Configurable PV Solutions and Resultant Impacts to our Ever-Changing Electrical Grid

August 2\textsuperscript{nd} 2013
IEEE Sustainable Technologies Conference
Presentation Overview

• PV Penetration Impacts on Electrical Infrastructure
  ➢ Interconnection Variation and Configurability Needs
  ➢ Power Electronics and Inherent Capabilities

• Deterministic Solution Set
  ➢ Features / Functions
  ➢ Control Modes
  ➢ Asset Coordination

• Case Study
  ➢ Modeling, Lab Validation, Field Deployment
  ➢ Baldock Solar Site
PV Penetration and Existing Electrical Infrastructure

AE Solar Energy
Distributed Generation Resource Management

- Aging Infrastructure
- Increasing PV Adoption
- Configurable, Deterministic Solution Set
- System and Load Diversity
Electrical Distribution Systems

• One of the “Supreme Engineering Achievements of 20th Century”
  - Reliably
  - Safely
  - Economically

• Significant Technology Developments
  - Automatic circuit re-closers
  - Automated sectionalizing and tie switches
  - Digital metering infrastructure
  - Digital relays
  - PMU capability for system analysis

* Data for graph courtesy of US Energy Information
The Aging Electrical Infrastructure

• “Deterministic” System Design
  ➢ Short / long term forecasting
  ➢ VR equipment settings
  ➢ Protection settings

---

Distribution Engineering Factors

<table>
<thead>
<tr>
<th>Traditional</th>
<th>Additional Factors Today</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage levels</td>
<td>Voltage Stability</td>
</tr>
<tr>
<td>Phase balance</td>
<td>Minimum load for DG</td>
</tr>
<tr>
<td>Maximum demand</td>
<td>Net load/supply variability</td>
</tr>
<tr>
<td>Load factor</td>
<td>Load &amp; DG Harmonics</td>
</tr>
<tr>
<td>Power Factor</td>
<td>System Transients</td>
</tr>
<tr>
<td>Short Circuit Current</td>
<td>Protection coordination</td>
</tr>
<tr>
<td>Deterministic Modeling</td>
<td>Stochastic Modeling</td>
</tr>
</tbody>
</table>

---

Evolving Customer Loads

• Digital era
• Agricultural – consolidation
• Demand response
• Energy conservation
US Solar Market Growth

Mapping Solar Growth in the U.S.

2001 2002 2003 2004 2005 2006 2007 2008


1,9 GW 3.2 GW 3.9 GW 5.4 GW 6.7 GW 8.6 GW

1,000 MW

*charts courtesy GTM
PV Integration Projections

- Increasing # installations
- Increasing system size
- Geography and adoption

- High penetration
  - Capacity / min load
  - Output / nameplate
- Advanced services
  - Intermittency mitigation
  - Fault handling
- Capacity factor
  - Reliability

*charts courtesy of IMS 7/12
Obstacles | Barriers to PV Growth

**Short Term**
- Interoperation with VR Equipment
  - Cap banks
  - LTC’s
- Coordination with Protection Schemes
  - TOV
  - Re-closer events
- kWh vs. kVAr
  - Incentive programs
  - Voltage support

**Medium Term**
- System Level Impacts
  - Storage Integration
  - Forecasting
  - Protection Enhancements
- Economic Comm’s Network
  - Function Management
  - Reliable / Robust
- Capacity Factor
  - System Overdesign
  - Burst Operation
  - Storage integration
Inverter Capabilities:

Power Electronics Enabled Features and Functions

AE Solar Energy
Voltage and Frequency Trip Points

- **EXISTING AND RECOMMENDED VOLTAGE RIDE THROUGH**

- **EXISTING IEEE-1547 LIMIT a**
- **EXISTING IEEE-1547 LIMIT b**

- **PROPOSED CEC/CPUC VOLTAGE RIDE-THROUGH PROFILE**

- **HECO PROPOSED VOLTAGE RIDE-THROUGH PROFILE**

- **HECO PROPOSED FREQUENCY RIDE-THROUGH PROFILE**
Inverter Response to Grid Transients

Example settings for providing % of available vars:

- P1 (V = 97%\text{V}_{\text{Ref}}, Q = 50\%\text{VAR}_{\text{Avl}})
- P2 (V = 99\%\text{V}_{\text{Ref}}, Q = 0\%\text{VAR}_{\text{Avl}})
- P3 (V = 101\%\text{V}_{\text{Ref}}, Q = 0\%\text{VAR}_{\text{Avl}})
- P4 (V = 103\%\text{V}_{\text{Ref}}, Q = -50\%\text{VAR}_{\text{Avl}})

VAr response (reactive power)

Watt response (real power)

VAr response (dynamic)
Configurable Platform of Solutions

- Voltage Support Functions
  - Loop Type (Open / Closed)
  - Reactive Power Control (VARs)
  - Real Power Control (Watts)
  - Trip Points Voltage / Frequency

- Priority Control Structure
  - 1. Directly Commanded
  - 2. Wide Area Information
  - 3. Scheduled Operation
  - 4. Fixed Operation

- Degree of Communications
  - Secure Robust
  - Internet Connectivity
  - Intermittent / No Communications

- Management / Configuration Tools
  - Deterministic
  - User configurable
  - Authentication and authorization
  - IMC vs. Stand-alone
Inverter Architecture Function Management

- Service / Support
- User Interaction
- Configuration / mgmt

- Pre-stored operating conditions
- Function Management
- Data aggregation / communication mgmt

- Output current
- Safety functions
- MPPT / Active UIC
Basic Inverter Controls / Inverter Management

- Real Power Curtailment
  - Managing watt output
- Reactive Power Management
  - % Nameplate VAr’s
  - % Available VAr’s
- Global Control Variables
  - Ramp time
  - Reversion
  - Randomization
- Enable / Disable
- Network Configuration
User Configurable Voltage Trip Points

- Curve Settings:
  - LVRT envelope allows 0.3 to 0.75 p.u. for <= 5 sec

- RS90 (Grid Event)
  - Voltage sag to 0.7 p.u. for 6 sec
Volt – VAr Response to Grid Transient

Device Configuration  ——— Grid Event  ——— Inverter Response
User Configurable Frequency Trip Points

- **Curve Settings:**
  - Trip envelope allows 57 – 59.5 Hz for <= 2 sec

- **RS90 (Grid Event)**
  - Go to 58 Hz for 2.5 sec (for clarity, voltage will go to 0.98 p.u. as well)
Frequency–Watt Response to Grid Transient

Device Configuration — Grid Event — Inverter Response
Case Study:
Baldock PV Site
Modeling, Lab Verification and Field Validation
Modeling and Simulation

- Data gathering / Modeling
  - Detailed models built of all of the selected PGE and PEPCO feeders
  - AE transient inverter model detailed and leveraged with volt-VAr and frequency-watt functions implemented.
  - Complete feeder level model analyzed for sub-transient, transient and steady state response.
AC Voltage Response to Motor Start Event

- Simulation results to date: Canby-Butteville
Voltage Regulator Response to Motor Start Event

- Canby-Butteville (simulation)
Laboratory Testing and Validation

- **Sandia National Laboratories**
  - Scaled testing (50 kVA inverter)
  - Preliminary functions

- **Advanced Energy Lab Testing**
  - Scaled testing (50 kVA inverter)
  - 500 kVA preliminary tests
  - User interface testing

- **National Renewable Energy Laboratories (ESIF)**
  - 500 kVA full power testing
  - Full system tests “black box”
  - HIL and PHIL Testing
Inverter Response to Grid Sag Event

Grid Sag Event
1) Step change from 1.0 per unit to 0.7 per unit

Inverter Response
Transition to VAr source per defined user configurable profile and maintain until sag ends or trip point envelope is reached.
Frequency Ride-Through and Inverter Response

Frequency Ramp:
1) Start 60 Hz
2) Ramp to 61.5 Hz (2s)
3) Ramp to 60 Hz (3s)

Inverter Response
Curtail output to rising frequency according to defined watt-frequency curve
Feeder Performance – Equipment Installation

• West Coast: Canby-Butteville Feeder
  - Installed 5 PMU’s along service feeder
  - PMU with GPS clock, Radio, Logging Capability
  - Transmitting data to Baldock PV site
Baldock PV Site Equipment Installation

All equipment for long term demonstrations installed at site
- IMC, meter, radio receivers, inverter connections, etc.

Data collection and analysis ongoing to validate models
- Volt/VAr response, ramp rate controller response, island detection validation
Butteville Regulator Response (April)

788 tap changes in 20 days
Results of System Study (to-date)

• In summation, the volt-VAr functions ~can~ provide major benefits on feeders
  ➢ Definitely effective in mitigating the local impacts of cloud transients
  ➢ Can provide significant benefit in improving the feeder voltage profile under other contingencies, such as large load or capacitor switching

• However, the level of benefit ranges from zero to a lot, depending on the feeder configuration as well as the installation size and location
  ➢ High penetration
  ➢ Distributed model
A Look Ahead -- Wide Area Control
Conclusions

• PV adoption rates driving need for additional grid supportive functions throughout distribution circuits

• Interconnection standards evolving to allow for distributed generators to perform voltage and frequency stability functions.

• Power electronics based inverter solutions offer flexible, deterministic programmable response

• Solution set can be re-purposed to accommodate circuit reconfigurations and load modifications.

• Field tests, and long term case studies ongoing to validate models, simulation results, and opportunities
Practical Implications of Functionality

• Distributed Voltage Stabilization
  - Brown-out mitigation
  - Demand charge reduction / elimination

• Interconnection Rules Conformity
  - Electrical and geographical needs
  - Load forecasting and future control modifications

• Electromechanical Voltage Regulation Equipment
  - Reduce cycle counts (regulators, cap banks, LTC’s)
  - Reduce / eliminate need for re-conductoring

• Feeder, Sub-Transmission and Transmission Efficiency
  - VAr source – load match
  - Response time / distance
  - Congestion reduction
Practical Implications of Frequency Watt

• Electrical System Inertia
  ➢ Rotating machine impacts
  ➢ Island operations

• Droop Response
  ➢ Programmable to match system requirements
  ➢ Isochronous vs. droop (sharing the “load”)
  ➢ Aggregate plant damping

• Micro-Grid Compliant
  ➢ 4 – quadrant operation finalizes system
  ➢ PLL capabilities scale across platforms
  ➢ Deterministic operation
Inverter Master Controller (IMC)

• **Real Time Automation Controller**
  - Communications flexibility
    - DNP 3.0, IEC 61850, Modbus
  - Aggregation of controls / monitoring
  - Industry accepted solution

• **Coordination of multiple resources**
  - Risk mitigation for inverter interaction
  - Extension of system visibility

• **Integration of functions**
  - Voltage support functions
  - Island detection
  - Ramp rate controller (storage)
Utility Scale Site Mock-Up (IMC Role)