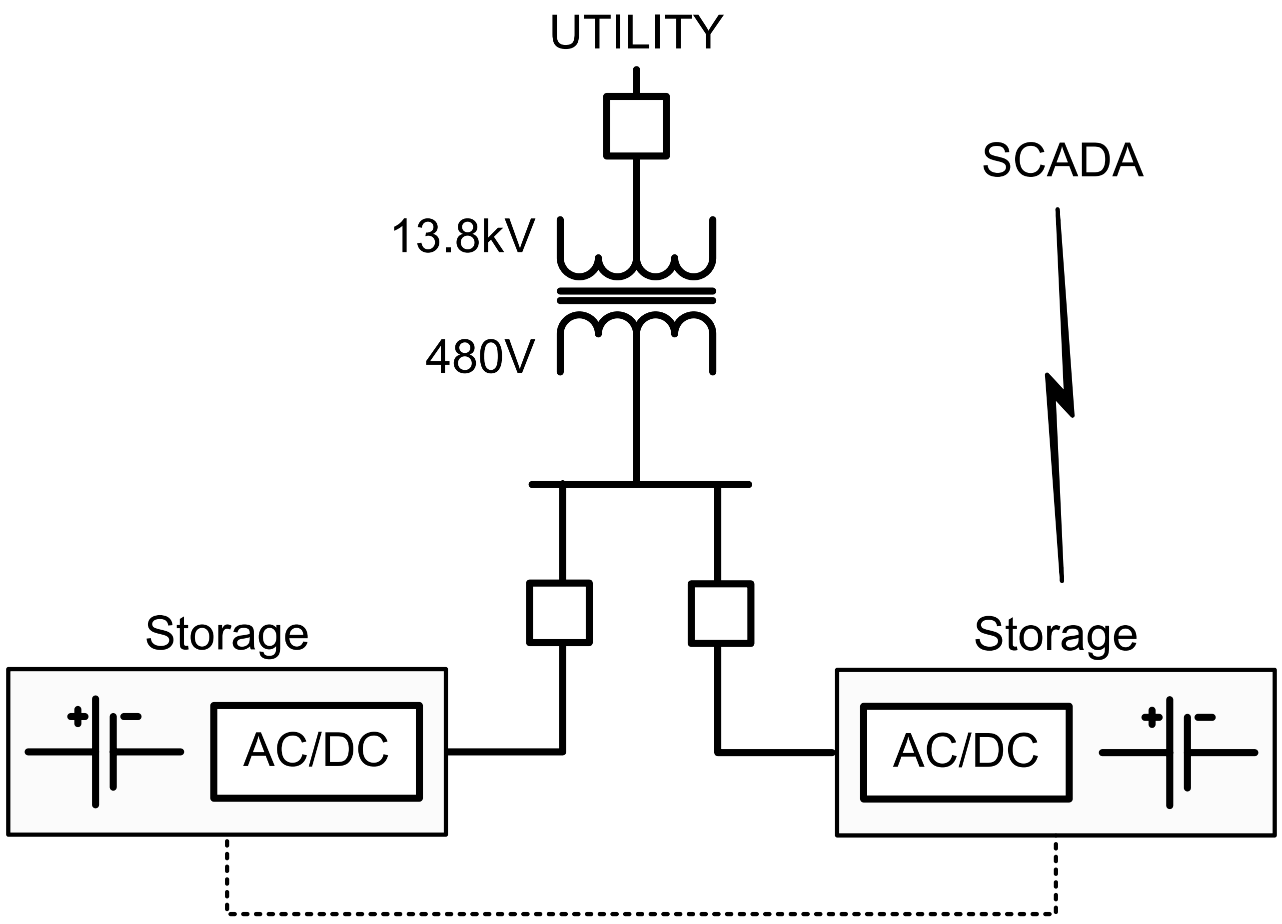
- "Ramp Rate" or "Capacity Fill" Dispatch
  - Conventional "fast start" distributed generation to supply real/reactive power
  - Distributed synchronous condensers to supply/sink reactive power
  - Storage/conversion to supply/sink real power
  - Storage/conversion to supply reactive power
- May be accomplished by DSM or local control from nearby large DER variable asset
  - Starting/Stopping
  - Direct setpoint control or initiating setting group changes

Storage Applications



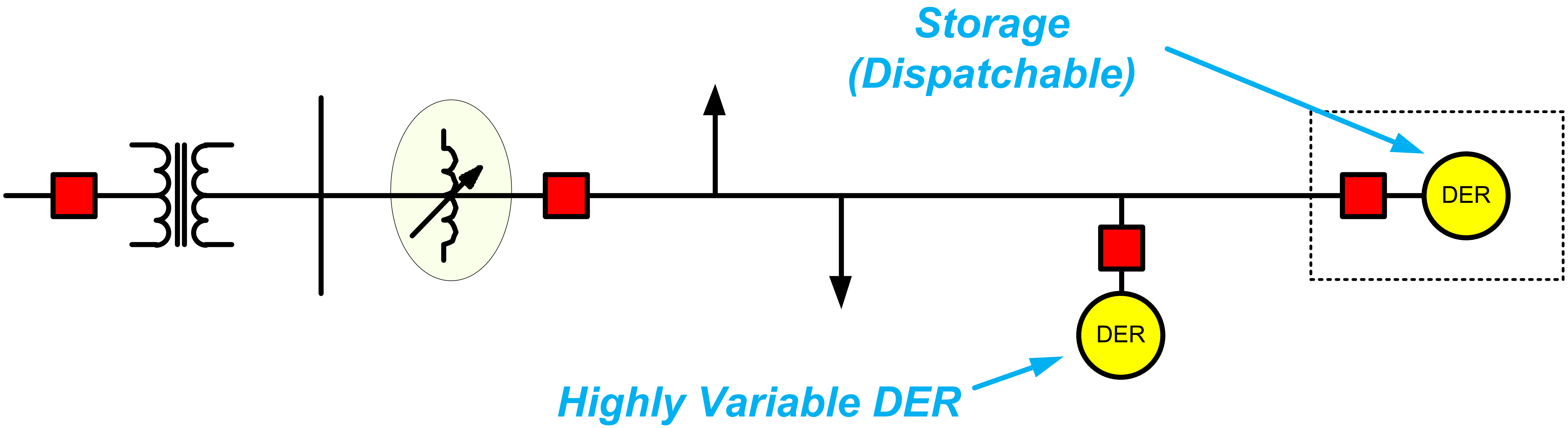
Utility Distribution Substation Storage for
Demand Response Use

Storage Modularity and Scalability



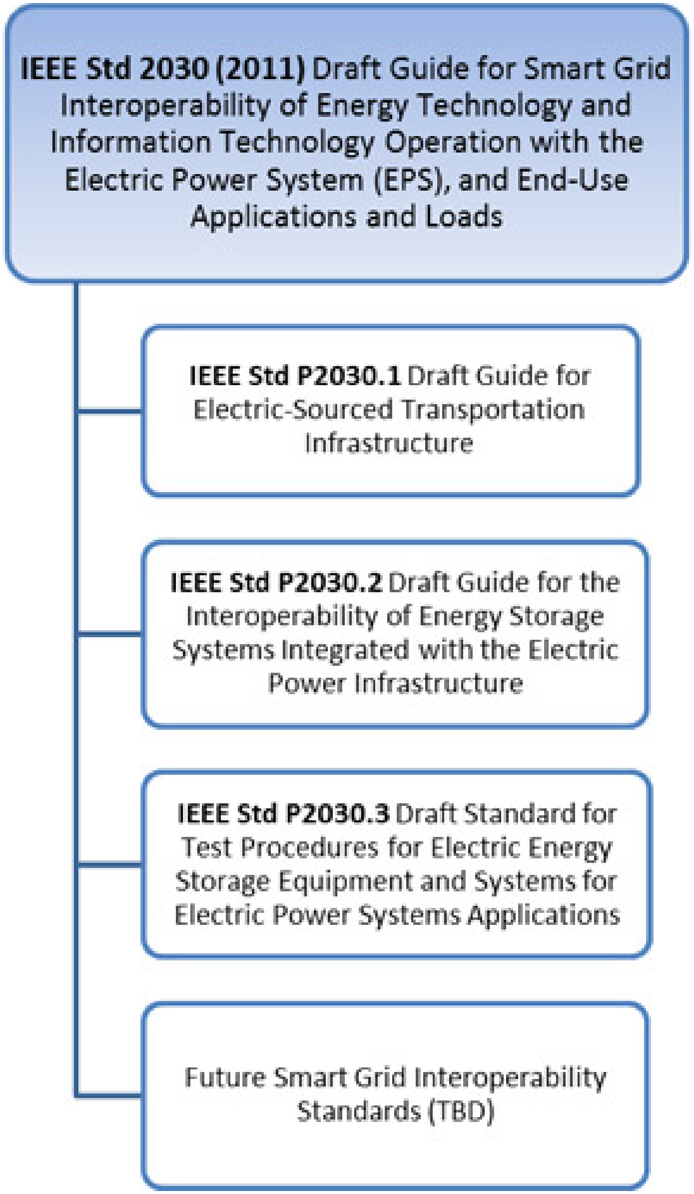
Build Capacity for Storage Demand and Duration

Storage Placement



Energy Storage Standard

- IEEE 2030.2
- Standards for Smart Grid and Storage



PCC Interface Applications THD and TDD Issues

Distribution System Loads

- Load types have changed
- Proliferation of Electronic Loads
  - Power Electronics
    - Variable Speed Drives
    - DER (Inverter Based)
  - Switching Power Supplies for Lighting and Other Loads
- Proliferation of Capacitors and Harmonic Filter Banks

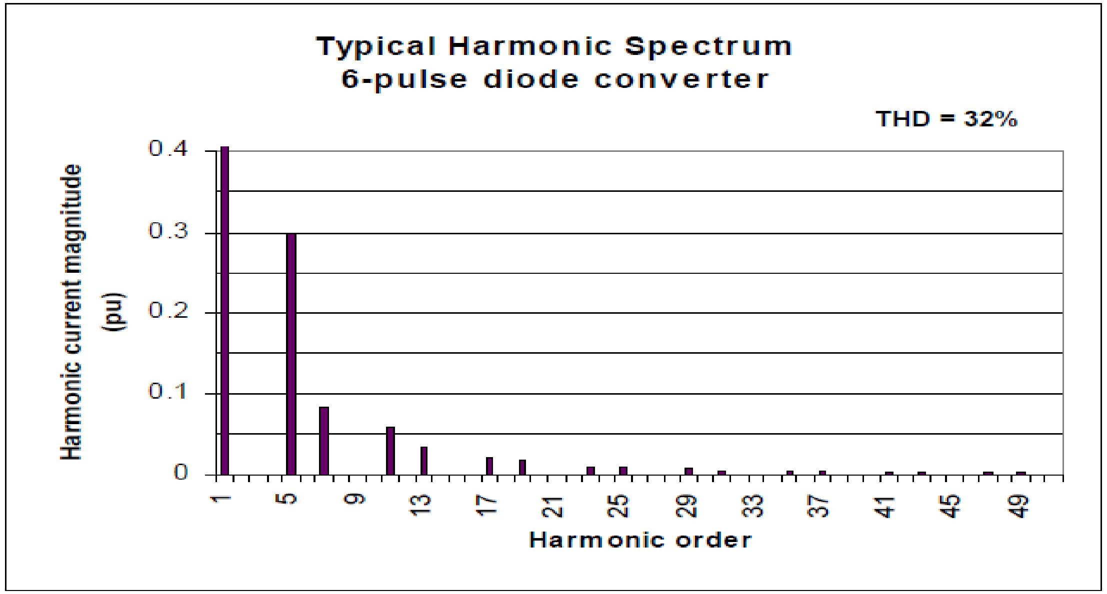
Rise in Harmonics

- Rise in Harmonics
- Harmonics can interfere with operation of sensitive loads
- Harmonics can overload transformers and conductors
- Harmonics can raise motor heating
- Resonance can sometimes develop between harmonic sources and capacitor/filter banks
- Harmonics are strongest at the source and decrease as they travel through system impedances
  - Strong sources absorb harmonics better than weak sources

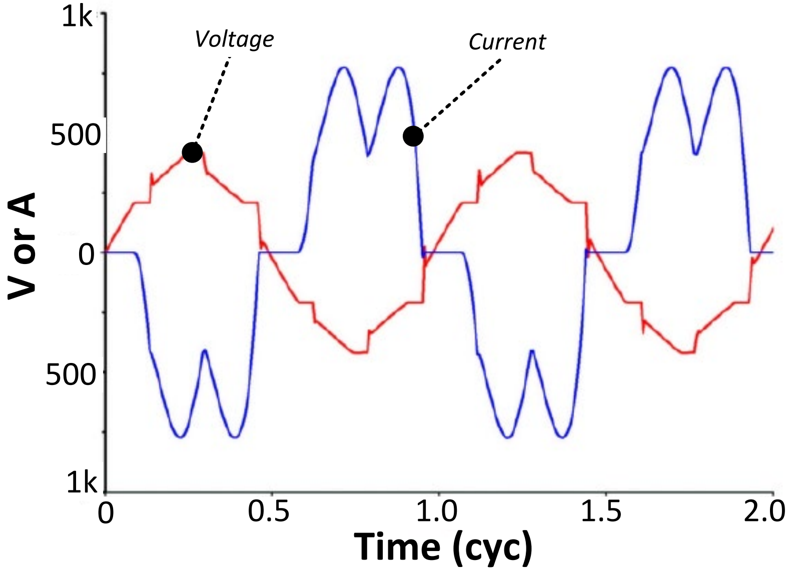
Inverter-Based DER and Harmonics

- Many inverter-based DER will produce higher percentage of harmonics at low output levels
  - Low output = energy source not at inverter maximum rating
- If the inverter-based DER is “making noise” with little real power output, alarm, trip or “cease-to-energize” the inverter
  - It is not making any watts to speak of anyway
  - Example: PV-based DER at early morning and evening

Recloser in PCC Interface Applications THD and TDD Issues



6 Pulse Converter
ASD Harmonic Order



Note: Current inverted to ease of viewing

6 Pulse Converter
ASD Harmonics

Credit: TMEIC
Medium Voltage Application School

Recloser in PCC Interface Applications THD and TDD Issues

Typical values of harmonic current (% of fundamental current) of different types of frontend configurations (% I_h / I_1)

Harmonic order (h)	5	7	11	13	17	19	23	25	THD_i
6-pulse without line reactor (Stiff source)	80.0%	58.0%	18.0%	10.0%	7.0%	6.0%	5.0%	2.5%	**101.5%**
6-pulse with 2-3% line reactor	40.0%	15.0%	5.0%	4.0%	4.0%	3.0%	2.0%	2.0%	**43.6%**
6-pulse with 5% line reactor	32.0%	9.0%	4.0%	3.0%	3.0%	2.0%	1.5%	1.0%	**33.9%**
6-pulse with line harmonic filter (LHF)	2.5%	2.5%	2.0%	2.0%	1.5%	1.0%	0.5%	0.5%	**4.9%**
12-pulse	3.7%	1.2%	6.9%	3.2%	0.3%	0.2%	1.4%	1.3%	**8.8%**
18-pulse	0.6%	0.8%	0.5%	0.4%	3.0%	2.2%	0.5%	0.3%	**3.9%**

Credit: Siemens Whitepaper
Harmonics in Power Systems; Causes, Effects and Control

Recloser in PCC Interface Applications THD and TDD Issues

IEEE has Guidelines for Harmonic Levels

- **IEEE 519**, Recommended Practice and Requirements for Harmonic Control in Electric Power Systems

Table 2—Current distortion limits for systems rated 120 V through 69 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a, b]						
I_{SC}/I_L	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	TDD
< 20[c]	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

[a]Even harmonics are limited to 25% of the odd harmonic limits above.

Credit: IEEE 519

Recloser in PCC Interface Applications THD and TDD Issues

IEEE has Guidelines for Harmonic Levels

- **IEEE 519**, Recommended Practice and Requirements for Harmonic Control in Electric Power Systems

Table 1—Voltage distortion limits

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \le 1.0$ kV	5.0	8.0
1 kV $< V \le 69$ kV	3.0	5.0
69 kV $< V \le 161$ kV	1.5	2.5
161 kV $< V$	1.0	1.5[a]

Credit: IEEE 519

Recloser in PCC Interface Applications THD and TDD Issues

IEEE has Guidelines for Harmonic Levels

- **IEEE 1547**, Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces

Table 26—Maximum odd harmonic current distortion in percent of rated current (I_{rated})[a]

Individual odd harmonic order h	$h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h < 50$[109]	Total rated current distortion (TRD)
Percent (%)	4.0	2.0	1.5	0.6	0.3	5.0

[a]I_{rated} = the DER unit rated current capacity (transformed to the RPA when a transformer exists between the DER unit and the RPA).

Table 27—Maximum even harmonic current distortion in percent of rated current (I_{rated})[a]

Individual even harmonic order h	$h = 2$	$h = 4$	$h = 6$	$8 \le h < 50$
Percent (%)	1.0	2.0	3.0	Associated range specified in Table 26

[a]I_{rated} = the DER unit rated current capacity (transformed to the RPA when a transformer exists between the DER unit and the RPA).

Credit: IEEE 1547

Harmonics

Table 3—Maximum odd harmonic current distortion in percent of rated current (I)a

Individual odd harmonic order h	h < 11	11≤ h < 17	17 ≤ h < 23	23 ≤ h < 35	35 ≤h	Total demand distortion up to the h=50 harmonic (TDD)
Percent (%)	4.0	2.0	1.5	0.6	0.3	5.0

Table 4—Maximum even harmonic current distortion in percent of rated current (I)a

Individual even harmonic order h	h=2	h=4	h=6	8≤h
Percent (%)	1.0	2.0	3.0	Associated range specified in Table 3

Source: 1547 D3.1, unapproved draft

- Single DER harmonic limits
- What about high penetration with different inverter firing methods?

Harmonic Concerns

- If high penetration of inverters causes great enough harmonics at system resonant point, currents flow to cap banks and cause hearting and possible damage
  - Inverters are the source
  - Caps are the sink
- A good defense is a good defense
  - Employ DER protection and CAPC with harmonic monitoring, alarming and tripping

Harmonic Monitoring, Alarming and Tripping

- DER Protection should monitor, log, alarm and trip for:
  - THD, voltage or current
  - TDD, current
    - TDD is called out in IEEE-1547
- CAP Control should monitor, log, alarm and trip for:
  - THD, voltage

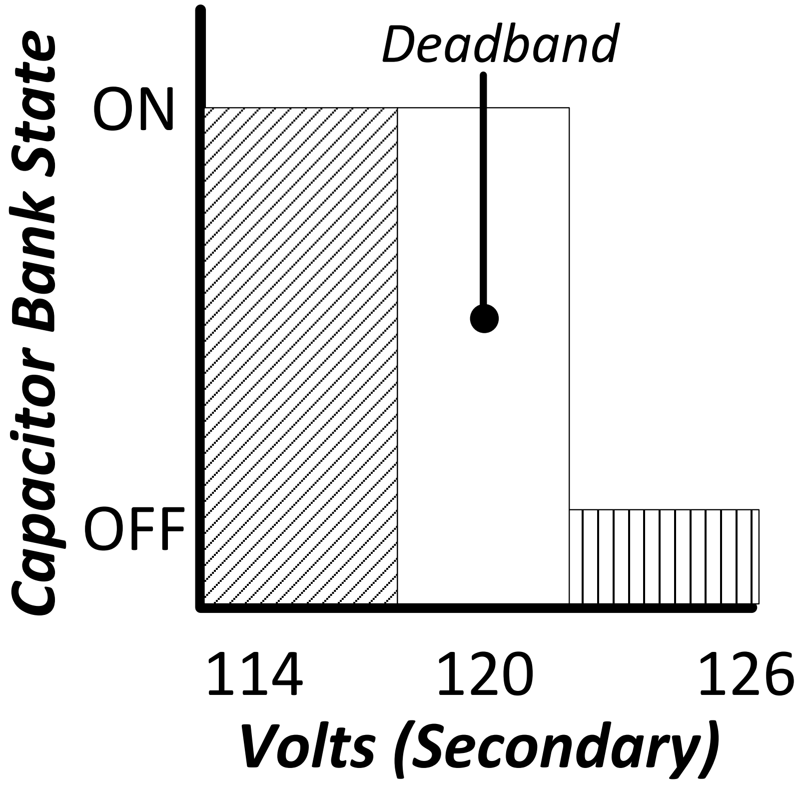
Improved Volt/VAR Coordination between CAPCs and REGCs/LTCCs

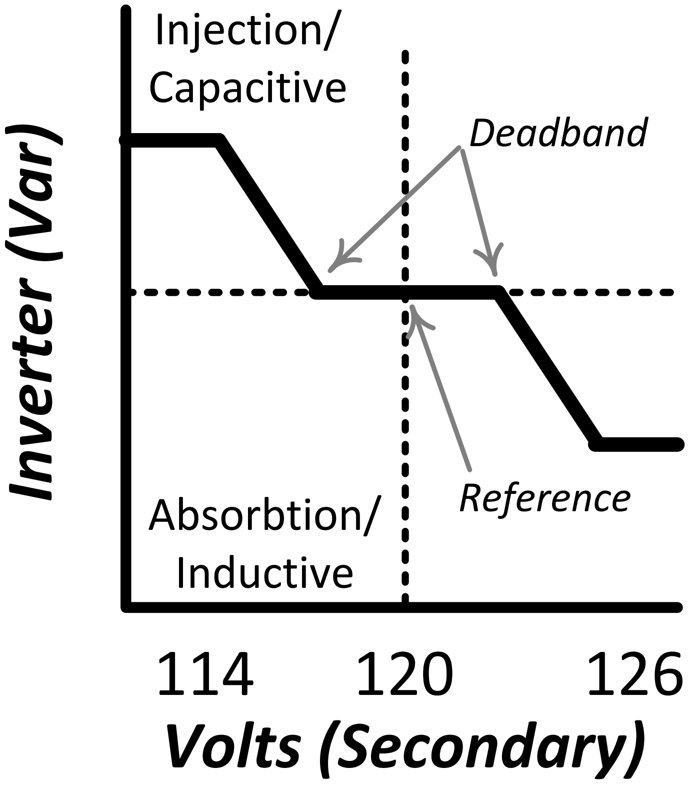
- REGCs and/or LTCCs:
  - Typically use LDC or LDZ
  - No direct feedback mechanism using LDC/LDZ for PF or VAR control
- Voltage-control based CAPCs:
  - VAR measurement not available
  - Switch on voltage
    - Less expensive than VAR control and sensors
    - May be used at end of line

How do we coordinate to obtain optimum VVO/IVVC?

CAPs and DER

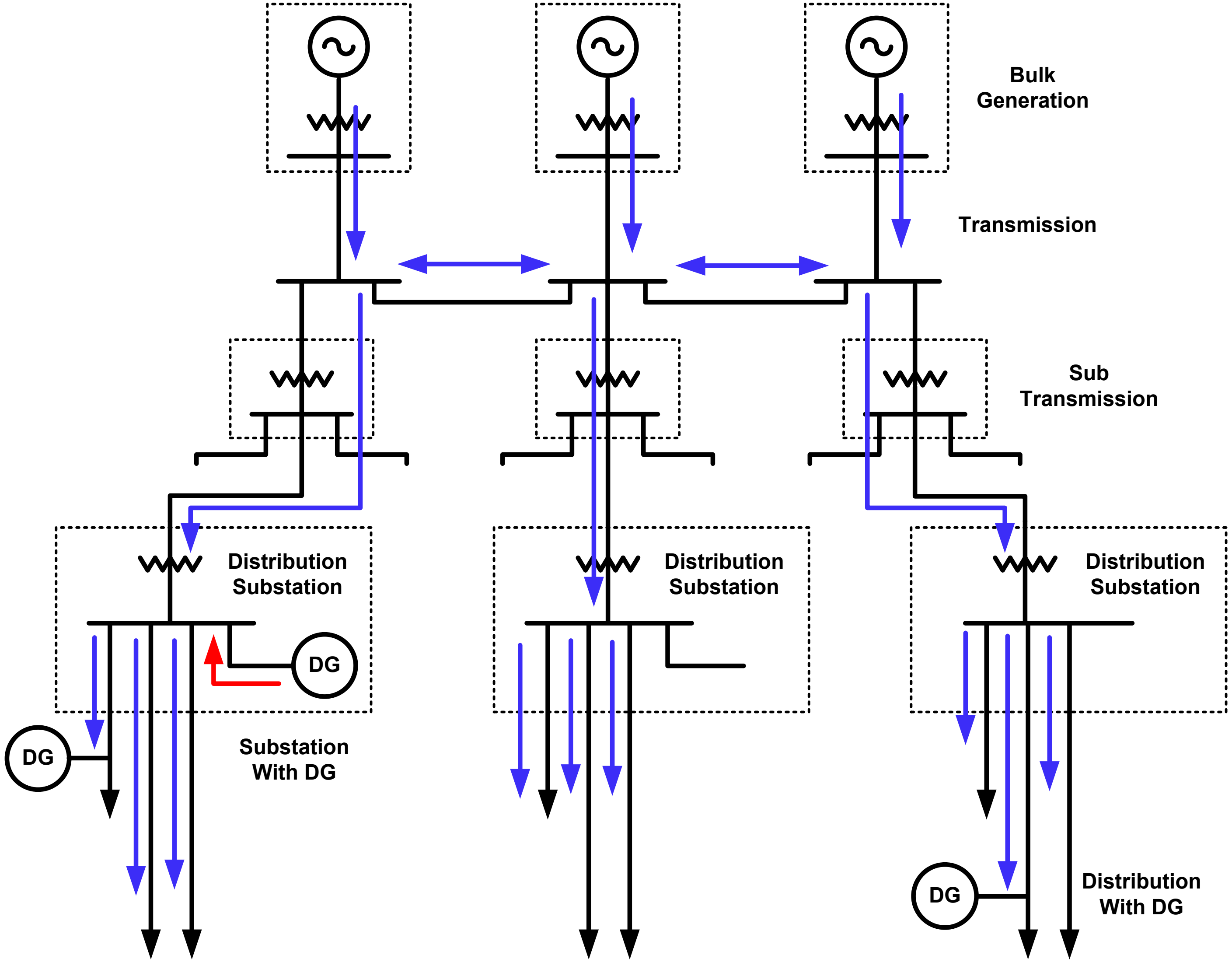
- As power flows and assumed reactive voltage drops can change as DER proliferates, consider changing fixed CAPs to switched to avoid overvoltage (from excessive VAR support) under high DER output conditions
- Consider active voltage (VAR) control of DER as proliferation increases





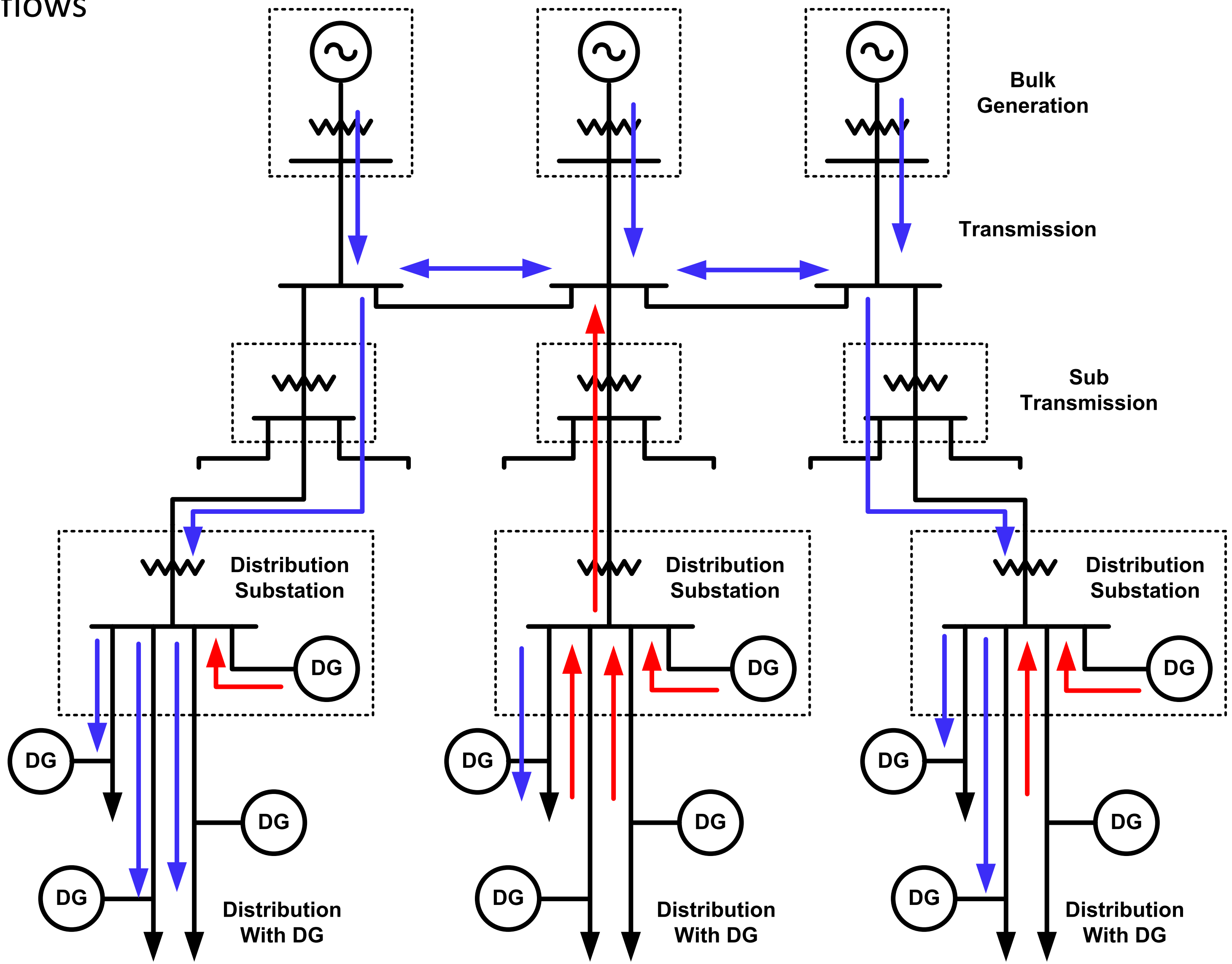
DER Today

Gen→Tran→SubTran→Dist→Utilization



DER Tomorrow

Bi-Directional Powerflows



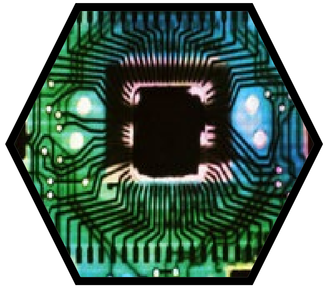
Smart Grid and DER

- Enables Green Power Interconnected at the Distribution Level
- Smart Grids Must Overcome Many Limitations:
  - Loss of Protective System Coordination
  - Voltage Control (reactive support)
  - Restoration Problems
  - Capacity/Load balance
  - Green power variability and non-dispatchability
- IEEE 1547 is presently too restrictive for large amounts of DER
  - Issue with high amount of DER capacity being lost at once for disturbance or other recoverable event
  - 1547A helps address that

Smart Grids

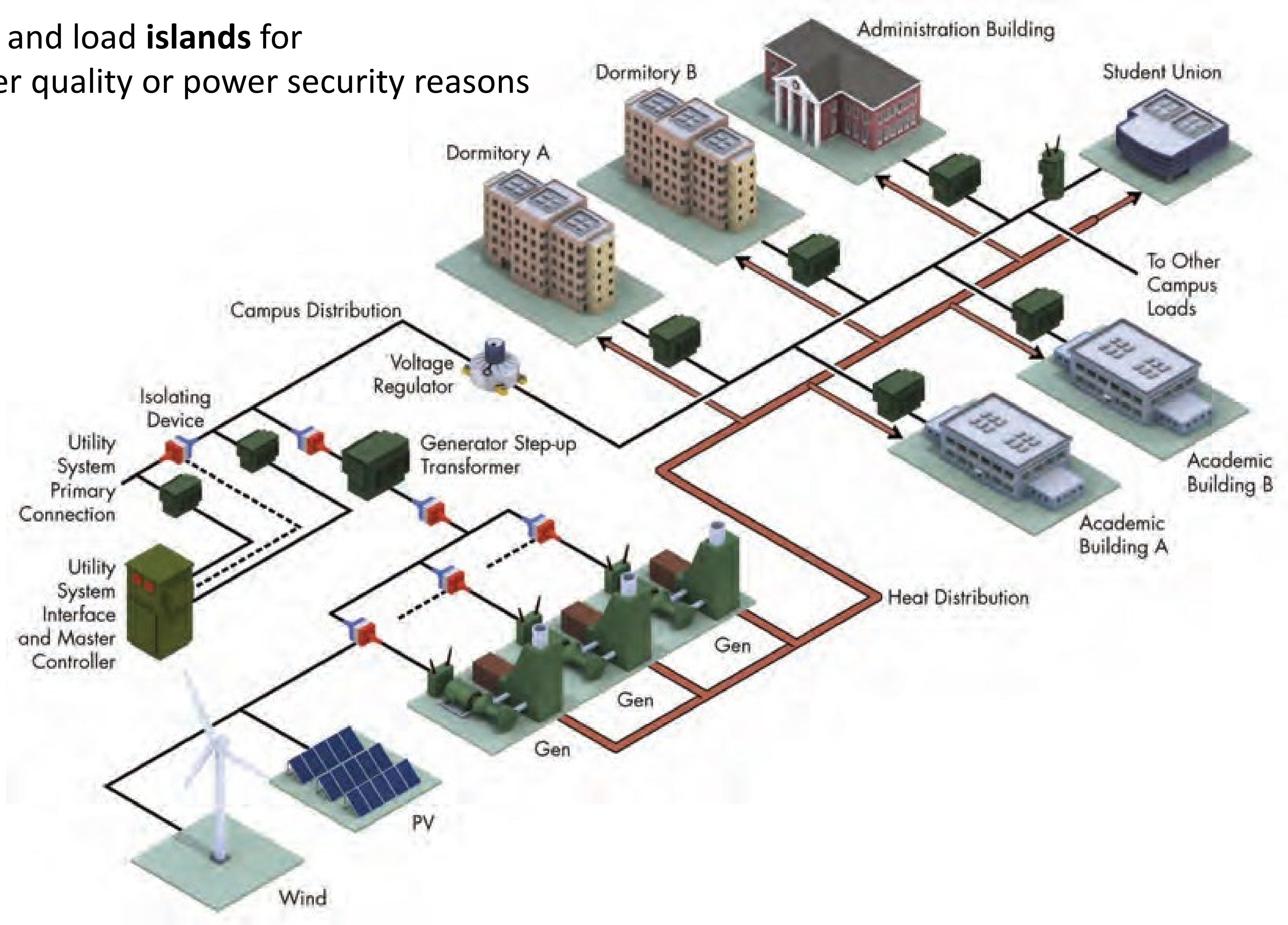
Full Integration of all Components of the Distribution System Through By-Directional Communication

- Peer-to-Peer Relay and Control Communication
- Adaptive Relaying
- Control with Real-Time Feedback
- Load Control (for demand response)
- Full Control of DER Output (watt and VAR output)
- Energy Storage (to firm variable and non-dispatchable renewable DER)
- Microgrid Operation System During Contingencies



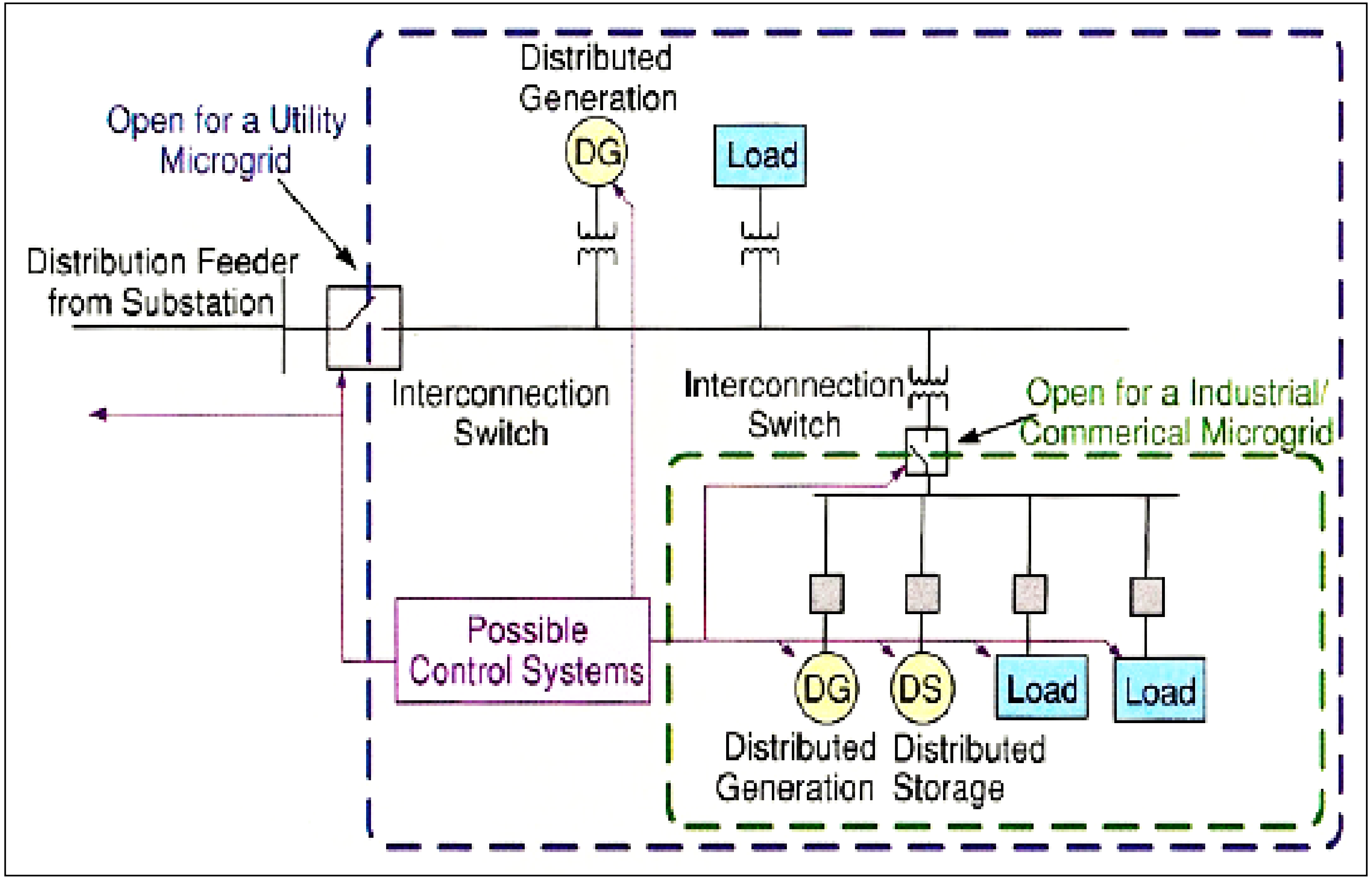
University Campus Microgrid

Creation of DER and load **islands** for
economic, power quality or power security reasons

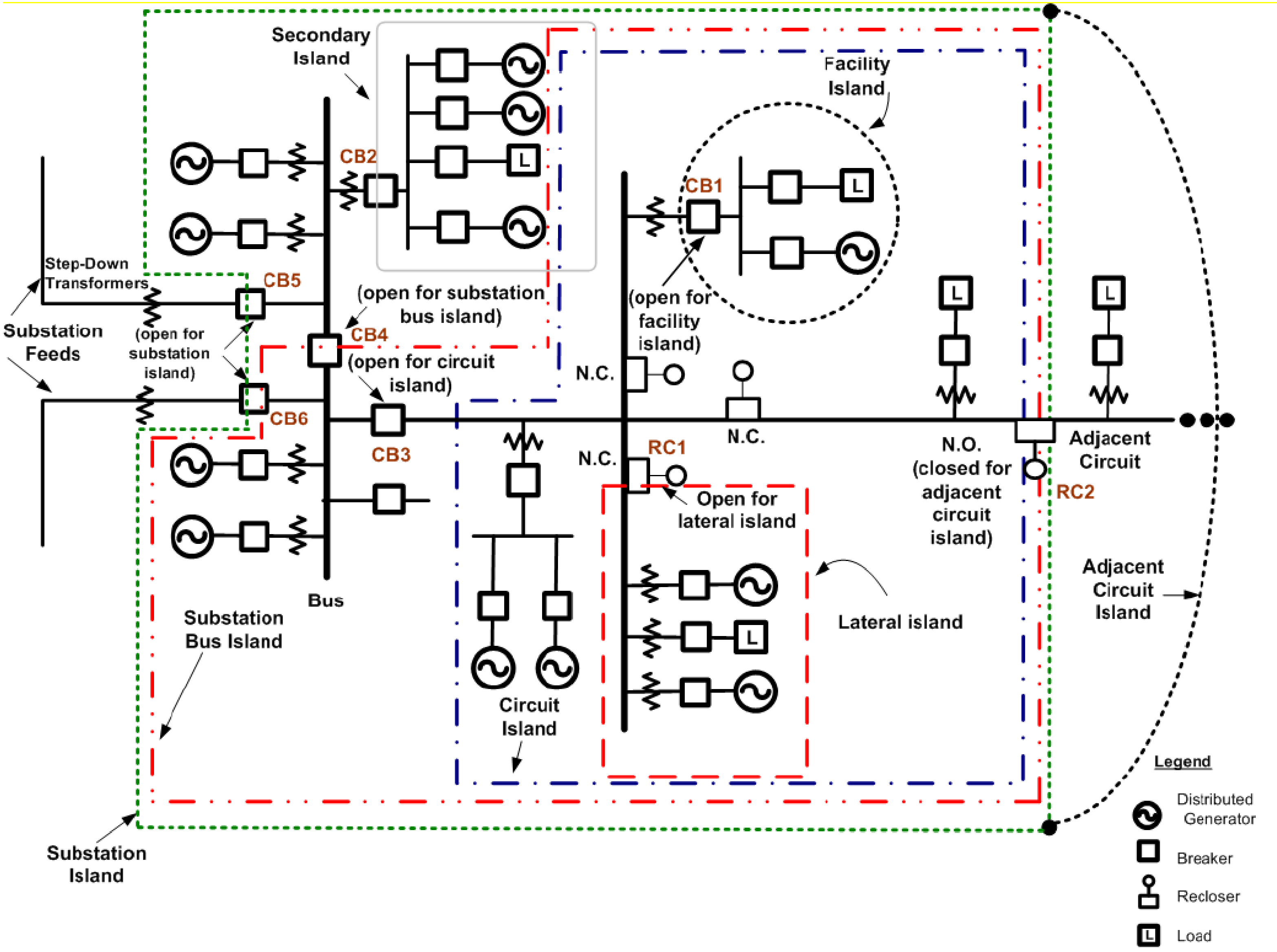


Smart Grids – Microgrids

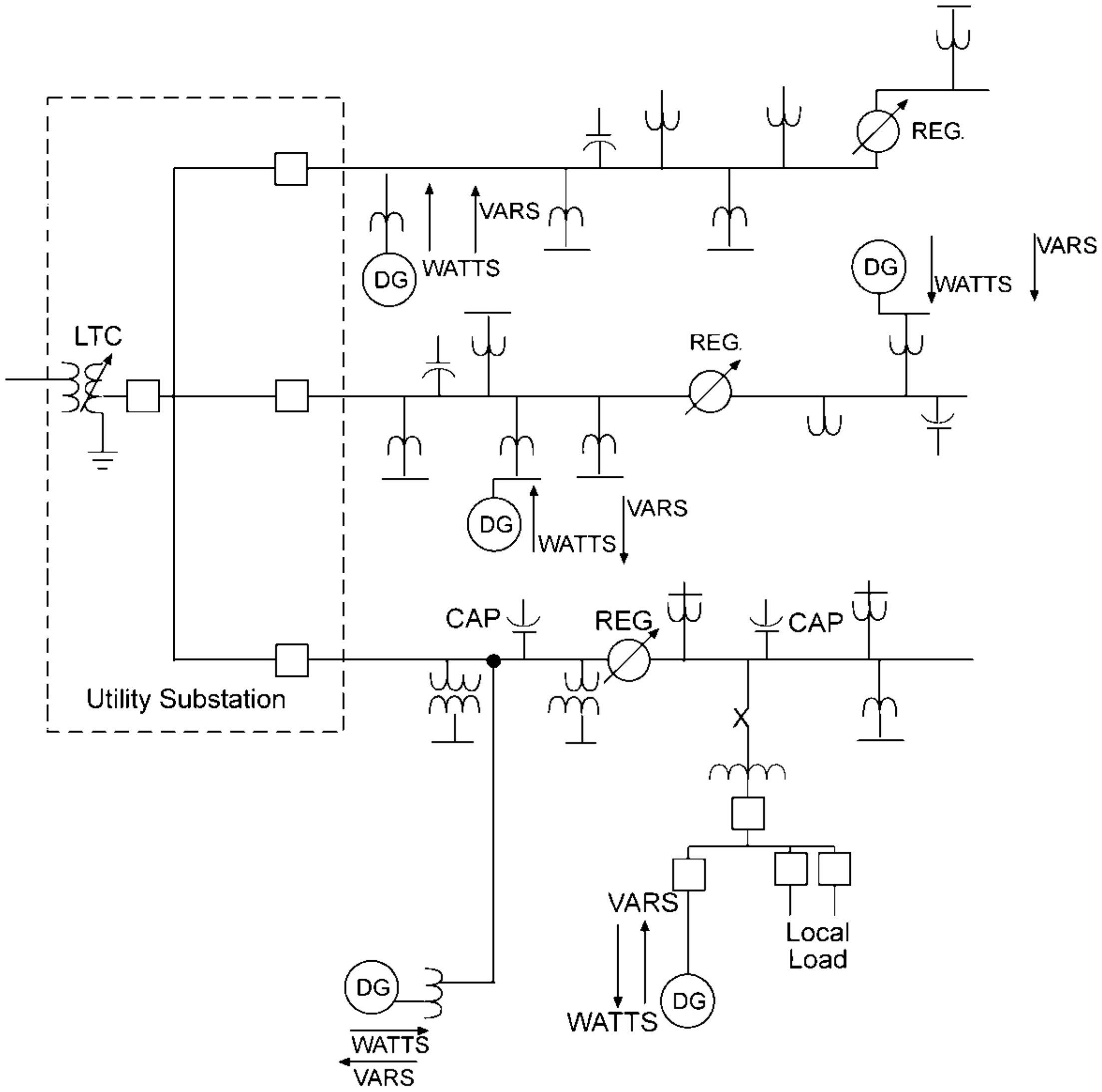
Just as a single DER is synced to the utility, groups of DER as a Microgrid are synced to the utility after operating islanded



Smart Grid Application of DER: Microgrids



High Penetration of DER on Distribution Systems Will Require Smart Grid Technology to Control System Voltage



- Voltage control with high levels of DER require some type of adaptive watt/VAR control
- Advanced control will be needed on DER, voltage regulating and reactive support (capacitors) elements
- Normal power from Utility to load
  - Utility strong source
- DER may backfeed
  - Typically a weaker source
- What to do with power reversal from sectionalizing?
- What to do with power reversal from DER?
- What to do about LDC with DER influencing?

Summary

- Properly designed interconnection protection addresses concerns of both DER owners and utility
- State and national regulators, and the IEEE, continue to create and update interconnection guidelines
- Interconnection transformer configuration plays a pivotal role in interconnection protection

Summary

- Restoration practices need to be part of the overall interconnection protection
- Smart Grid Solutions will be needed to meet high penetrations of DER
- Protective Relays for DER interconnection protection may find greater application in inverter-based systems due to the adoption of IEEE 1547

Recommended Reading

- IEEE 1547 Series of Standards for Interconnecting Distributed Resources with Electric Power Systems, http://grouper.ieee.org/groups/scc21/
- On-Site Power Generation, by EGSA, ISBN# 0-9625949-4-6
- Intertie Protection of Consumer-Owned Sources of Generation 3 MVA or Less, IEEE PSRC WG Report
- Evaluation of Islanding Detection Methods for Utility-Interactive Inverters in Photovoltaic Systems, Sandia National Laboratories, Ward Bower and Michael Ropp

Recommended ReadingO

- "Update on the Current Status of DG Interconnection Protection—What 1547 Doesn't Tell You," Charles Mozina, Beckwith Electric, presented at 2003 Western Protective Relay Conference on Beckwith website
- Distribution Line Protection Practices Industry Survey Results, Dec. 2002, IEEE PSRC Working Group Report
- Combined Heating, Cooling & Power Handbook, Marcel Dekker, by Neil Petchers, ISBN# 0-88173-349-0

Recommended Reading

- "How to Nuisance Trip Distributed Generation,"
  W. Hartmann, presented at Power System Conference, Clemson University, Clemson, SC, March 2003
- "Relay Performance in DG Islands," Ferro, Gish, Wagner and Jones, IEEE Transactions on Power Delivery, January 1989
- Effect of Distribution Automation on Protective Relaying, 2012, IEEE PSRC Working Group Report
- 1547a and Rule 21, Smart Inverter Workshop, June 21, 2013, SCE

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