Distributed Generation Protection & Control

Including IEEE 1547, Green Energy and Microgrids

May 29, 2014

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Wayne Hartmann is a Protection and Smart Grid Solution Manager for Beckwith Electric. He provides customer and industry linkage to Beckwith Electric's solutions, as well as contributing expertise for application engineering, training and product development.

Before joining Beckwith Electric, Wayne performed in application, sales and marketing management capacities with PowerSecure, General Electric, Siemens Power T&D and Alstom T&D. During the course of Wayne's participation in the industry, his focus has been on the application of protection and control systems for electrical generation, transmission, distribution, and distributed energy resources.

Wayne is very active in IEEE as a Senior Member serving as a Main Committee Member of the IEEE Power System Relaying Committee for 25 years. His IEEE tenure includes having chaired the Rotating Machinery Protection Subcommittee ('07-'10), contributing to numerous standards, guides, transactions, reports and tutorials, and teaching at the T&D Conference and various local PES and IAS chapters. He has authored and presented numerous technical papers and contributed to McGraw-Hill's "Standard Handbook of Power Plant Engineering, 2nd Ed."

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Presentation Objectives

- Define Distributed Generation (DG)?
- Explore Types of DGs
- Why DG?
- Utility and Facility Drivers for DG
- Mission Critical Power and Conversion to DG
- Rates and DG Operational Sequences
- Industry Concerns
- IEEE 1547: Industry DG Guide
- Sample Utility DG Interconnection Guide

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Presentation Objectives

- 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 DG
- Impact of IEEE 1547A
- A Word on System Control with DG
- Summary and Q&A

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What is DG?

- Generation of electricity from small energy sources
  - Typically <=10MW
- May be based at facilities, including industrial, commercial and residential, as well as utility based
- For this exploration, connected into distribution
- Distributed Generation (DG) allows collection of energy from many sources and may provide lower environmental impacts and improved security of supply

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What is DG?

- **Also called:**
  - **Distributed Electric Resource (DER)**
  - **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)**

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Types of DG: Sorted by Utility Connection

- **Prime Power**
  - On-site generation powers loads
  - No connection to a Utility grid
  - Does not require DG interconnection protection
  - Things change if Utility power is brought out to site

- **Emergency Power**
  - Normally power from the Utility; in the event of Utility power failure on-site generation is used
  - Momentary parallel connection of on-site power to Utility grid allowed (<=100mS)
  - Does not require DG interconnection protection

- **Grid Paralleled (Emergency Power + Grid Paralleled Operation)**
  - Power from Utility, on-site power or combination of Utility and on-site power in long term parallel operation
  - Uses circuit breakers to control and allow parallel operation
  - Utility DG interconnection protection is required

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DG: Green or Conventional by Energy Source

- **Conventional (Not Green)**
  - Burn conventional fuel
    - Diesel, oil, gasoline
    - Natural Gas (although natural gas being seen as “greener”)

- **Green (Renewable)**
  - Use renewable sources to reduce reliance of fossil fuels:
    - Hydro
    - Solar (PV)
    - Solar (thermal to steam generation)
    - Wind
    - Biogas (methane from decomposition)
    - Biomass (direct burn or gasification)
    - Biodiesel (instead of refined diesel)
    - Tidal
    - Storage (battery)

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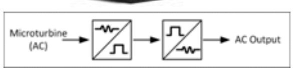
Conventional DG

Industrial Gas Turbine

Reciprocating Diesel

Microturbine Gaseous Fuel



Reciprocating Gaseous Fuel

Reciprocating aka: Internal Combustion Engine (ICE)

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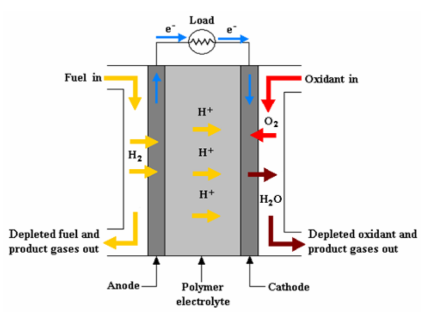
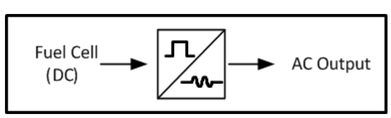
Conventional DG

Fuel Cell





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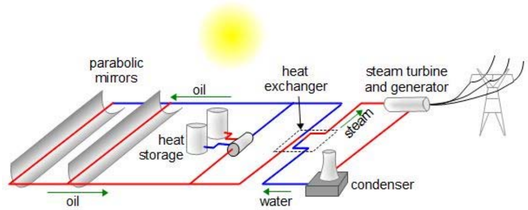
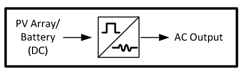
Renewable DG

Solar (Thermal)



Solar (PV)



Small Hydro

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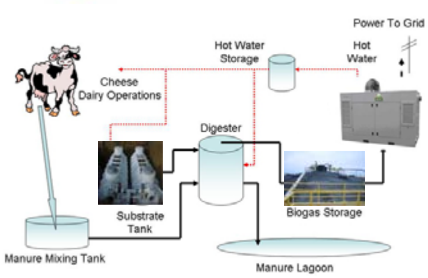
Renewable DG

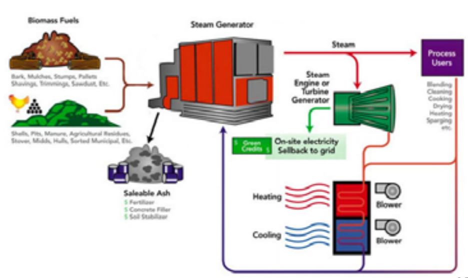
Wind

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

Biogas



Biomass



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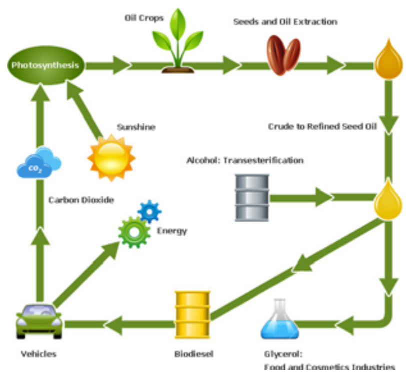
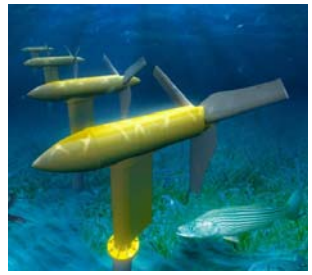
Renewable DG

Biodiesel

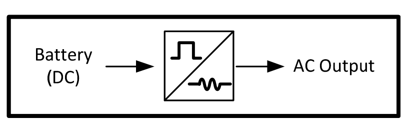


Tidal



Renewable DG

Storage Battery



Why Green Power ?
(aka: Renewable Energy)

- **Federal and State Governments Push for Renewable Resources**
  "Green Power Is In."

- **Two Basic Penetration Drivers:**
  1. PUC mandates 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
  2. Increase the buy back rate and let market forces install green generation. This typically fosters smaller generators connected to distribution systems.

- **Technological advances have reduced green power costs**

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Why DG: Utility Drivers

- T&D Issues
  - Decrease losses
    - DG at the point of use is not subject to transport loss
    - T&D losses range 3-7%
  - Demand Response ("Turn On Local DG 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
  - Transmission decongestion
  - Distribution decongestion
  - Distribution build-out deferral

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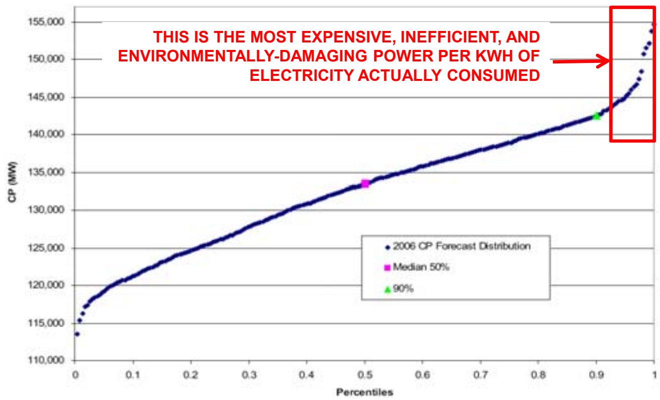
Reality of Grid Load Dynamics (Peak Demand)



- **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**

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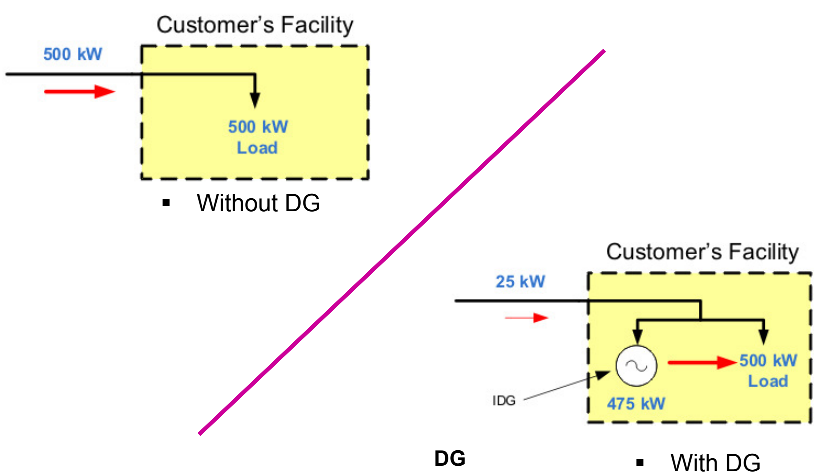
DG in a Demand Response Role



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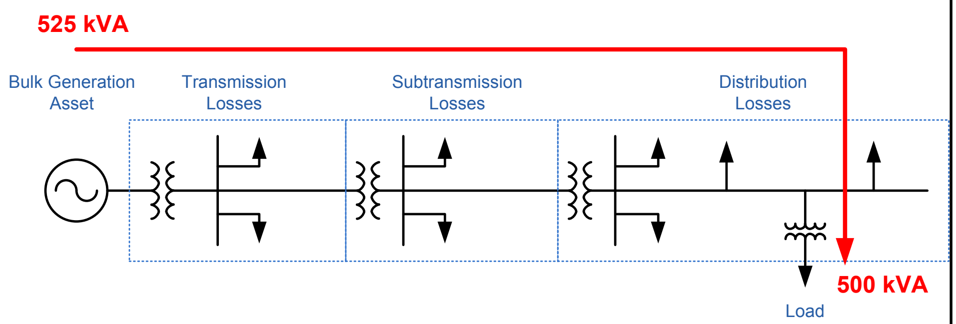
Sustainability & Losses: Conventional Power Delivery



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

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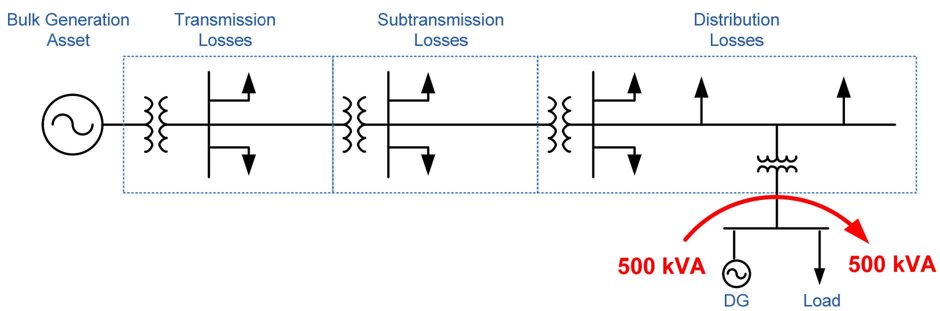
Sustainability & Losses: Use of DG at Load



- Heat rates (efficiency) of modern engine/gensets applied in DG systems are as good if not better than combustion turbines (CTs) [1,2].
- DG capacity has a heat rate of 9,800 btu/kWh saving approximately 2,200 btu/kWh of fuel input compared to the overall peak power generation portfolio published by eGrid [3].

[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

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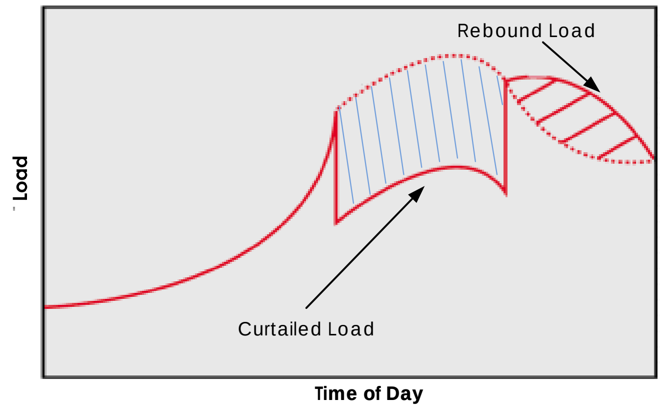
Non-Signaled Passive Demand Response: Rebound Effect



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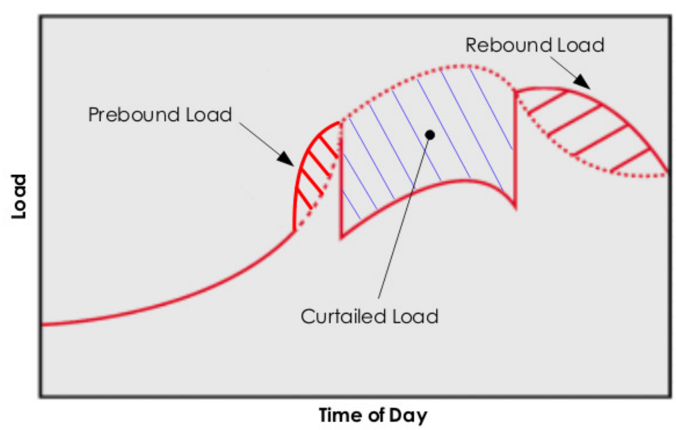
Signaled Passive Demand Response: Prebound-Rebound Effect



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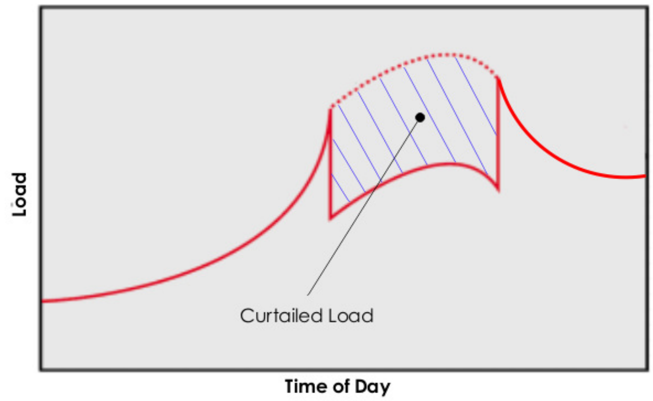
Signaled DG-based Demand Response: No Prebound-Rebound Effects



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Why DG: Utility Drivers

- T&D Issues (con't)
  - Grid Support
    - Ancillary Services
      - o Voltage regulation (1547A)
      - o VAR Support (1547A)
  - Firming of Green Power
    - Green power has intermittency issues
    - Can be answered with fast syncing DG
      - o Conventional DG
      - o Storage
  - Ready and Standby Reserves
    - Fast syncing prime movers
    - Storage
  - Spinning Reserves
    - Storage (as it is synchronized)

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Why DG: Consumer Drivers

- **Rate Incentives**
  - Demand Reduction
  - Interruptible Rates
  - Load Curtailment Rates
  - Energy Reduction (if power produced is less expensive than Utility)
- **Using renewable to offset energy costs**
- **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 cab be repurposed and used for demand rate reduction incentives

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The first rule of power quality is you have to have it!

- Provide constant power through redundancy and fault elimination
  - *Redundancy* is obtained by fault tolerant design
  - *Fault elimination* attempts to design a "fault proof" system
- Emergency power systems used when the process or operation cannot be interrupted
- Emergency power systems are designed for "Mission Critical Facilities"
- Mission Critical Facilities with Emergency Power Systems are often planned or retrofit for operation in parallel with the Utility for demand deduction

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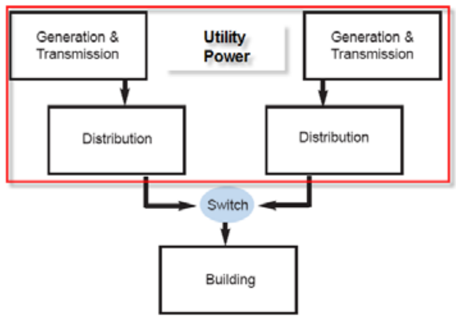
Fault Tolerance: Utility Outages



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

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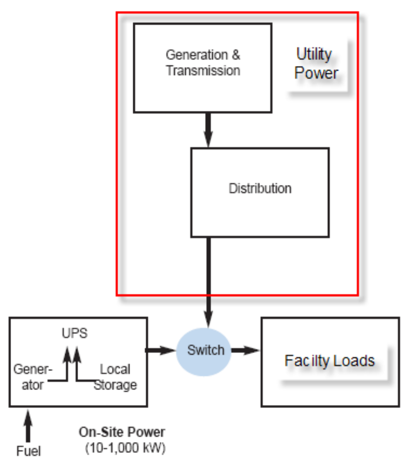
Fault Tolerance: Utility Outages



- Employ utility feed(s) and on-site power
- On-site power functional even in the event of total utility failure

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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 DG is installed

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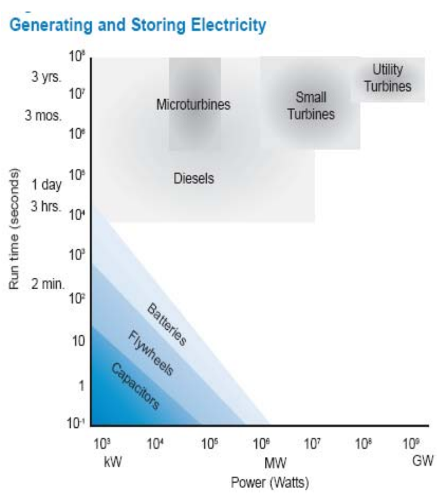
On-Site Generation: Sustainability Times



- For outages greater than 3 hours, fuel burning on-site generation is generally applied
- Short time outages may be handled by electrical storage, chemical storage or stored energy
- Reciprocating engines are used most widely to provide sustainable on-site power

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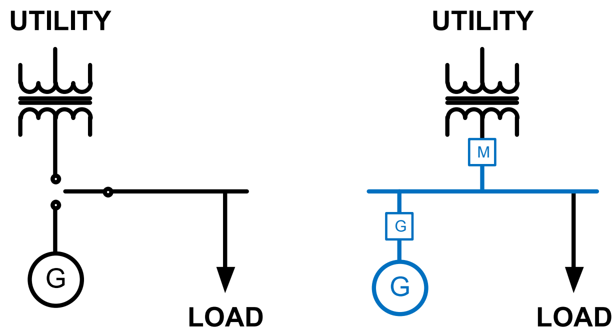
ATS vs. Circuit Breakers



ATS *Circuit Breakers*

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

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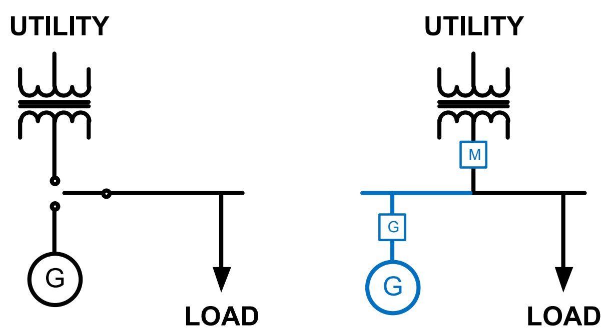
Conversion of ATS-based emergency system to dual purpose emergency and "bumpless" peak shaving system



Existing Facility

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

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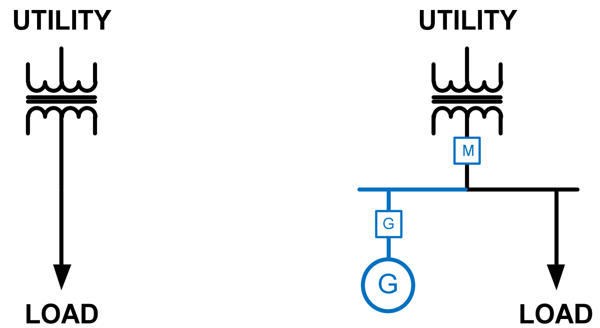
Greenfield <u>dual-purpose</u> emergency and "bumpless" peak shaving system



Existing Facility

Facility with Generator and Switchgear/Protection/Controls Added

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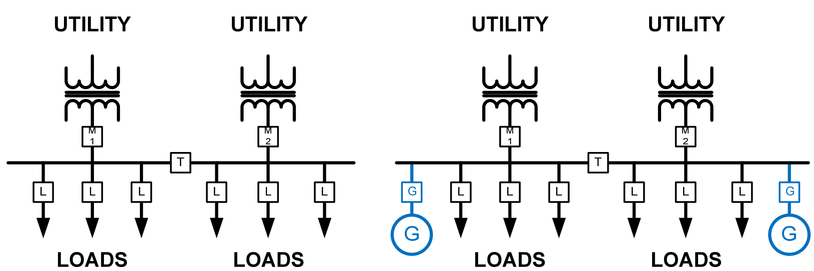
Complex Application: Dual Fed Facility Main-Tie-Main



Existing Facility

Facility with Generators and Switchgear/Controls Added

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Prime Power (No Utility Connection)

- On-Site 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). The control system will accomplish this to the limits of the generation.
  - As **real power demand** (watts) **increases**, the governor is signaled to **increase the fuel to the generation** to maintain rated frequency output.
  - As **real power demand** (watts) **decreases**, the governor is signaled to **decrease the fuel to the generation** to maintain rated Hz frequency output.
  - As **reactive power demand** (VARs) **increases**, the voltage regulator is signaled **to increase the field current**, thereby increasing VAR output to maintain rated voltage.
  - As **reactive power demand** (VARs) **decreases**, the voltage regulator is signaled to **decrease the field current**, thereby decreasing VAR output to maintain rated voltage.

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Paralleled Operation (Interconnected to Utility)

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

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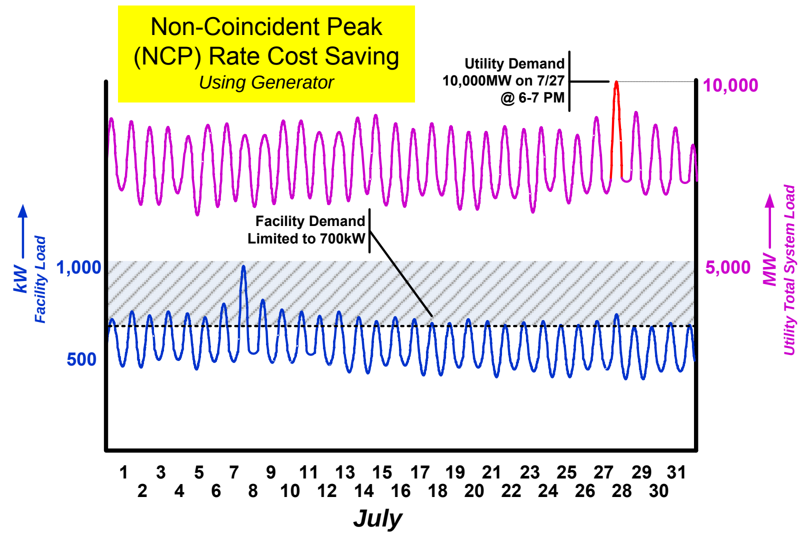
Monthly Demand: Facility and Supplying Utility



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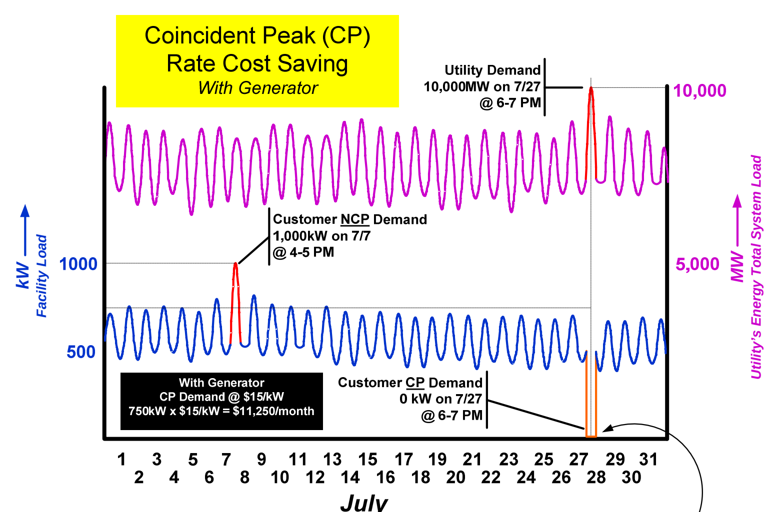
Monthly Demand: Facility and Supplying Utility



Note: Customer CP Demand registered when Utility's 1-Hour peak for the month occurs

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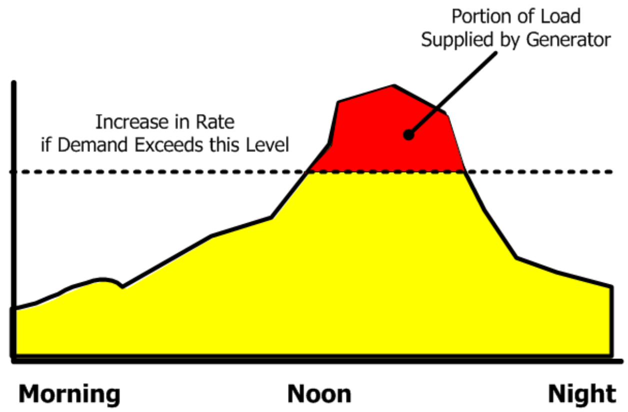
Consumer Demand Reduction Strategies



Peak Shaving

No electrical export to Utility

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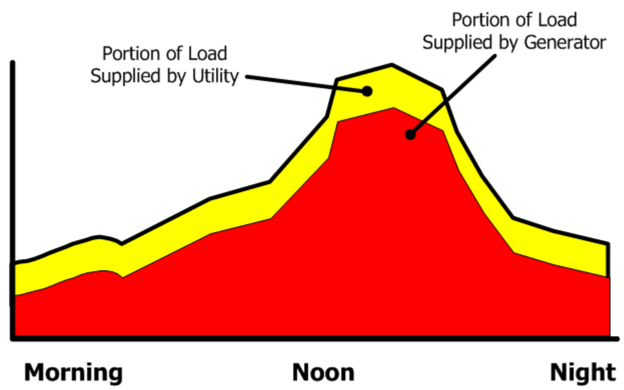
Consumer Demand Reduction Strategies



Load Following

No electrical export to Utility

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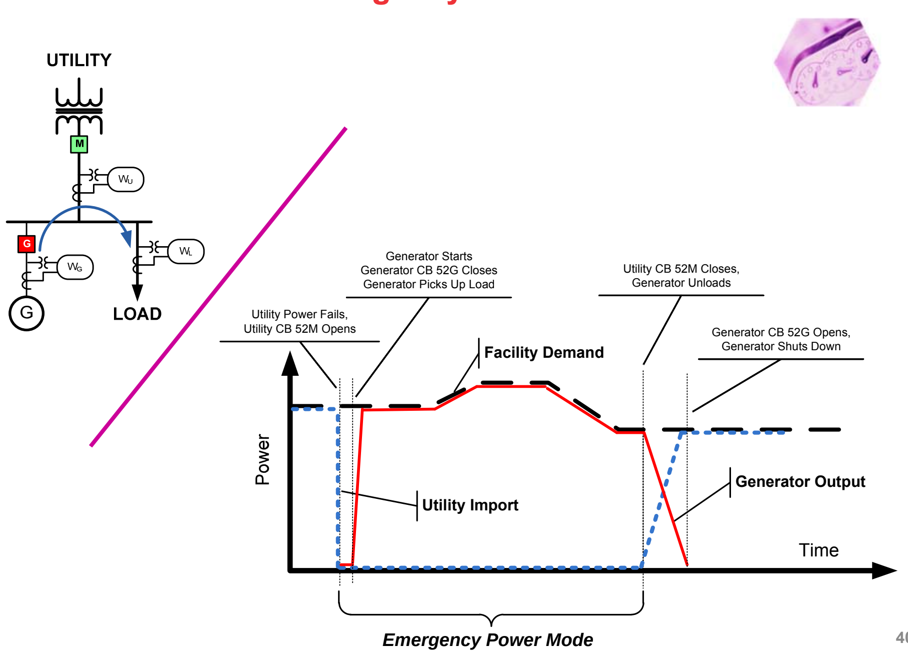
Operational Sequence Details

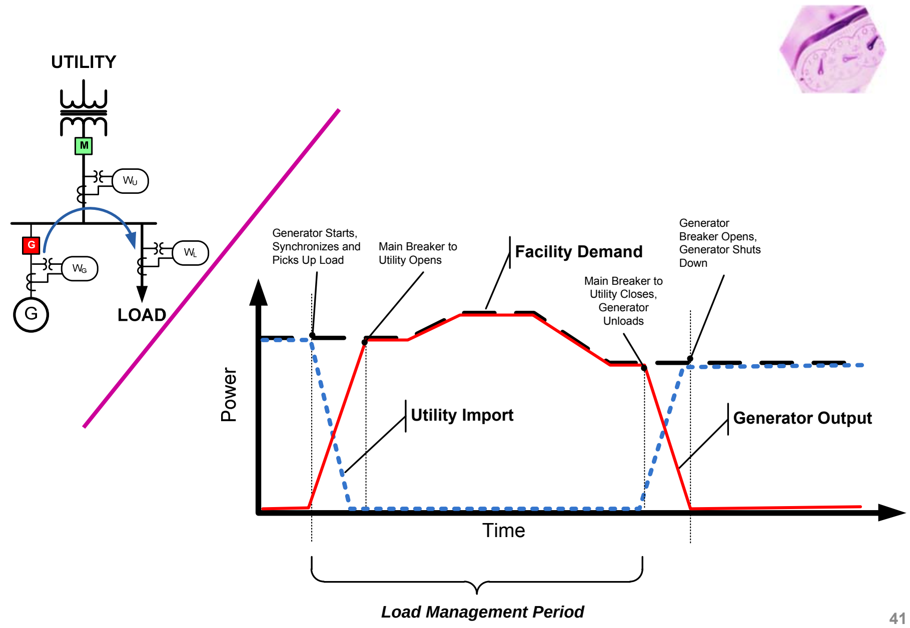
- Emergency Power
- Load Isolation
- Load Following
- Export

  - ➢ To know how DG is controlled in parallel with a Utility is important for DG Interconnection protection application
  - ➢ When control fails, protection is the safety net

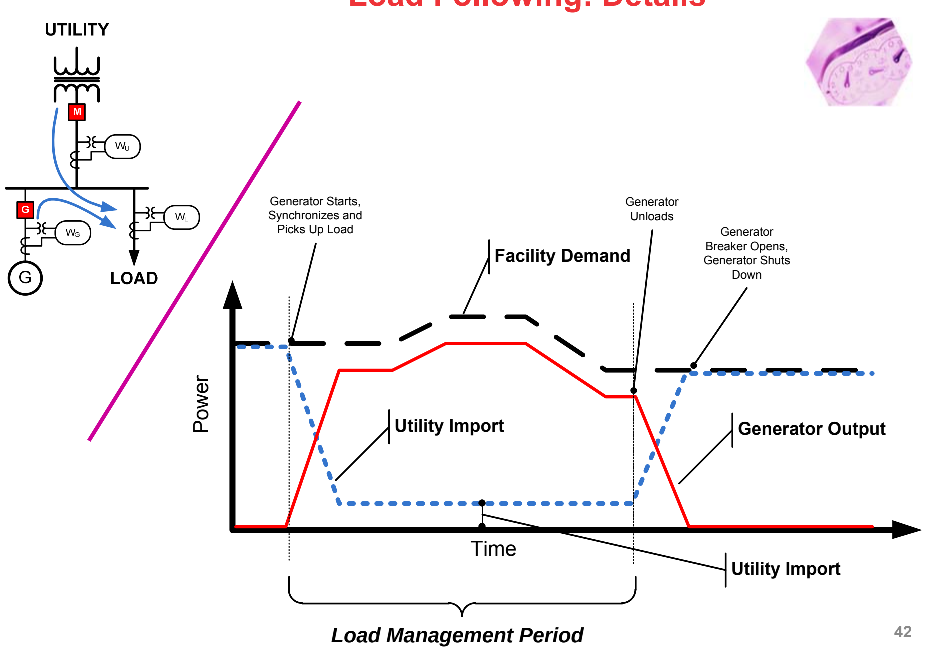
Emergency Power: Details



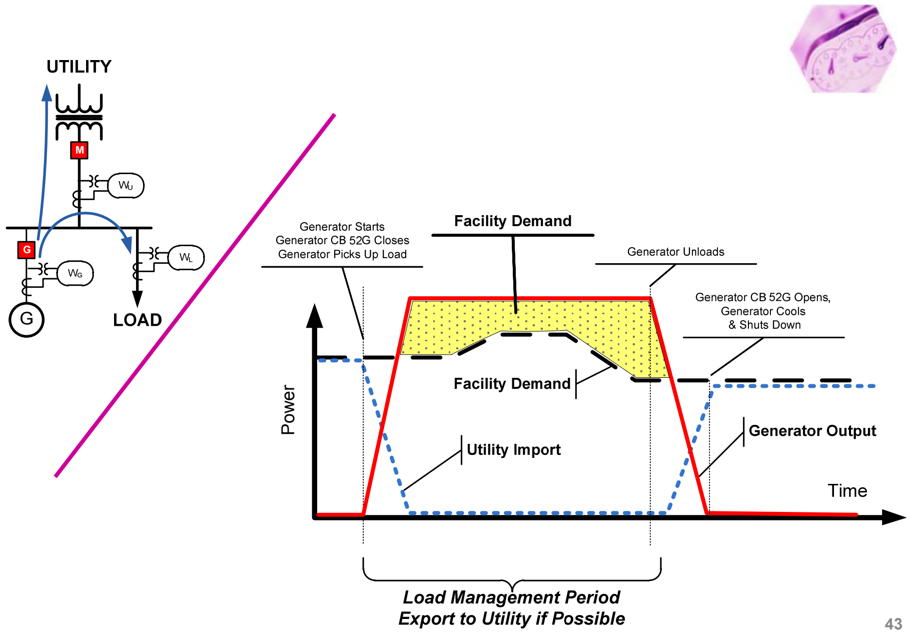
Load Isolation: Details



Load Following: Details



Export: Details



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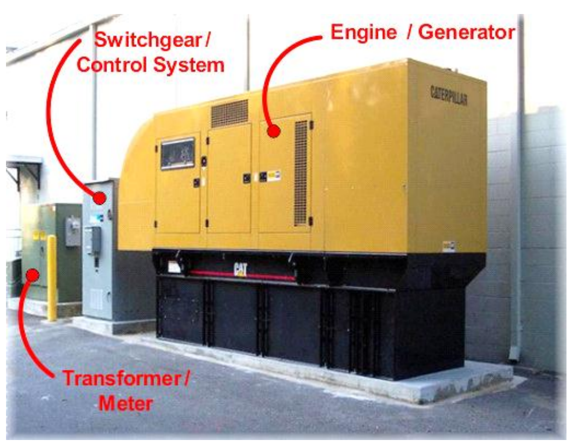
Example DG System



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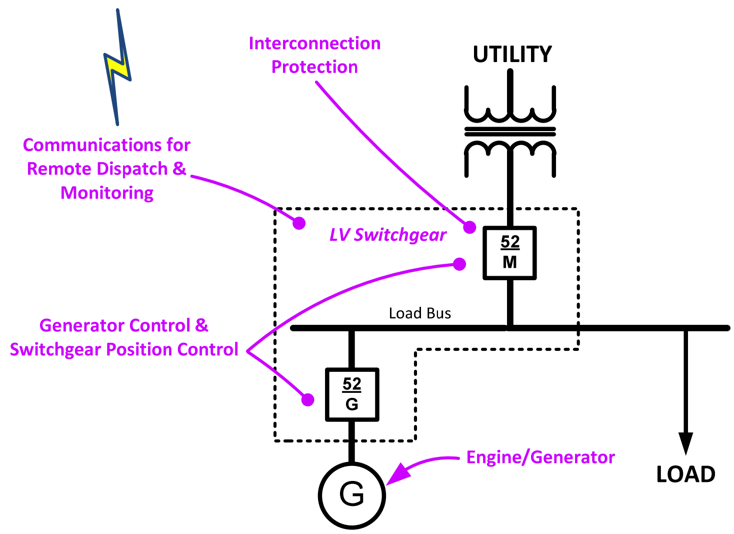
Interconnection Protection in LV Switchgear



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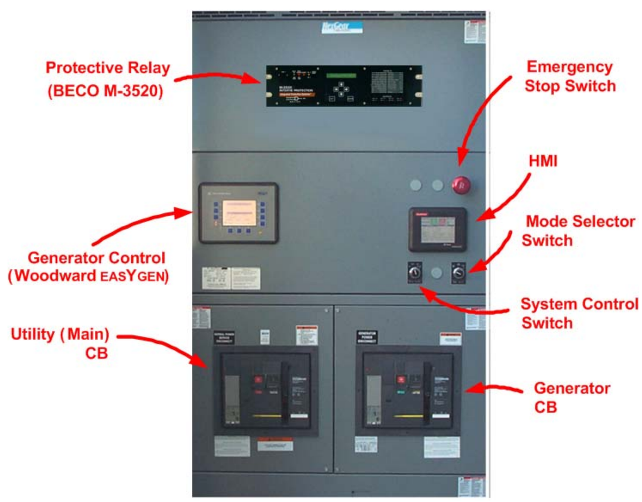
Interconnection Protection in LV Switchgear



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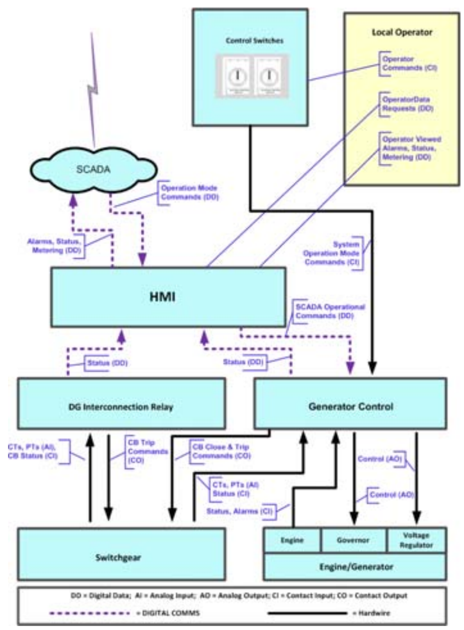
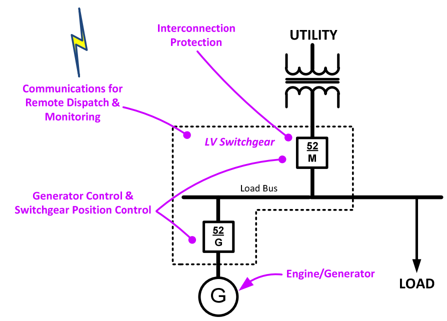
Protection and Control





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Factors that *discourage* DG installations

- Capital Equipment Cost
  - Generator, prime mover, infrastructure
- EPC Cost
- Cost of DG 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

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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 misoperation of utility protection and control equipment
  - Relays, reclosers, fuses, regulators, caps
- Power quality issues

DG Owner and General Interest Concerns

- Cost of interconnecting equipment, including protection
- Minimizing utility involvement and promoting standardized methods
- Achieve simple, non-controversial interconnection requirements so DG is not discouraged

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What is DG Interconnection Protection?

- Protection that allows the DG to operate in parallel to the 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 DGs do require specific interconnection protection

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DG Protection Engineering Challenges

- **Seamless integration of DGs into the utility protection system despite:**
  - "Too many cooks in the kitchen"
    - Owner, Consultant, Packager, Utility
  - Ownership boundaries
  - Conflicting objectives of DG Owners vs. Utility
    - DG 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 the installation**
  - Settings are properly developed
  - If installation or the EPS changes, assess the impact on the existing protection

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Industry Developments

- IEEE has developed DG Standards and Guides
- UL has developed DG Standards and Guides
- Utilities have developed DG Interconnection Guides
  - These typically reference IEEE 1547 for base requirements
  - Some Utilities add on requirements
- Interest from Federal Energy Regulatory Commission (FERC)
- To supply DG interconnection needs, manufacturers have developed protective relay systems and self-protecting power electronic systems (embedded in UL-1741 complaint inverters)

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DG Interconnection Guides

- **IEEE 1001 – 1988 (Withdrawn)**
  - *IEEE Guide for Interfacing Dispersed Storage and Generation Facilities with Utility Systems*
  - Published in 1988
  - First standard addressing DG 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.

- **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 .8)**
  - A "universal" DG interconnection protection document set to used as a minimum technical requirement base
  - Harmonized with UL 1741
    - http://grouper.ieee.org/groups/scc21/

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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.

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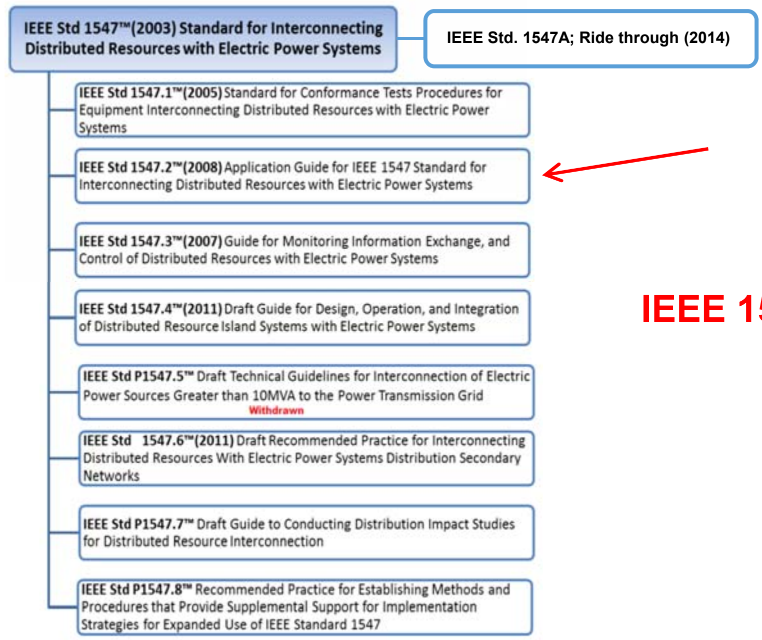

IEEE 1547

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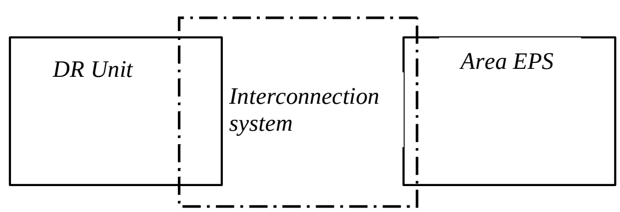
IEEE 1547 Definitions



- **DR Unit:** Distributed Resource (DG)
- **EPS:** Electric Power System
- **Interconnection**: The result of the process of adding DR 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 DR unit(s) to an Area EPS.

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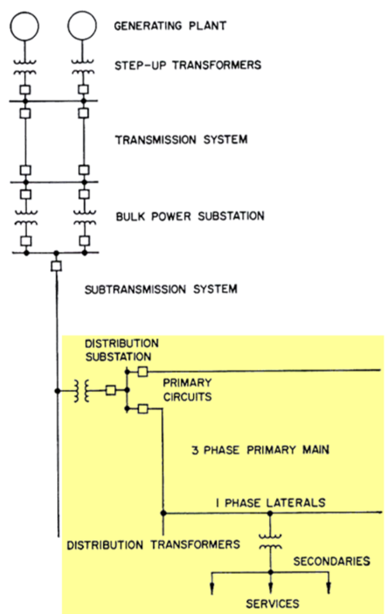
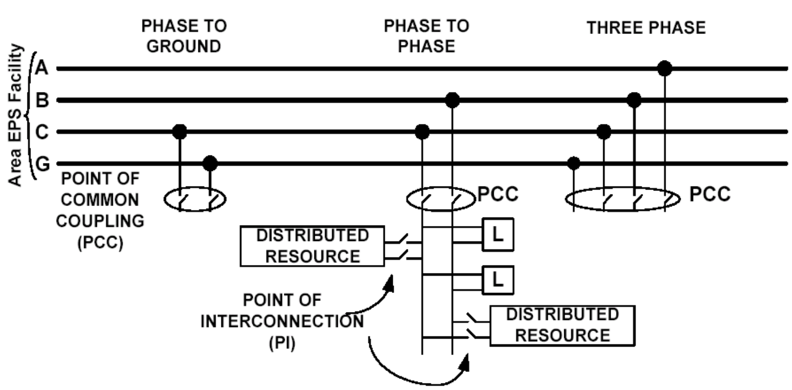
Area EPS



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

IEEE 1547 Definitions



- **PCC: Point of Common Coupling**
- **PI: Point of Interconnection**
- **EPS: Electric Power System**

IEEE-1547: 50,000' Overview

- **Safety**
  - Personnel working on a Utility system must be protected from backfeed or accidental energization from DG
- **Impact of size**
  - Intended to cover up to 10MW
- **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

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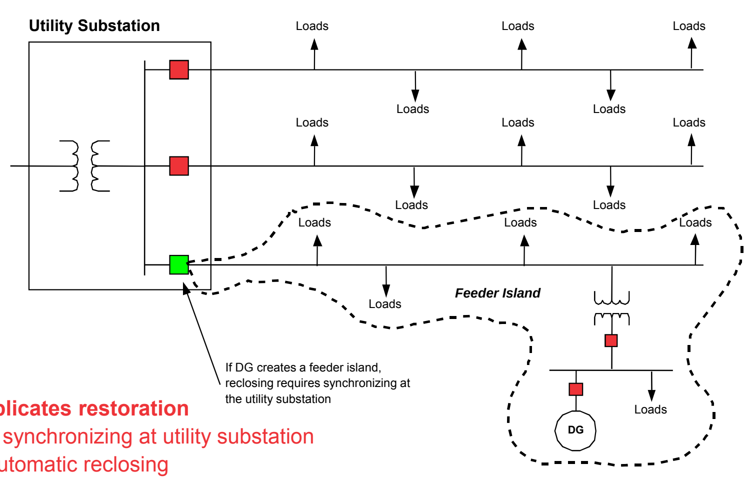
Islanded Operation of DG with Utility Load Is Generally Not Allowed



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

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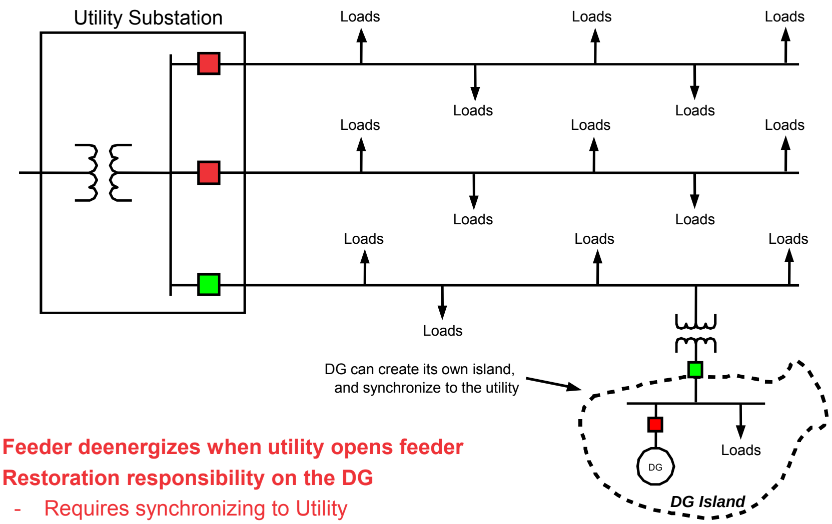
DG Facility Islanding to the Utility is Allowed



- **Feeder deenergizes when utility opens feeder**
- **Restoration responsibility on the DG**
  - Requires synchronizing to Utility

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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 DR system
  - Grounding for safety
  - Effect on EPS ground protection
- Abnormal system configurations
  - Alternate source
  - Abnormal sectionalizing
  - Alternate breaker or transfer bus

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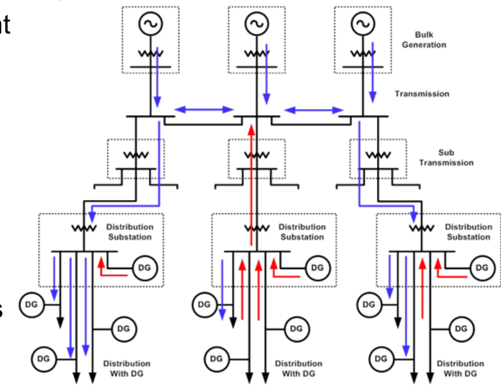
IEEE 1547 Standard Series: Addressed Areas

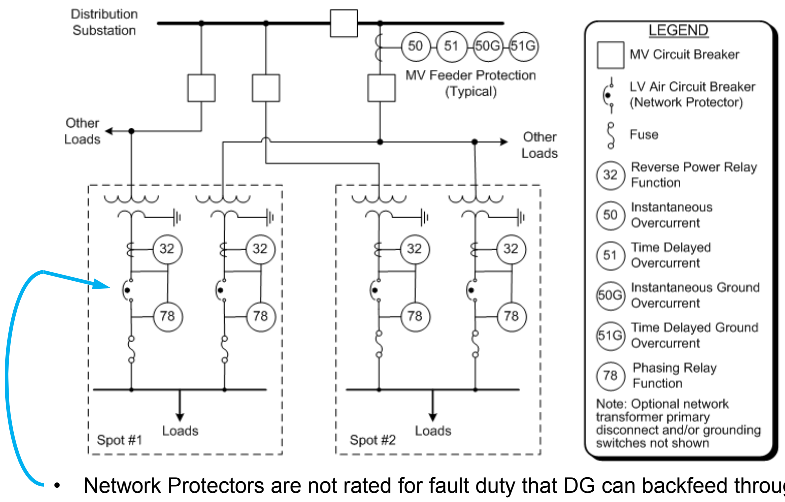
- Radial versus bidirectional power flow
  - Effect on protective equipment
  - Effect on voltage regulators
  - System modifications
  - System costs
- Voltage deviations
  - Three-phase
  - Single-phase
  - Induction versus synchronous
  - Voltage rise phenomenon
  - Surges, sags, and swells



IEEE 1547 Standard Series: Addressed Areas

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

Spot Network



- Network Protectors are not rated for fault duty that DG can backfeed through them
- They are also not rated for larger than rated voltage that can occur when DG is on-line and the network protector is open

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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

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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

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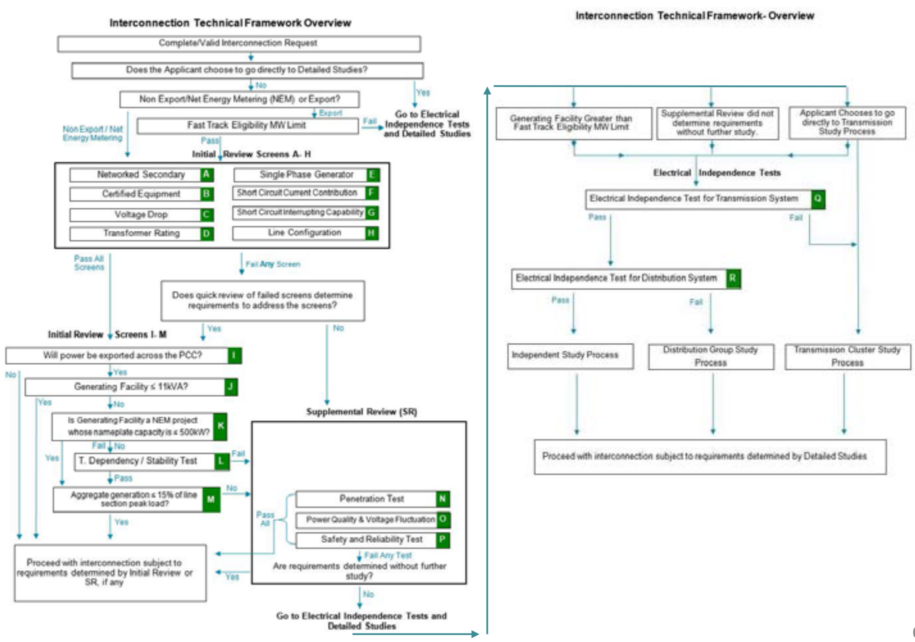
Sample: Utility Flowchart for DG Interconnection



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Protection Elements and Use

- "The Five Food Groups":
  - 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 DGs
    - Induction, Synchronous, Asynchronous (Inverters)

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Interconnection Protection

"The Five Food Groups"

- **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***

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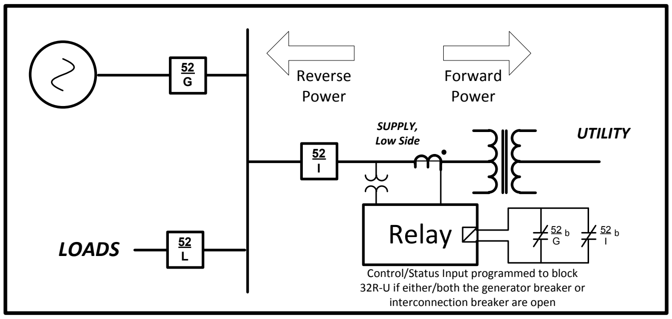
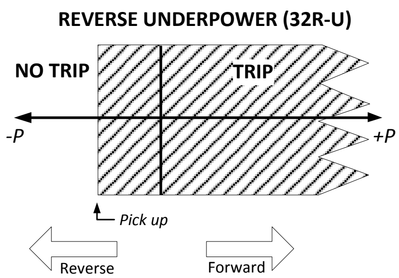
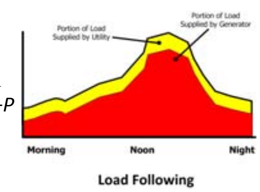
Low Import Power: *32R-U*

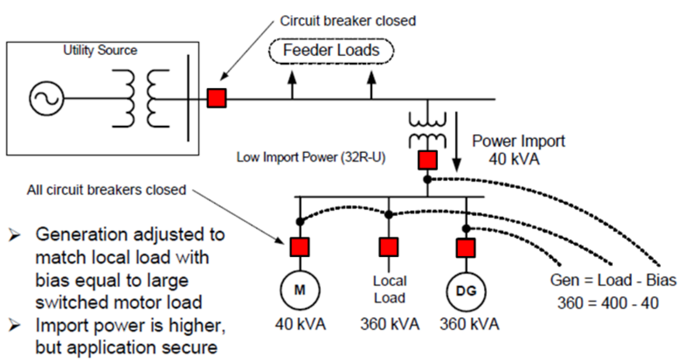






- 32R-U Relay pickup set to at least 5% of total connected generator rated KVA
- 32R-U Relay programmed to trip when imported power falls below the pick-up level
- Switching off a large amount of Facility load may cause nuisance tripping
- Generator Control should have proper bias power margin set

Low Import Power: *32R-U*



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

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Interconnection Protection
"The Five Food Groups"

- **Fault Backfeed Detection**
  - Phase and overcurrent (51V, 51), grounded systems
    - Directional overcurrent (67) 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***

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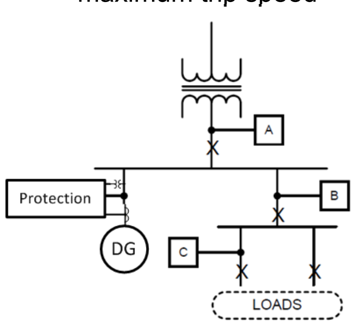
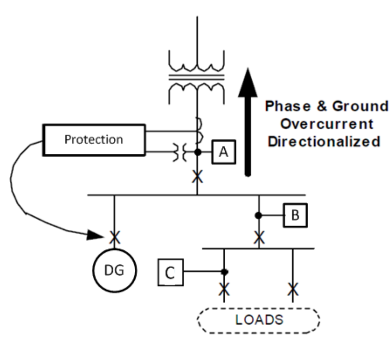
Direction vs. Non-Direction Elements at the PCC

- 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





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Interconnection Protection

"The Five Food Groups"

- **Damaging System Conditions**
  - – 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 DG going out-of-step, or ferroresonance***
- **Facilitate proper restoration**
  - – All elements reset, voltage and frequency within limits
  - – Reconnect timer (79) (all DG)
  - – Sync check (25)
    - Synchronous generators and some self-commutating inverters

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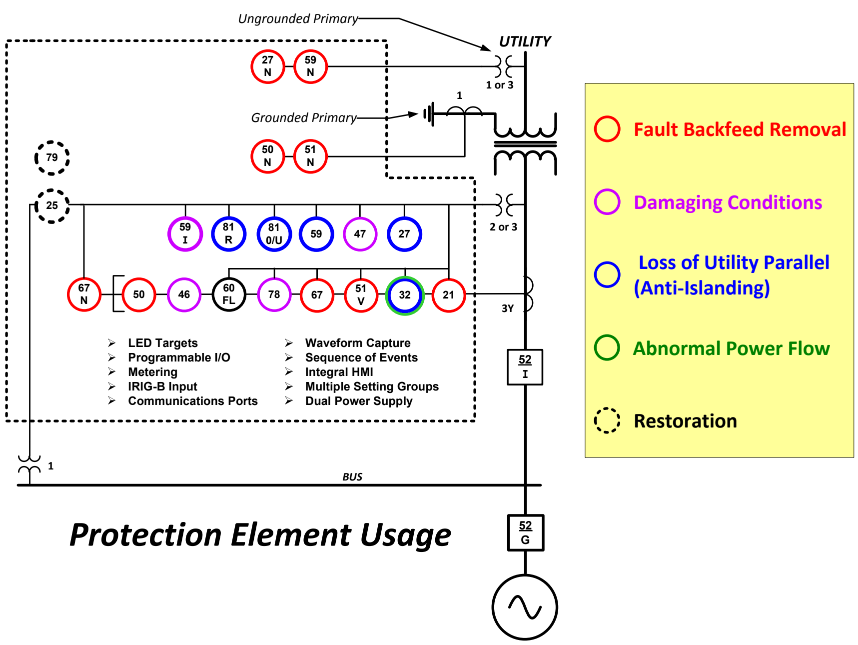

Protection Element Usage

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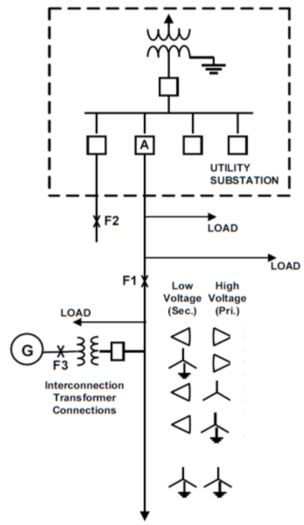
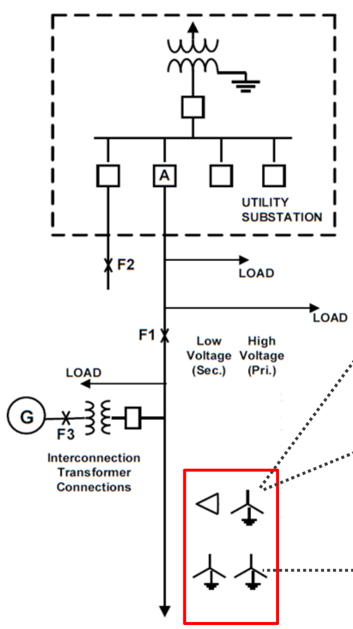
Interconnection Transformer Winding Arrangements Impact Protection

- 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

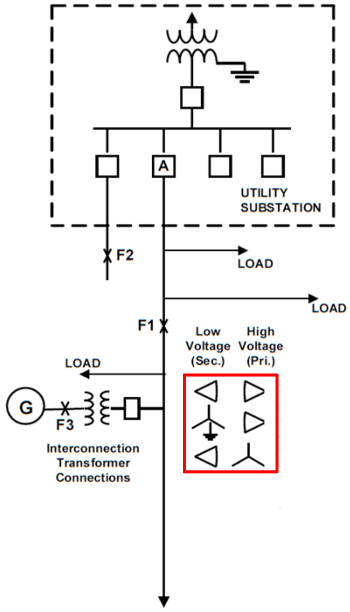


Grounded Primary:

✓ **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 (Y_{gnd}-Y_{gnd} 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**

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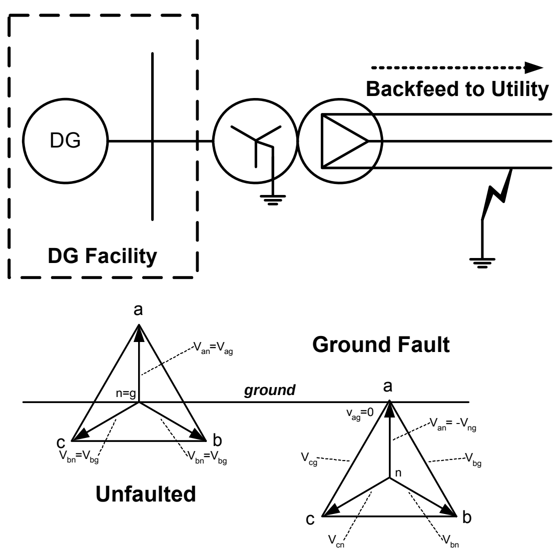
Ungrounded Primary: System Backfeed Overvoltage



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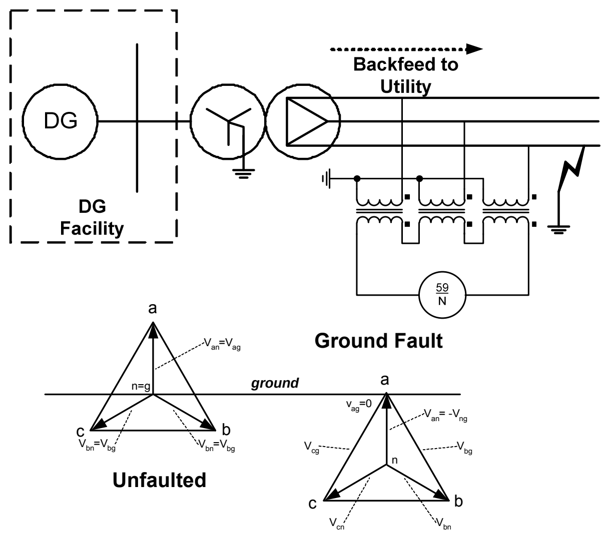
Sensing Ungrounded System Ground Faults with 3 Voltage Transformers



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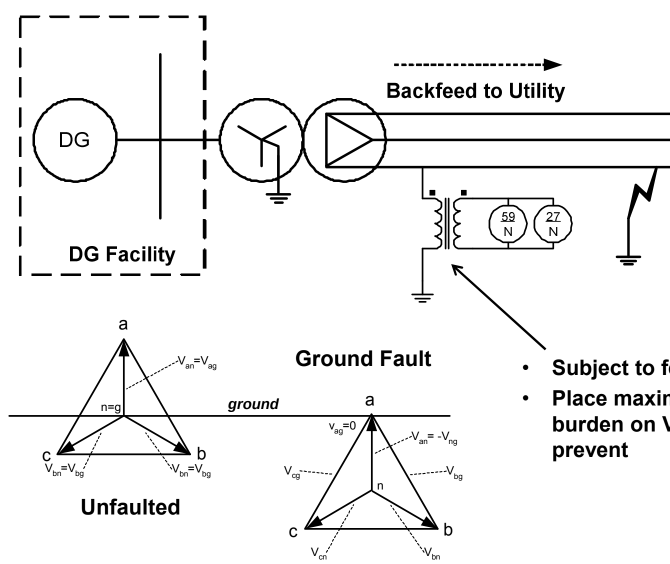
Sensing Ungrounded System Ground Faults with 1 Voltage Transformer



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

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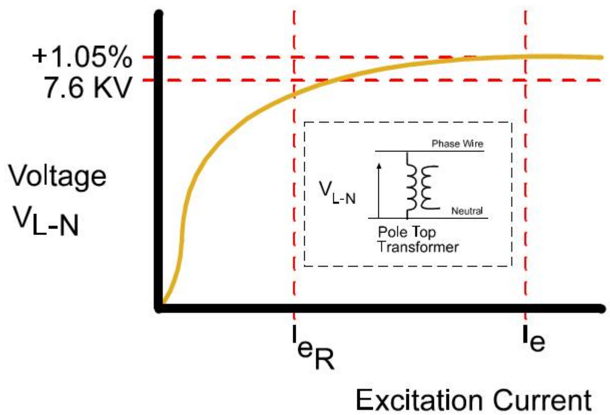
Impact of Overvoltage:
Saturation Curve of Pole-Top Transformer



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

Types of Power Sources

- **Induction**
- **Synchronous**
- **Asynchronous (Static Power Converters)**

Types of Power Sources

- Capable of limited fault current
- Line-commutated and self commutated variants
  - Self-commutated may be capable of fault backfeed and fault ride-through capability
  - Self-commutated may require sync check depending control sensing/design

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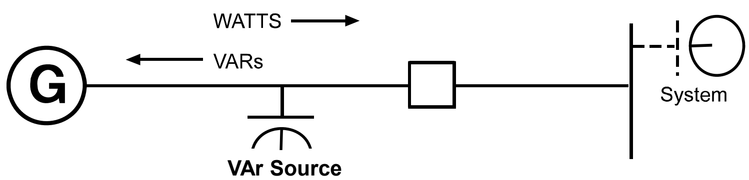
Induction Generator



- **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 KVA
  - 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

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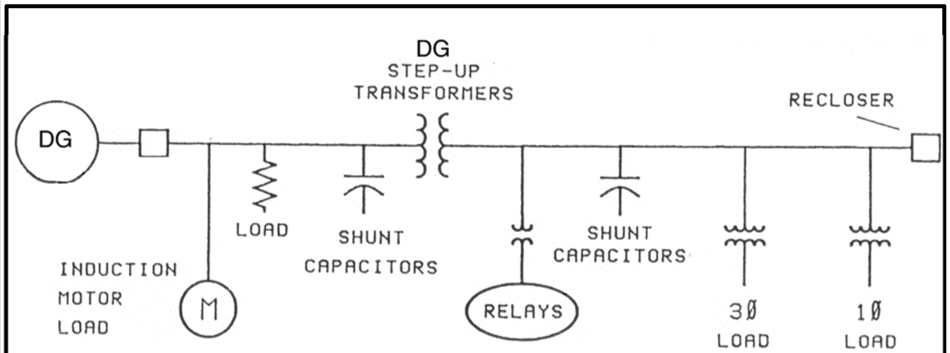
Ferroresonance

- 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 for Ferroresonance

New York Field Tests- 1989

Field Test Circuit

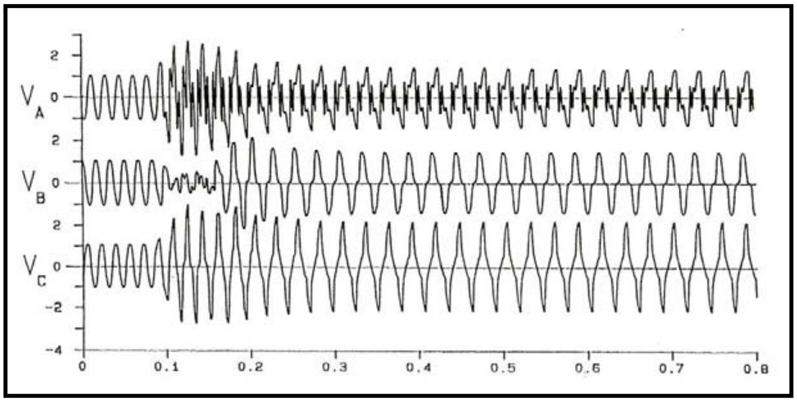


Schematic of Test Circuit.

Ferroresonance: Test Circuit Setup

New York Field Tests- 1989

Field Test Circuit



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

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Induction Generator: Ferroresonance

- Overvoltage from ferroresonance can damage insulation, damage arrestors and cause flashovers
- Standard overvoltage (59) element may not detect this condition…they filter the waveform, missing the high peaks, and may have a long time delay (e.g. 30+ cycles)
- A peak instantaneous overvoltage (59I) element will detect and protect against this condition
  - -This element should sense on all three phases

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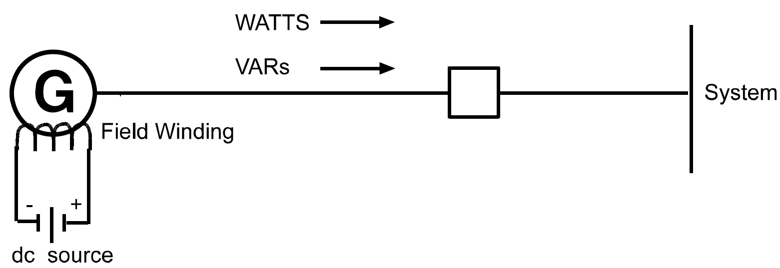
Synchronous Generator



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

- **Types of Generators**
  - Prime mover driven
  - Some wind
  - Some hydro (larger)

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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 PMG)
  - x''_d used for initial fault level determination
    - x''_d and t''_d is subtransient current time
  - x''_d used for next interval of fault level determination
    - x'_d and t'_d is transient current time
- Consult genset manufacturer for alternator data sheets!

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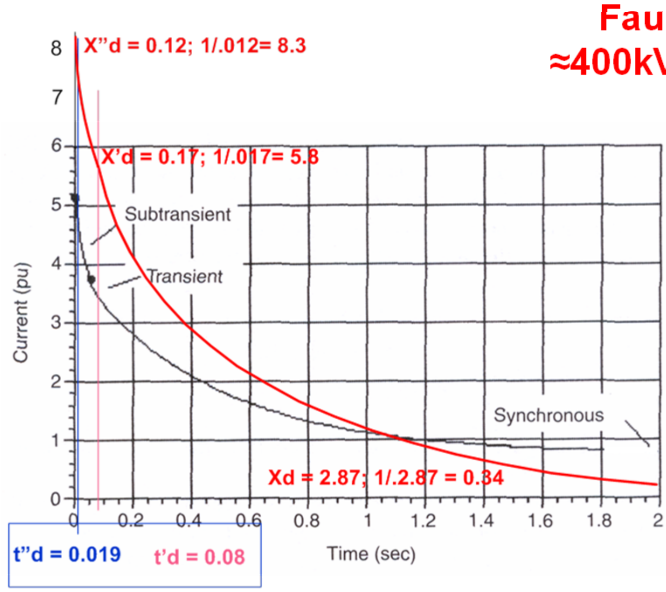
≈400kVA Generator

	50 Hz				60 Hz			
TELEPHONE INTERFERENCE	THF<2%				TIF<50			
COOLING AIR	0.8 m³/sec 1700 cfm				0.99 m³/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	[redacted]							2.87
X'd DIR. AXIS TRANSIENT	[redacted]							0.17
X"d DIR. AXIS SUBTRANSIENT	[redacted]							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.	[redacted]	0.08s						
T"d SUB-TRANSTIME CONST.	[redacted]	0.019s						
T'do O.C. FIELD TIME CONST.	1.7s							
Ta ARMATURE TIME CONST.	0.018s							
SHORT CIRCUIT RATIO	1/Xd							

Rated Amps = 482A

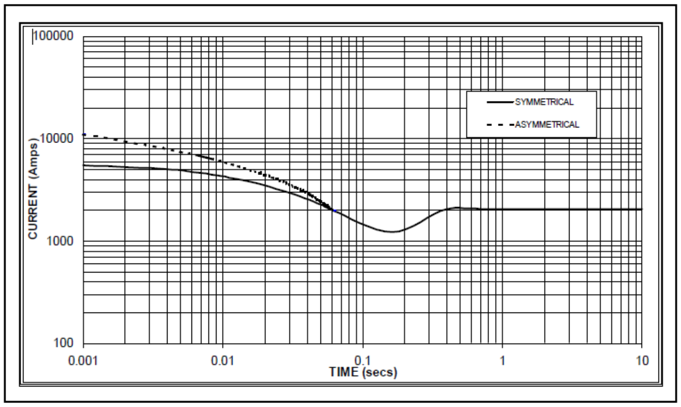
Fault Current for ≈400kVA Generator



Self Excited Genset

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 600A rated current**

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

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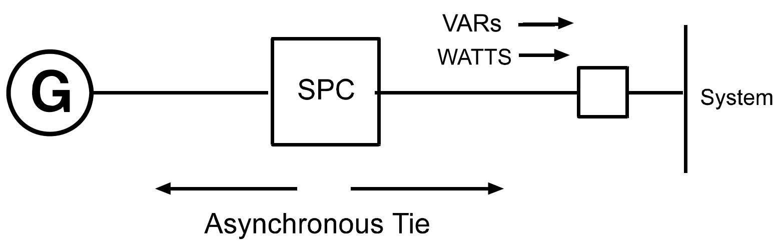
Asynchronous Generator:
Static Power Converter or Inverter



- **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**

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Self-Commutated Inverter

- 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 as Unity Power Factor*: Fault current will have a real component if inverter is operating at unity power factor
    - *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)

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Line-Commutated Inverters

- 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)
- Most line commutated inverters have built-in anti-islanding protection (if UL 1741 compliant)
  - SPC tries to periodically change frequency
    - If grid is hot, SPC cannot change the frequency
    - If grid has tripped, the frequency moves and the controller trips the machine
  - Difficult to test; some utilities do not trust and require other protection

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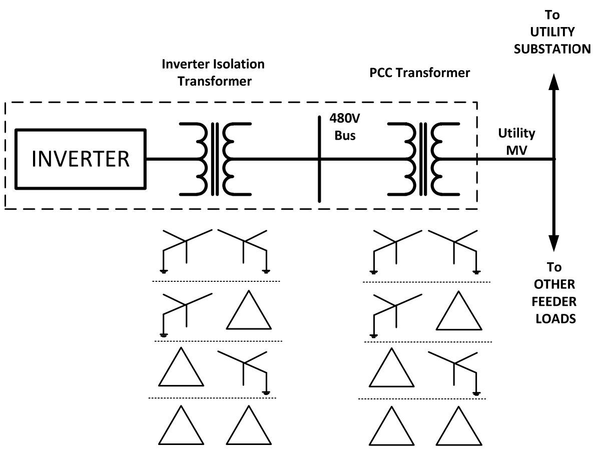
Inverters, Sudden Load Rejection and Overvoltage

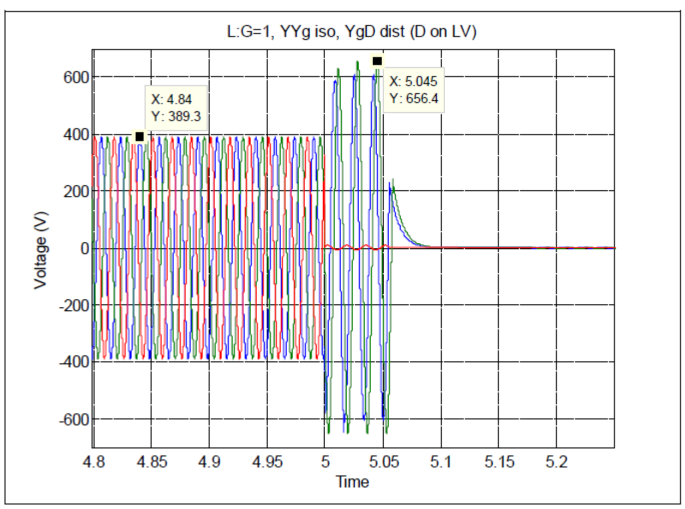


- Tests run on inverter to connected to 480V Bus, then connected to Utility MV feeder
- Used different ISOLATION transformer winding arrangements and PCC transformer winding arrangements
- Varied the level of load rejection (load:gen) to see transient voltage response effects

"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

99

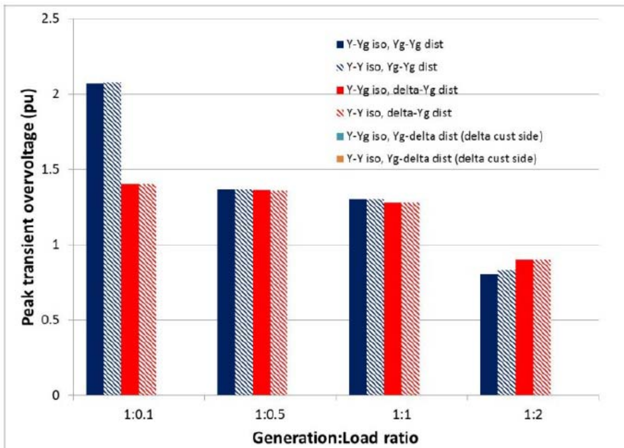
Inverters, Sudden Load Rejection and Overvoltage



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

100

Inverters, Sudden Load Rejection and Overvoltage

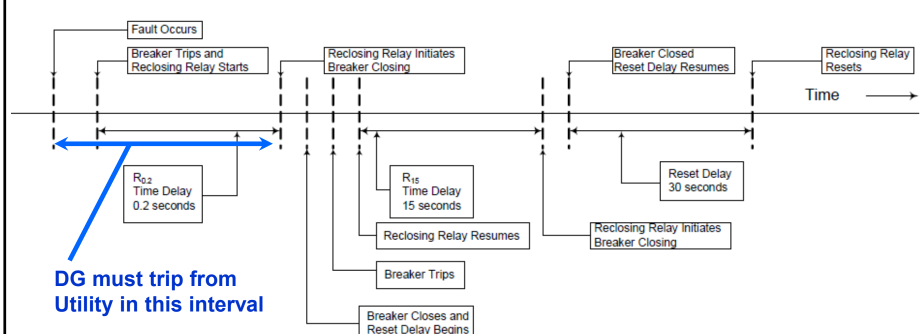


Transient overvoltage an inverter control issue, not a grounding issue

101

DG Reconnect Timer & Reclose Permissive

- 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

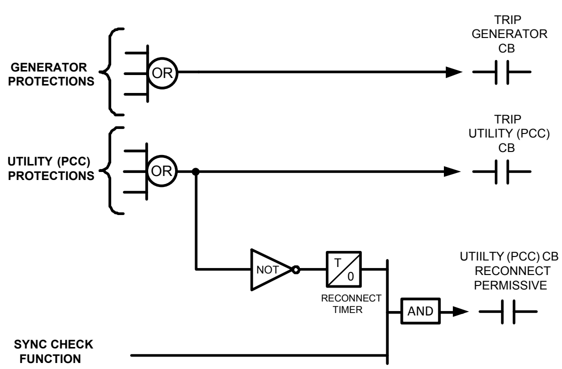
102

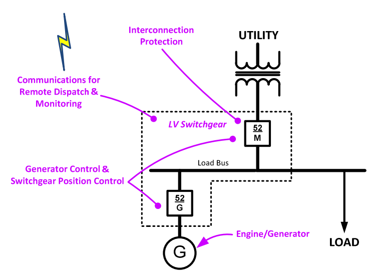
DG Protection Coordination

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

103

Typical Trip/Reconnect Logic



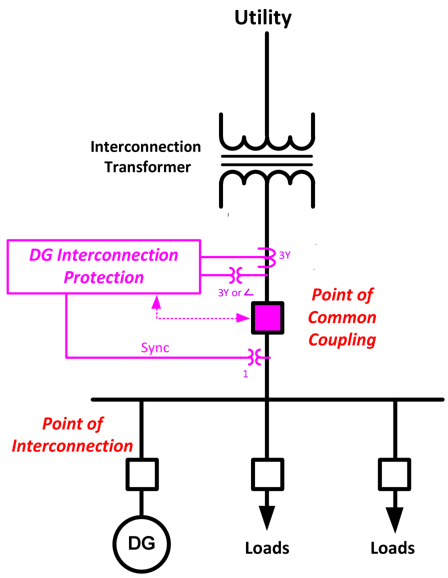


NOTES:

- "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)

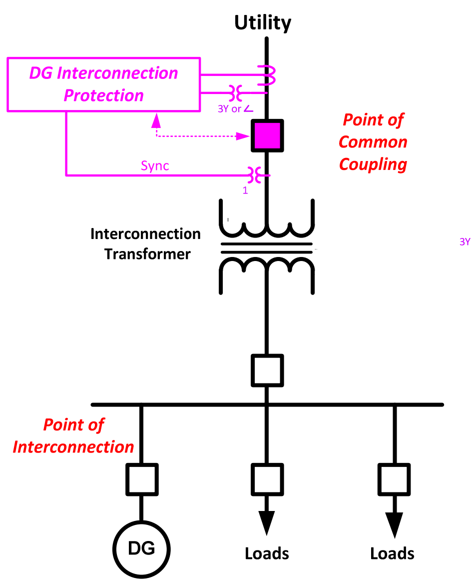
104

Interconnection Protection Placement



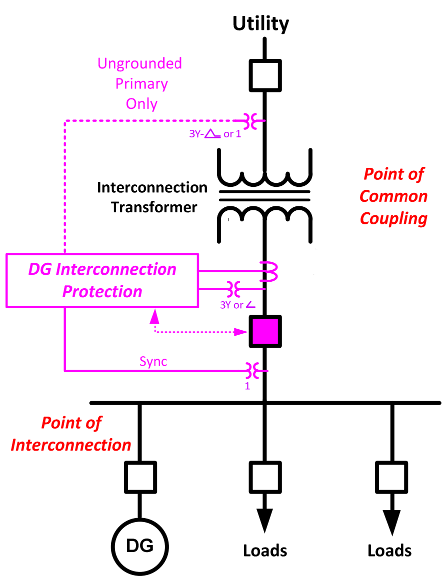
105

Interconnection Protection Placement



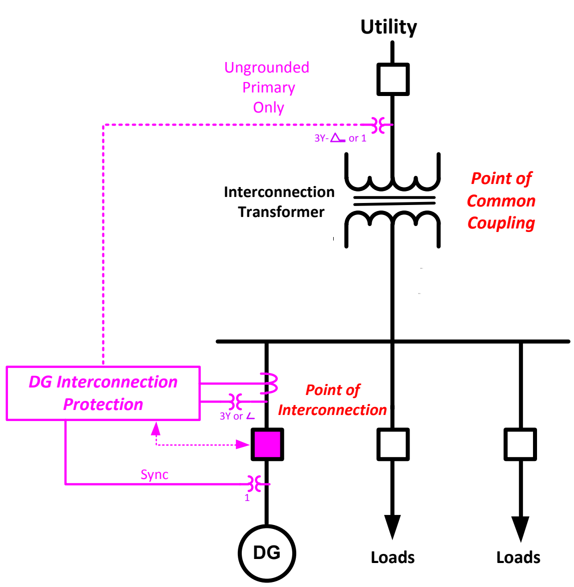
106

Interconnection Protection Placement

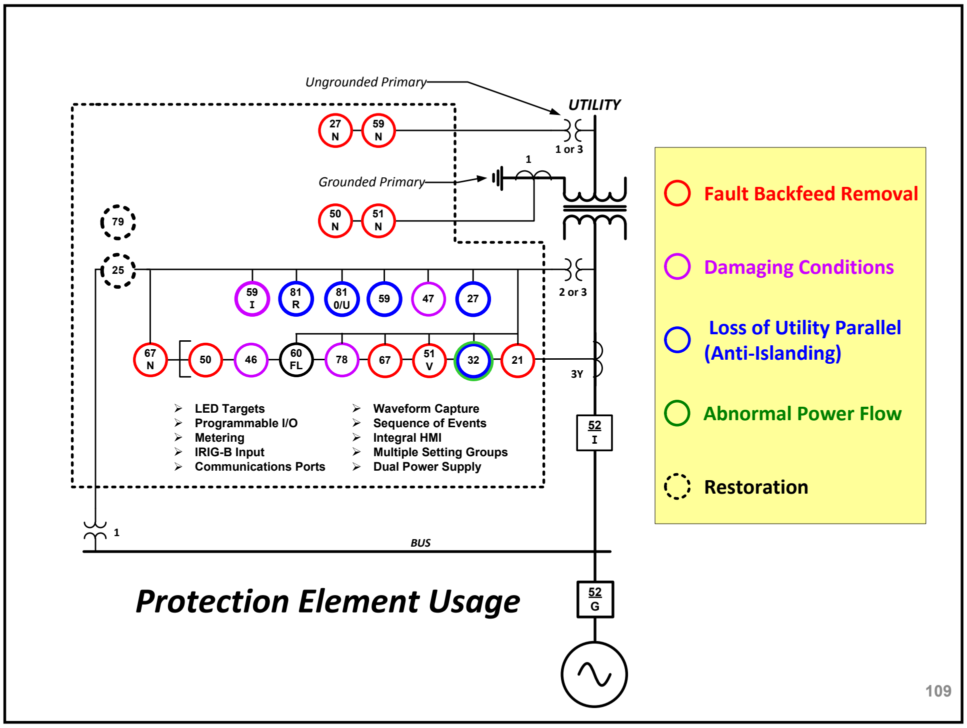


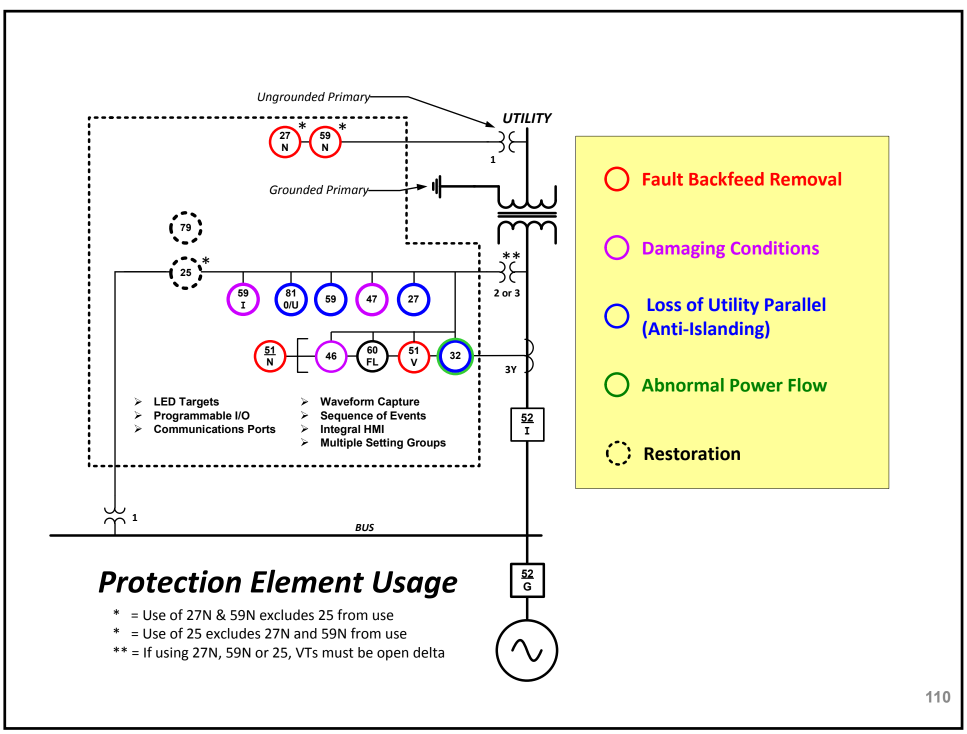
107

Interconnection Protection Placement



108

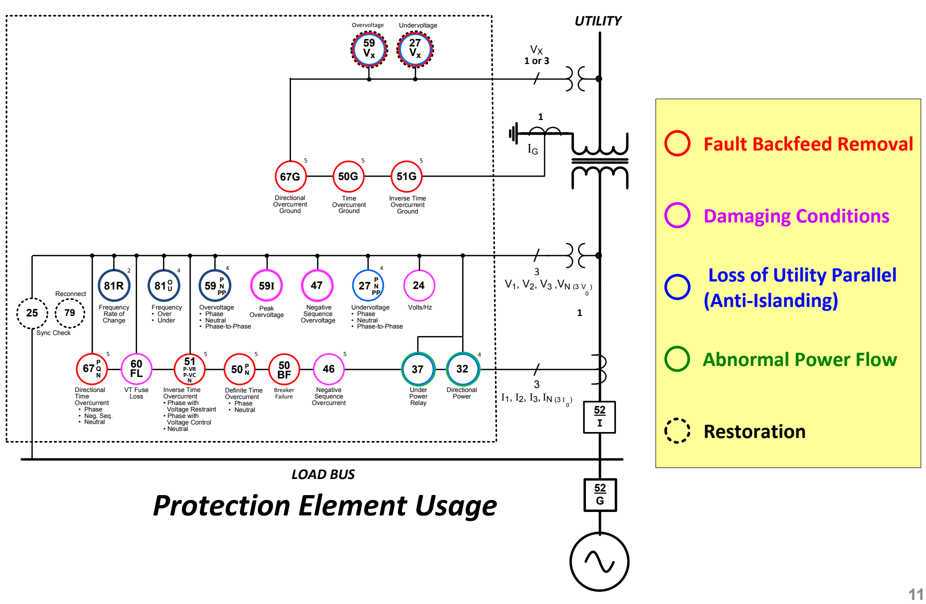

Ungrounded Primary
UTILITY
1 or 3
Grounded Primary
1
27 N
59 N
50 N
51 N
79
25
2 or 3
59 I
81 R
81 0/U
59
47
27
67 N
50
46
60 FL
78
67
51 V
32
21
3Y
LED Targets
Programmable I/O
Metering
IRIG-B Input
Communications Ports
Waveform Capture
Sequence of Events
Integral HMI
Multiple Setting Groups
Dual Power Supply
52 I
1
BUS
52 G
Fault Backfeed Removal
Damaging Conditions
Loss of Utility Parallel (Anti-Islanding)
Abnormal Power Flow
Restoration
Protection Element Usage
109


Ungrounded Primary
UTILITY
27 N *
59 N *
1
Grounded Primary
79
25 *
**
2 or 3
59 I
81 0/U
59
47
27
51 N
46
60 FL
51 V
32
3Y
LED Targets
Programmable I/O
Communications Ports
Waveform Capture
Sequence of Events
Integral HMI
Multiple Setting Groups
52 I
1
BUS
52 G
Fault Backfeed Removal
Damaging Conditions
Loss of Utility Parallel (Anti-Islanding)
Abnormal Power Flow
Restoration
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
110

Modern Convergent Protection Attributes

- 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



Protection Element Usage

112

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%

113

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%

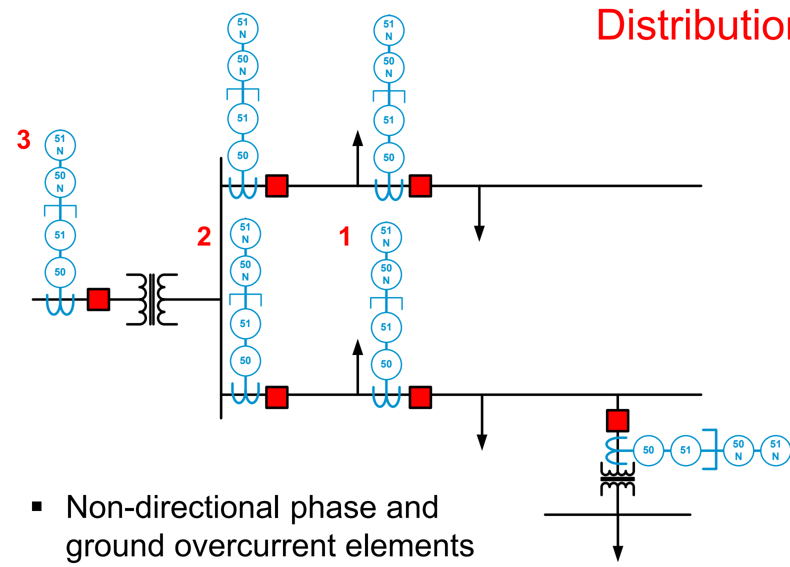
114

Bidirectional Fault Currents: Coordination

- Use directional elements in substation protection, mid-line reclosers and DG
  - Substation
    - Directionalize using 67 and 67N (instead of 50/51 and 50/51N)
    - Trip toward DG (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
  - DG
    - Directionalize using 67 and 67N (instead of 50/51 and 50/51N)
    - Trip direction away from DG (upstream)

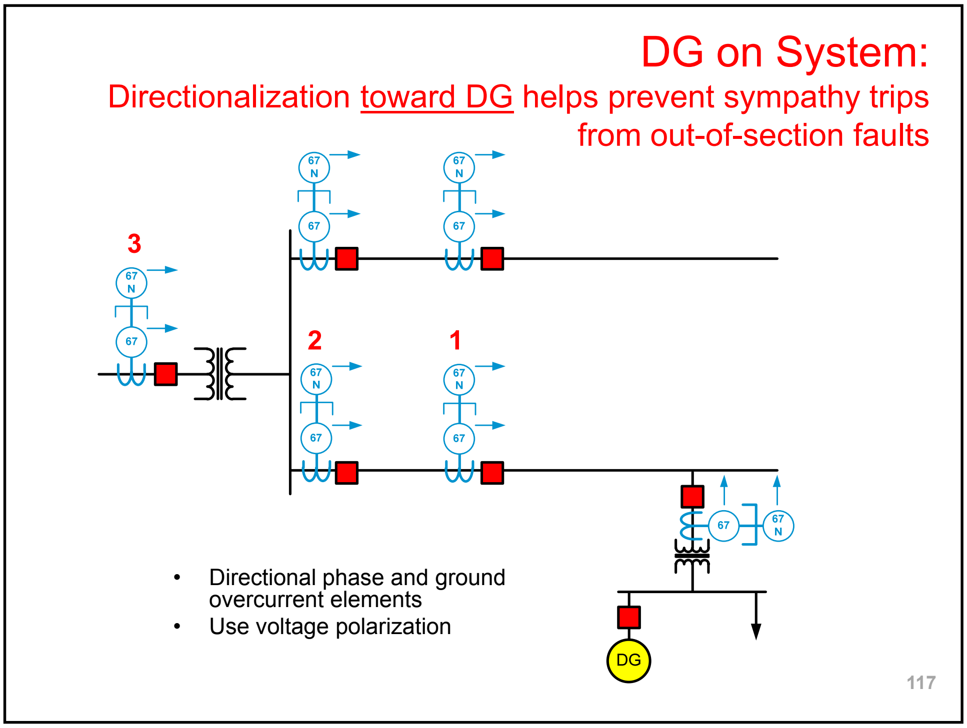
115

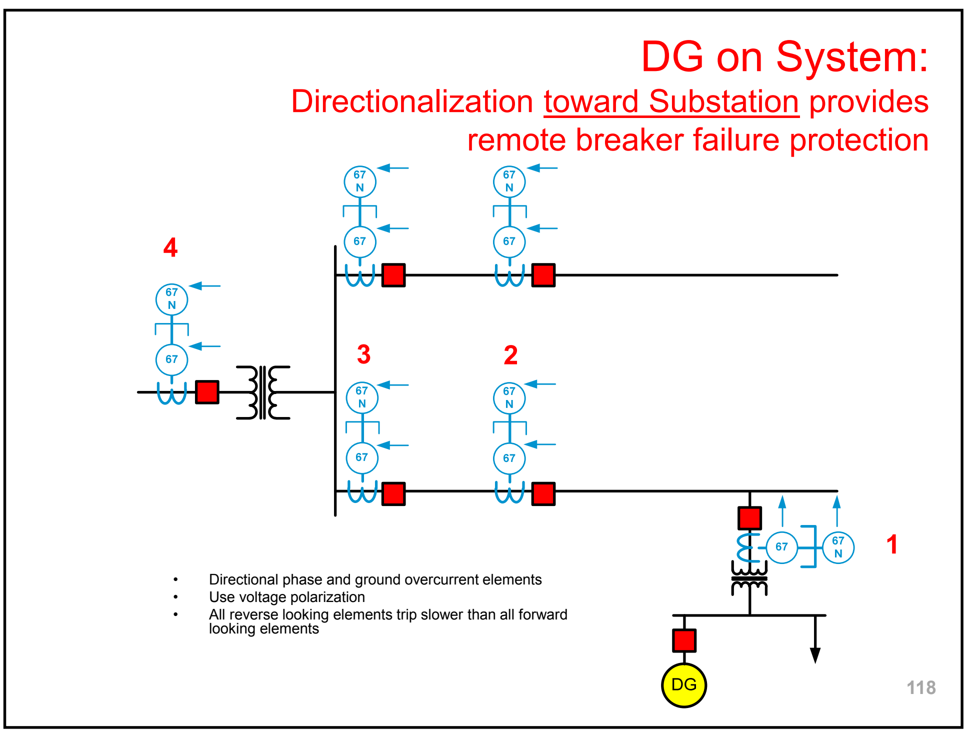
Regular Distribution



- Non-directional phase and ground overcurrent elements

116


DG on System:
Directionalization toward DG helps prevent sympathy trips from out-of-section faults
3
2
1
67
67 N
Directional phase and ground overcurrent elements
Use voltage polarization
DG
117


DG on System:
Directionalization toward Substation provides remote breaker failure protection
4
3
2
1
67
67 N
Directional phase and ground overcurrent elements
Use voltage polarization
All reverse looking elements trip slower than all forward looking elements
DG
118

IEEE Distribution Practices Survey – 1/02

DG 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%

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IEEE 1547 Addendum: *IEEE 1547A*
It's all about "Ride-Through" and Active VAR/Voltage Control

- As DG penetration increases, the ability to "ride-though" transient faults on adjacent feeders and transmission is becoming more important
- IEEE 1547 is currently under revision to include "loosening" of voltage and frequency limits to allow fault "ride-through"
- IEEE 1547 "A" addresses ride-through by making it a utility choice to allow or disallow it
- Off-nominal voltage and frequency may be greatly widened, offering ride-through capability
- Impact: Changes for protection setpoints for all types of DG

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IEEE 1547 Addendum: *IEEE 1547A*

- If large amounts of DG 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
  - o Distribution: Having large amounts of DG "shaken off" for transient events suddenly upsets loadflow and attendant voltage drops.
    - Impacts include unnecessary LTC, regulator and capacitor control switching
    - If amount of DG shaken off is large enough, voltage limits may be violated
  - o Transmission: Having large amounts of DG "shaken off" for transient events may upset loadflow into transmission impacting voltage, VAR flow and stability

121

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

Voltage range (% of the base voltage[a])	Clearing time[b] (s)
V<50	0.16
50≤V<88	2
110<V<120	1
120≤V	0.16

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

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

122

Proposed IEEE 1547A Trip values for Voltage (59, 27)

Default settings[a] 1		
Voltage range (% of base voltage[b])	Clearing time (s)	Clearing time: adjustable up to and including (s)
V < 45	0.16	0.16
45 < V < 60	1	11
60 < V < 88	2	21
110 < V < 120	1	13
V > 120	0.16	0.16

[a] Under mutual agreement between the EPS and DR operators, other static or dynamic voltage and clearing time trip settings shall be permitted 1

[b] Base voltages are the nominal system voltages stated in ANSI C84.1-2006, Table 1. 1

123

Present IEEE 1547 Trip values for Frequency (81-0, 81-U)

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

124

Proposed IEEE 1547A Trip values for Frequency (81-0, 81-U)

	Default settings		Ranges of adjustability[a]	
Function	Frequency (Hz).	Clearing time (s)	Frequency (Hz)	Clearing time (s)
UF1	57	0.16	56 – 60	0 – 10
UF2	59.5	20	56 – 60	0 – 300
Power reduction [b]	60.3	n/a	60 - 64	n/a
OF1	60.5	20	60 – 64	0 – 300
OF2	62	0.16	60 - 64	0 - 10

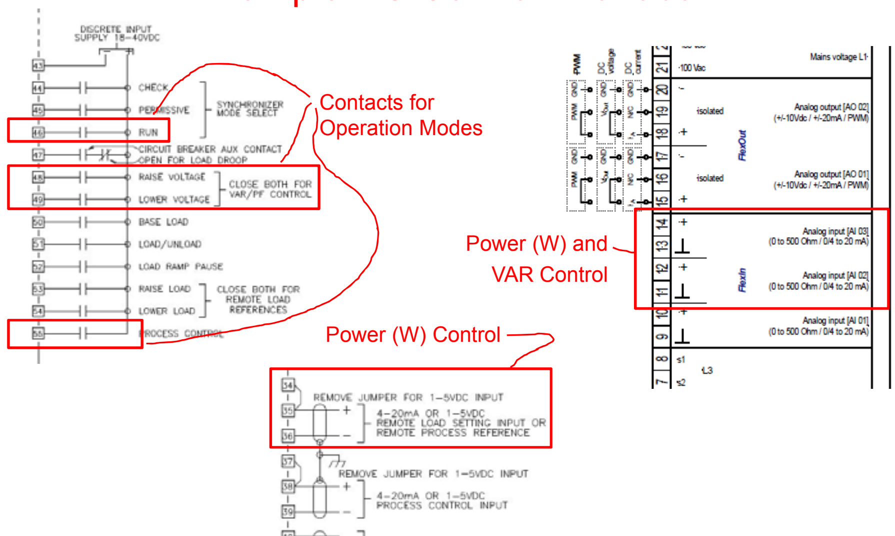
(a) Unless otherwise specified, default ranges of adjustability shall be as stated.
(b) When used, the DR power reduction function settings shall be as mutually agreed to by the area EPS and DR operators.

125

1547A: Active Voltage/VAR Control

- 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."

Example DG Control Interface



Controls incorporate setpoints, deadbands, ramp timers, etc.

DG Variability: V/VAR Issues

- Coping Methods for Fast DR Variability:
  - Consider that regulators change taps *sequentially* ensure voltage on feeder is quickly restored
    - Using sequential over non-sequential operation shortens time to restore voltage
  - Consider substation caps be controlled on VAR/pf with high voltage and low voltage override
  - Consider line caps be controlled on VAR/pf with high voltage and low voltage override

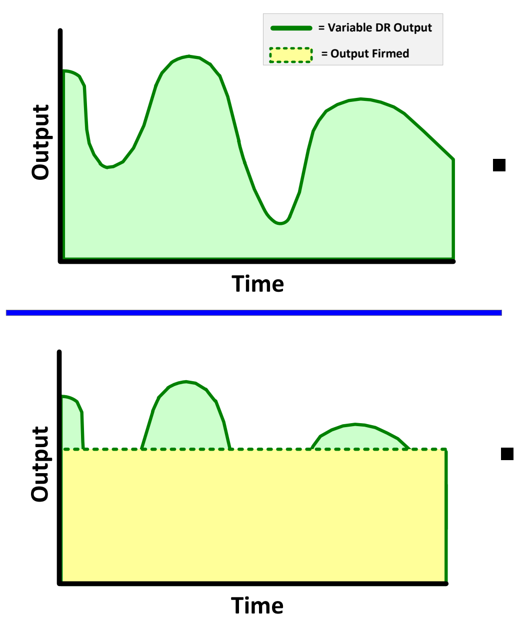
DG Variability: V/VAR Issues

Coping Methods for Fast DR 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 DG variable asset
    - Starting/Stopping
    - Direct setpoint control or initiating setting group changes

129

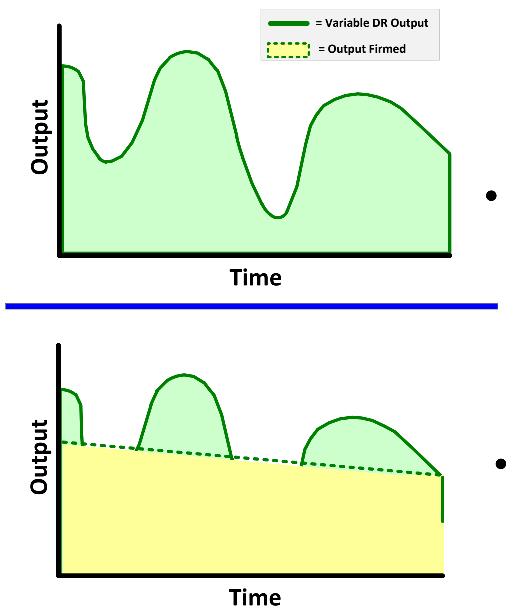
Constant Capacity from “Capacity Fill” Assets



- **Not Firmed**
- **Firmed**

130

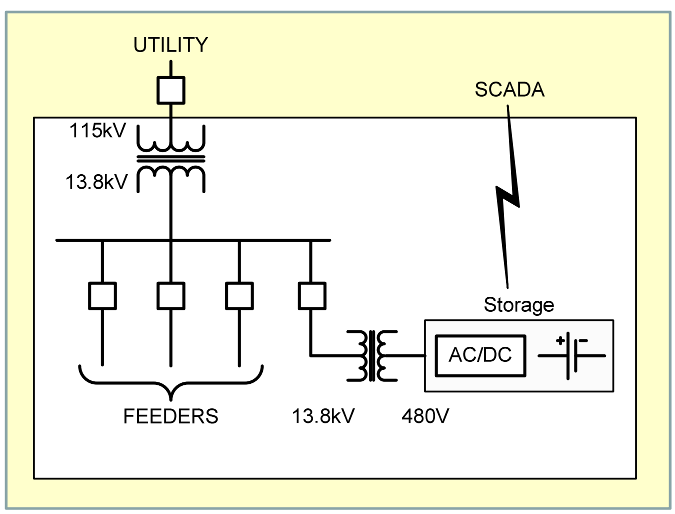
Ramped Capacity from "Capacity Fill" Assets



- **Not Firmed**
- **Firmed**

131

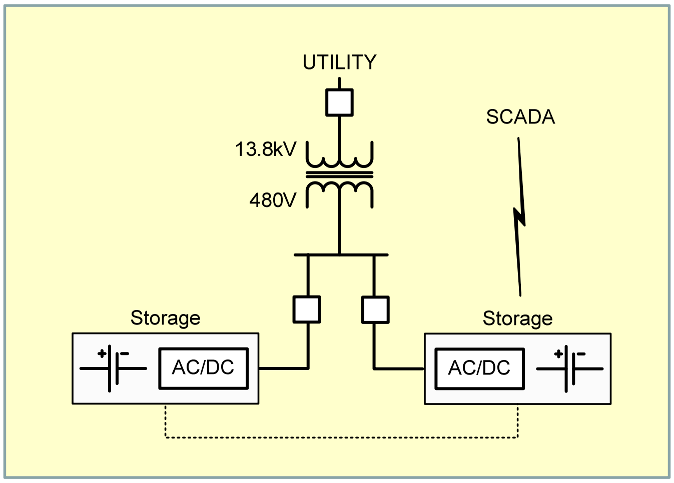
Storage Applications



Utility Distribution Substation Storage for Demand Response Use

132

Storage Modularity and Scalability

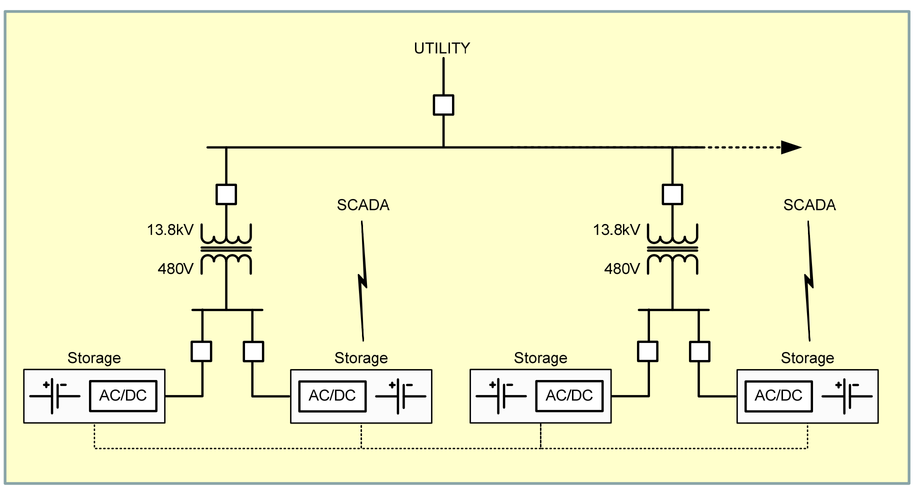


Build Capacity for

Storage Demand and Duration

133

Storage Applications

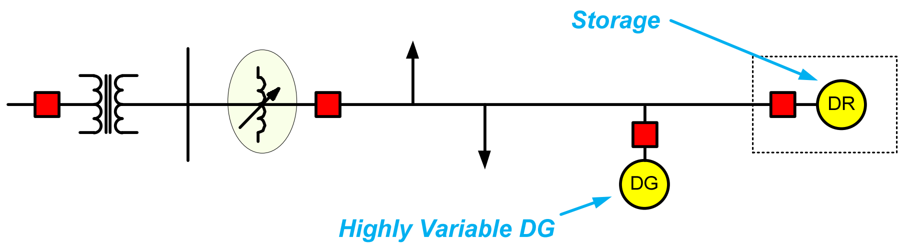


Adjust Storage Capacity for

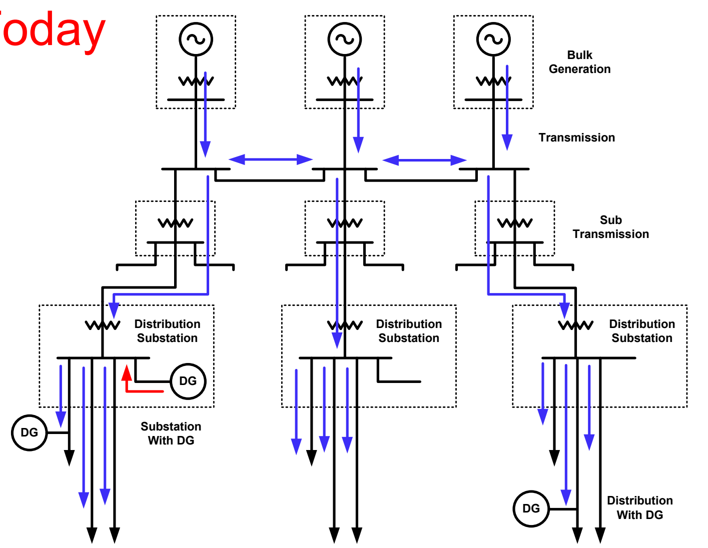
Scalable Demand and Duration

134

Storage Placement

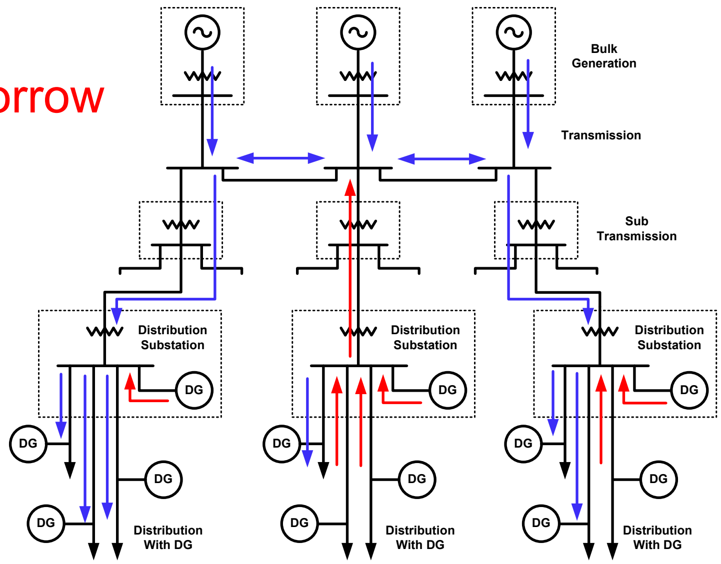


DG Today



Gen→Tran→SubTran→Dist→Utilization

DG Tomorrow



Bi-Directional Powerflows

137

Smart Grid and DG

- **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 DG**
  - Issue with high amount of DG capacity being lost at once for disturbance or other recoverable event
  - 1547A helps address that.

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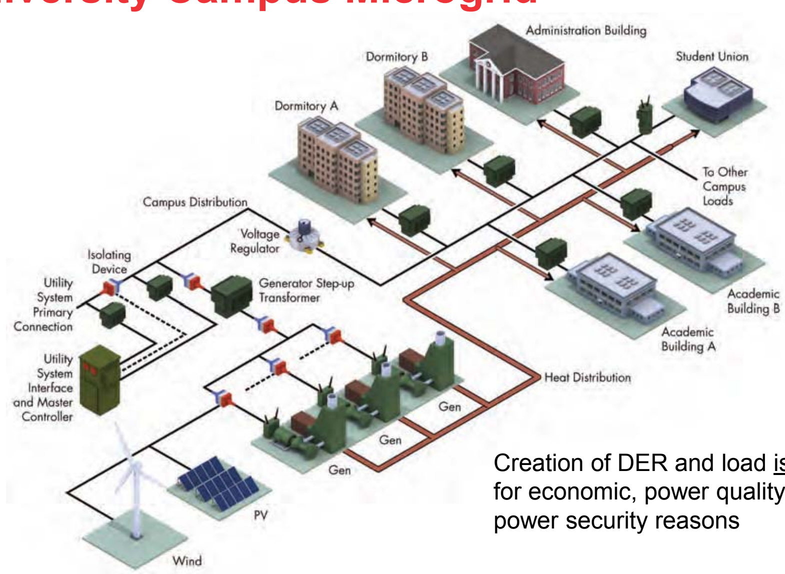
Smart Grids

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 DG Output (watt *and* VAR output)
- Energy Storage (to firm *variable* and *non-dispatchable* renewable DG)
- MircoGrid Operation System During Contingencies

139

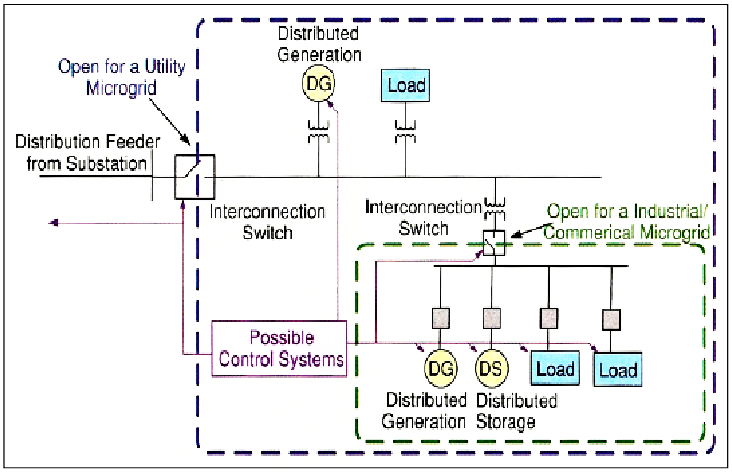
University Campus Microgrid



Creation of DER and load <u>islands</u> for economic, power quality or power security reasons

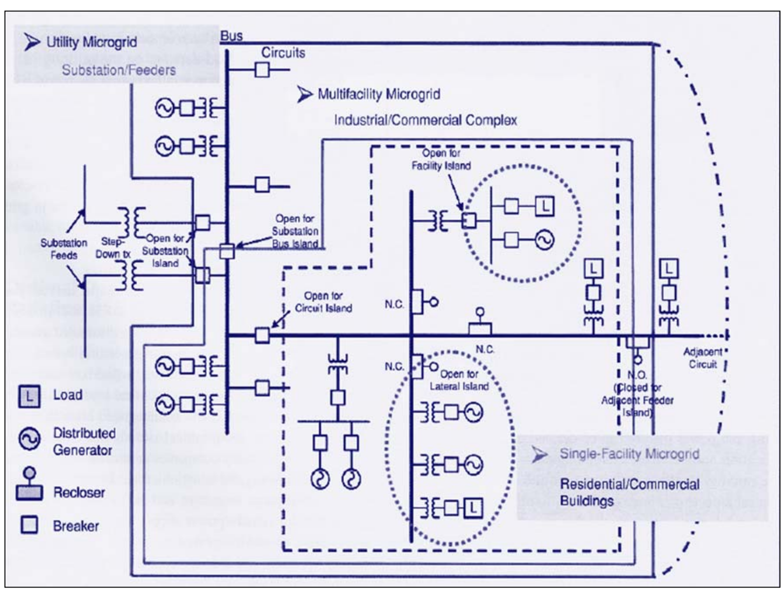
140

Smart Grids --- MicroGrids

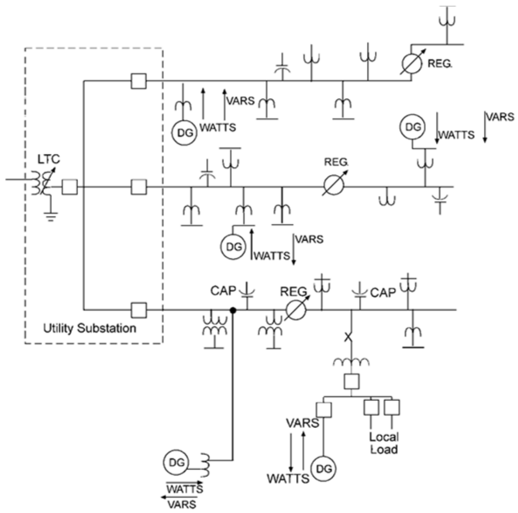


Just as a single DER is synced to the Utility, groups of DER as a Microgrid are synced to the Utility after operating islanded

Smart Grid Application of DG: Microgrids



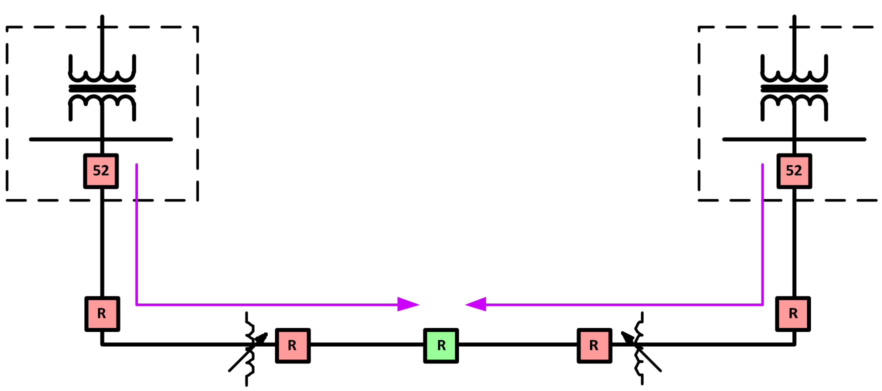
High Penetration of DG on Distribution Systems Will Require Smart Grid Technology to Control System Voltage



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

143

Voltage Control Considerations from Loop Restoration



- Consider this system with a two lines with an normally open tie
- Regulator forward direction is toward normally open tie point

52 = circuit breaker at station

R = Recloser on the line

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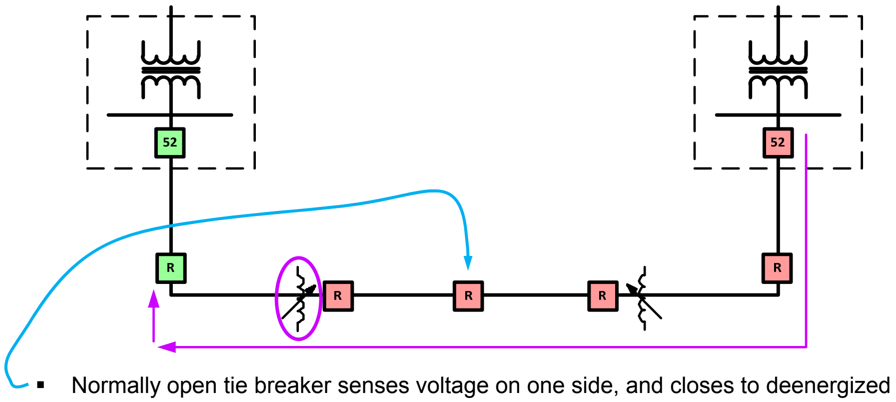
Voltage Control Considerations from Loop Restoration



- Normally open tie breaker senses voltage on one side, and closes to deenergized side
- In loop restoration mode, the circuit will reconfigure and power will flow backwards through some reconfigured sections
- The regulator control should be set to REVERSE to adopt to the reconfigured line's source power flow
- It should regulate in the reverse direction, and use settings for the new direction and line model for LDC

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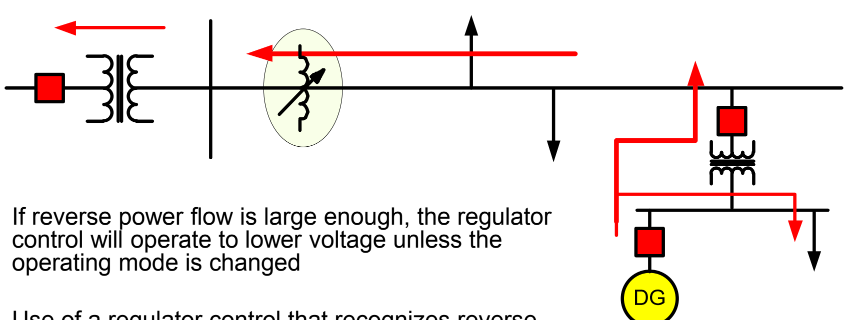
Effects of Reverse Power from DG on Line Drop Compensation (LDC)



- If reverse power flow is large enough, the regulator control will operate to lower voltage unless the operating mode is changed
- Use of a regulator control that recognizes reverse power flow can be set to BLOCK reverse power LDC effects
- The regulator control then ignores the negative LDC effects and maintains regulation in the forward direction

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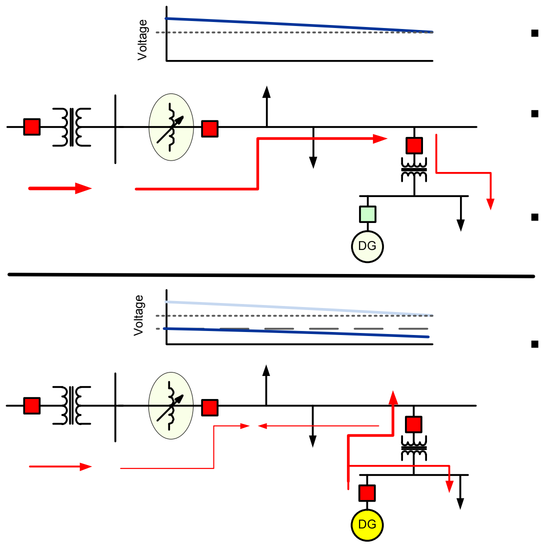
Effect of DG on Regulator Line Drop Compensation (LDC)



- LDC is reduced when DG contributes power
- More DG power = less load = less LDC = voltage setpoint lowers
- If DG is in PF mode, it maintains a VAR output to not import or export any VARs, so it cannot control voltage
- Result: Lower voltage at end of line than desired

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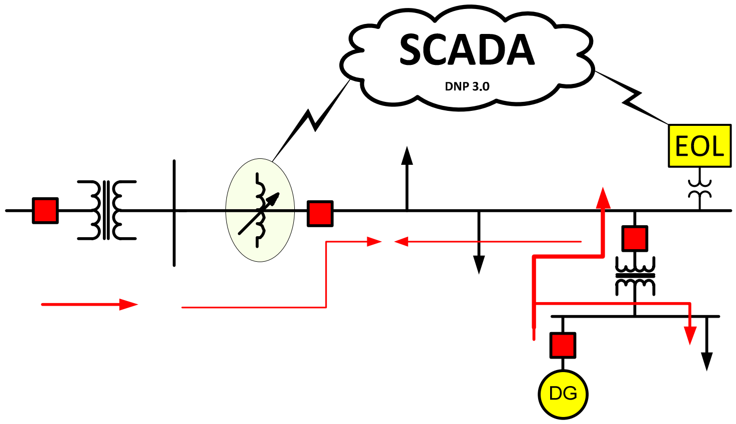
What do you do if your system is highly reconfigurable?

- DG all over the place
- Multiple locations to sectionalize making modeling difficult
- The DG move "move around" as the system is sectionalized and reconfigured
- The DG is highly variable, and can provide all the load or even backfeed to supplying substations
- You have Microgrid, and what is normally "top down" becomes multiple sources, variable sources and varying toplogies

Communications and Smart Controls

148

Use of an End-of-Line Monitor (EOL) to Transmit Voltage Value to the Regulator



- With EOL feedback, you are not modeling the EOL voltage. You measure it.
- EOL monitoring, working with a regulator, can handle dynamic situations and multiple sources to adjust line voltage

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Summary

- Properly designed interconnection protection addresses concerns of both DG 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
- Restoration practices need to be part of the overall interconnection protection
- Smart Grid Solutions will be needed to meet high penetrations of DG
- Protective relays for DG interconnection protection will find greater application in inverter-based systems due to the adoption of IEEE 1547A
- Active VAR control of DG will allow compensation for variable power output

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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
- Update on the Current Status of DG Interconnection Protection--What 1547 Doesn't Tell You, Charles Mozina, Beckwith Electric, presented at the 2003 Western Protective Relay Conference On Beckwith Web site
- Standard Handbook of Power Plant Engineering, McGraw Hill, ISBN# 0-07-0194351 Section 4.3, Electrical Interconnections, W. Hartmann

151

Recommended Reading

- 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
- How to Nuisance Trip Distributed Generation, W. Hartmann, presented at the 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

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