NEXT-GENERATION GRID COMPONENTS R&D PROGRAM PLANNING WORKSHOP

August 17-18, 2016

University of Pittsburgh
Swanson School of Engineering, Benedum Hall
3700 O'Hara Street, Pittsburgh, PA 15213

Proceedings Document

Contents

Overview

This document contains the organized results of the Next-Generation Grid Components R&D Program planning workshop held on August 17-18, 2016 at the University of Pittsburg in Pittsburg, PA.

Purpose

- To identify gaps in the landscape of grid transmission and distribution components, highlight opportunities for R&D, and outline goals and priorities.
- Inform the development of DOE's Transformer Resilience and Advanced Components (TRAC) multi-year program plan (MYPP).

The agenda was structured around three breakout sessions that asked a series of focus questions to achieve the purpose of this workshop. Each parallel breakout group was led by a professional facilitator and consisted of no more than 20 participants to promote discussions and interactions.

Agenda

Day 1: Wednesday, August 17, 2016

Time	Activity
8:00 am	**Registration and Networking**, *Coffee*
8:30 am	**Welcome, Overview of the Electric Power Initiative** • *Dr. Gregory Reed, Director, Center for Energy, University of Pittsburgh*
8:50 am	**Overview of Workshop and the TRAC Program** • *Kerry Cheung, U.S. Department of Energy*
9:10 am	**Plenary Presentations: Equipment and Performance Needs for the Future Grid** • *Steve Griffith, NEMA* • *Jeff Hildreth, BPA* • *Steve Whisenant, Duke Energy* • *Dale Player, ComEd* • *Lilian Bruce, EPB* • *Joe Schatz, Southern Company* • *Kevin Berent, EPRI*
10:40 am	**Break**
10:55 am	**Overview of the City of Pittsburgh Microgrid Initiative** • *Ben Morris, Duquesne Light*
11:15 am	**Overview of Grid Components Landscape: Challenges and Opportunities** • *Dominic Lee, ORNL*
11:40 am	**Breakout Session Instructions and Charge to Participants** • *Brian Marchionini, Energetics Incorporated*
11:45 am	**Lunch** *(see Event Map for local options: https://goo.gl/pgb4XL)*

1:15 pm	**Parallel Breakout Session 1** • *Transmission Components R&D Gap Discussion*
3:00 pm	**Break**
3:15 pm	**Parallel Breakout Session 2** • *Distribution Components R&D Gap Discussion*
5:00 pm	**Break and return to Plenary Room**
5:15 pm	**Report Outs** (*5 min debrief from each group, with Q&A*)
5:30 pm	**Adjourn and instructions for next day**
7:00 pm	**No Host Dinner at The Porch, 221 Schenley Drive**

Day 2: Thursday, August 18, 2016

Time	Activity
8:00 am	**Coffee**
8:30 am	**Parallel Breakout Session 3** • *T&D Priorities and Goals Discussion*
10:00 am	**Break**
10:15 am	**Crosscutting Discussion (Program Portfolio)**
11:00 am	**Next Steps and Adjourn** • *Kerry Cheung, U.S. DOE*
11:15 am	**Optional tour of University of Pittsburgh's Energy Power Systems Lab**
12:00 pm	**End Tour**

Presentations

The presentations from this workshop can be found on the U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability, Transformer Resilience and Advanced Components R&D Program website:

https://energy.gov/oe/services/technology-development/transformer-resilience-and-advanced-components-trac-program

Transmission Components Discussions

Red Group

Parallel Breakout Session 1: *Transmission Components R&D Gap Discussion*	
Focus Question #1: What are the key issues or challenges facing current transmission system components that impact or limit their utility/performance in a future grid (2020-2040)?	
• High Bm/F/Low loss magnetic material innovations • VAR compensation – there is a need for this as generation is retired • Can't upgrade system transmission capacity easily • SF6 Gas as an interrupting medium • Intermittency of renewable generation • Lower stability due to reduced inertia • Changing geographic makeup of generation • High Z transformers to limit fault currents • Higher fault currents • Too much data; difficulty in translating to information • Integration: The existing infrastructure we have is copper. The new infrastructure is fiber, etc. • Lack of standards that apply to the technology being developed • Cables accumulate ice • Critical infrastructure designations and its limitations • Will trajectory of energy mix be the same? We may be wrong with what the future energy mix will look like. What will be the energy mix in the future? Will it be continually changing as it has up to this point? • Managing increasing complexity of protection (dynamic protection) • Health monitoring of aging infrastructure • Utility resource assessment survey • Perceived lifetime of power electronic systems → reliability • High cost of underground transmission (both installed and operating [VARS]) • Preventing busing failure/lifecycle extension	• Hindrance to integrate standards -> ANSI/IEC/IEEE/UL • Bidirectional/network power flow • Substations are vulnerable to flooding • System capacity & congestion issues, especially with variable renewables; no power flow control capability today • Time to replace failed equipment is too high • Modularity and standardization needed to LPTs; requires impedance control w/o impaction cost, life and efficiency • Customer built equipment • Large power transformer flexibility and modularity is low. Degrades system resiliency, restoration, long lead time, no control, too heavy & large • Large power transformer failure • Transmission & distribution systems integration for non IOU → lack of integration between G&T/D • "Sensors" vs measurement systems • Functional testing of new equipment at rated power • Seeking PMU solutions for asset health warnings • Moving PMU info into real time operations • Fast transformers replacement → asset utilization w/ change in industry/location • Aging infrastructure → Difficult to know what to monitor • Large geomagnetic disturbance can saturate transformers • Lack of cost effective wat to maximize use of right of way • How to integrate/connect economically high levels of variable renewable energy into the existing transmission system without impacting reliability • Lack of switchgear technology innovation • < 12 months availability → shorten time to market

Focus Question #2: What new requirements, capabilities, or functions will be needed or is desired for the range of transmission system components (see table below) to address the issues or challenges identified? (Numbers in parenthesis indicate the votes for top requirements, capabilities, or functions)

Transformers	**Cables and Conductors**	**Power Flow Controllers**
• Easy to transport transformers & flexible designs (9) • Solid state transformer for rapid deployment (9) • Low core loss magnetic material for large power transformers (5) • Transformer lead times – 1 week (4) • Large power transformer test bed for EMP/GMD (3) • Optimize stockpile quantities of LPT components (1) • Modular LPT with controllable impedance to allow paralleling. Fail normal, high efficiency, fault ride through, low cost • Distributed, smaller rated LPTs can realize larger systems but w/o reaching CIP circuits, more resilient	• Low cost, high capacity; easy to install underground cables (5) • Hybrid AC/DC line (1) • Minimal sag conductor (2) • Submarine cables for future offshore wind: cost/reliability improvement needed	• Power flow controllers to maximize utilization (6) • Lower cost HV converter (3) • Coordinated control/use of controllers (3) • For power flow controller on conductor: less weight, less icing, less wind profile (1) • For power flow controller on ground: clarity on real time operational benefits • Current handling capability enhancement of power electronic equipment • Lower cost HVDC (enabling underground transmission) • Synchronous condensers – convert retiring thermal plants • Using distribution assets for volt/VAR support
Protection Devices and Switchgear	**Equipment Sensors**	**Other/Cross-Cutting**
• Bushings that don't fail catastrophic (3) • Leveraging distribution technology (1) • Mobile switchgear • Environmentally friendly alternative for circuit breakers • Solid state devices used to replace VCBs • True settingless protection • More accurate fault locating	• Analytics/distributed intelligence & integration in to workflow (2) • Low cost (to install) current sensors with performance comparable to traditional CTs (1) • Extreme environment sensors (1) • Record failure data in extreme events	• Make inertia & frequency response irrelevant (4) • Cyber hard by design systems (4) • Standards initiative with cutting edge technologies (2) • Lower cost, more reliable cryogenics for HTS (2)Vendor-neutral equipment/solutions via standards (1) • Enhanced forecasting models for real time load flow calculations (1) • Work around variable speed drives to capture inertia • Controlling large number of distributed dynamic assets even when communications link fails or high latency • Equipment should be modular/scalable • Lifetime of assets (e.g. LPT) different from communications protocols & electronics • Active filters

Green Group

Parallel Breakout Session 1: *Transmission Components R&D Gap Discussion*		
Focus Question #1: What are the key issues or challenges facing current transmission system components that impact or limit their utility/performance in a future grid (2020-2040)?		
Transformers	**Cables and Conductors**	**Power Flow Controllers**
• Data enabled-scientific discovery (asset health monitoring/management) • High ΔV/ΔT change in voltages of solid-state transformers • Long-term effect of high-frequency power (>20 kHz) on insulation • Understanding loss mechanisms/micromagnetics at high frequency • No means to accurately predict transformer failure	• Underground transmission technology capacity is too low	• Develop and validate multi-terminal HVDC system above 220 kV • Today's transmission not compatible with the future digital world
Protection Devices and Switchgear	**Equipment Sensors**	**Other/Cross-Cutting**
• Microgrid protection – distinguish fault current and nominal current • Monitoring the "correct" location to detect faults (or predict them)	• Need to better understand data	• Generation interconnection process (study) • No incentive for transmission across state • Stiff-frequency dependence • There is a need for an economical grid energy storage system (battery) • Need human capital expertise • How to effectively integrate legacy equipment into aspects of a future grid • Materials constraints at high temperature and extreme environments • Interoperability • Cyber attack vulnerabilities • Custom design approach (lack of uniform designs) • Right-of-way availability for overhead transmission NIMBY • No new right-of-way – need other cost effective solutions • Limited real-time state observability • Stricter environmental regulations (greater requirements for component performance)

Focus Question #2: What new requirements, capabilities, or functions will be needed or is desired for the range of transmission system components (see table below) to address the issues or challenges identified? (Numbers in parenthesis indicate the votes for top requirements, capabilities, or functions)

Transformers	Cables and Conductors	Power Flow Controllers
• An asset health system that can predict component failure (3) ○ Data for maintenance and diagnosis – but what about using data during normal operations? • Configurable/tunable high voltage (HV) transformer (3) • Transformers - scaling of magnet materials for HF switching (1) • Equipment is not affected by variable/high frequency	• Higher heat withstanding capability of dielectric materials (5) • Self-healing dielectrics (treeing? Cables) (3) • Increased capacity using existing right-of-way (3) • High capacity cable technology >2 GW (3) • Lower cost cryogenic materials for superconductors	• HVDC converters - voltage source; full control for multi-terminal systems (4) • Modular standardized power blocks (3) • Standards for controlling HVDC grids (1) • HVDC breakers - need higher voltage; nominal size; water tight for off-shore wind
Protection Devices and Switchgear	**Equipment Sensors**	**Other/Cross-cutting**
• Faster protection? - Solid stage breakers; Fault characterization - what will we be dealing with? (6) • New protection relays/ algorithms for low fault current systems (high non-synchronous generation) (5) • Measurement criteria for evaluating SF_6 alternatives (1) • HV Insulator materials for bushings/lighting arrestors (failure analytics). Impulse testing? (1) • Resilient communication backbone that supports our protection equipment (1) • Auto-tuning of controls and protection • Relay-less protection	• New sensing platforms with attributes for wide area monitoring (cost and technical) (also cables) (3) • On board diagnostics for equipment in grid environment (like vehicles) that communicate (1) • Low-cost, wireless embedded sensors for transformer monitoring (1) • Some history storage capacity in sensors (1) • Communication for distributed controls (trusted platforms) (1) • Multi-scale component models with measureable predictions	• High energy storage system (9) • New material development at pilot scale (5) • Unbreakable cyber protection, authentication, and encryption (on a device) (4) • Building cyber aspects into product/device design (encryption, tamper resistance, being able to effectively measure) (1)

Blue Group

Parallel Breakout Session 1: *Transmission Components R&D Gap Discussion*

Focus Question #1: What are the key issues or challenges facing current transmission system components that impact or limit their utility/performance in a future grid (2020-2040)?

Transformers	Cables and Conductors	Power Flow Controllers	Protection Devices and Switchgear

• Health assessment: remaining life estimate
• Equipment life is too limited (New equipment has shorter life span vs. old)
• Transformers need to be more visible/interactive with operation
  – Health monitoring
  – New tech for replacement
• Difficult to replace
  – Long lead time
  – Expensive
  – Not easily moved
• Vulnerability
  – Electromagnetic pulse
  – Geomagnetic disturbance
  – Physical attack
	• The tradeoff between conductivity vs. strength precludes high strength, high conductivity cables
	• Inability to create fault current meshed network
	• Need to dig, create vaults, perform maintenance makes underground transmission cables too expensive relative to overhead
		• Lack of controllability: passive grid
		• Cost and O&M complications of large FACTS equipment
		• High cost, low reliability of solid state devices
		• SCD (short circuit duty) rising – need FCLs (Fault Current Limit)
			• SF6 replacement
			  – Cost
			  – Re-engineering/re-design
			  – Unknown unknowns
			• Electronic relays are difficult to program (offer too much configurability)

Equipment Sensors	Other	Cross-Cutting

• Data overload
  – Sensor data must be translated into actionable information
  – On-line, real-time conditioning monitors, i.e., transformers, breakers, relays
  – Health Risk Management System – most of data is static, i.e., doable, PM need real-time data
• Integration of new technology with legacy systems
  – Interoperability
  – Reliability
	• Cost
	  – Development
	  – Inventory
	  – Repair
	  – Operation
	• Aging: Monitoring and prevention
	• Loss of experience and knowledge 70% engineering students leave U.S.
	• Not all components are communicating
	• Physical damage to high voltage system e.g. from terrorism; lack of prevention, monitoring, new technologies
	• Lack of algorithms optimization for resilience
	• Security (cyber, physical) expectations not aligned
		• Bi-directional power flow
		• System components are too reactive; lack new technologies on major apparatus, i.e., breakers, switches, protection, instrument transformers.
		• Changing operating paradigm
		  – Renewables causing increase in LTC operations
		  – Generation mix changes
		  – Load uncertainty
		• Distributed controls of power electronics-based equipment
		  – Transformers
		  – PF controllers
		  – Protection devices
		  – switchgear

Focus Question #2: What new requirements, capabilities, or functions will be needed or is desired for the range of transmission system components (see table below) to address the issues or challenges identified? (Numbers in parenthesis indicate the votes for top requirements, capabilities, or functions)

Transformers	**Cables and Conductors**	**Power Flow Controllers**	**Protection Devices and Switchgear**
• Flexible Transformers (9) – Voltages; Impedance; Taps; AC & DC; MVA; Current limiting – Transformer configurable for multi-voltage (address lead time by being flexible) – Ability to withstand higher fluctuations (i.e. wider operating parameters) from variable generation or lower inertia • Improved soft magnetic materials for higher efficiency transformers resistivity permeability (3) • Replace custom LPTs with small modular controllable transformer units that are easier to make/replace (1) • Transformer oil advanced membranes (atomically precise) to separate water from oil solution	• Increased ampacity of conductors: low cost, conductor core with ↑conductivity (4) • Better aging/tension prevention and monitoring through nanotechnology (e.g., for insulators, coatings) (2) • Insulation for cables that is more flexible (easier to handle/install) (2) • Hydrophobic (ice-phobic), high emissivity, long-lived coatings for cables and conductors • Government support for NLOS (non-line of sight) flights UAV inspections	• Multi-functional components (FCL, transformers, etc.) (6) • PFC based on small-rated converters (size, cost) that can fail normal (4) • New semiconductor materials that are more reliable and efficient (for solid state transformers that are power flow controllers and protection devices (solid state protection devices) (3) • Flexibility adapt to varying systems requirements (handle variety of future states, distribution at load and generation)	• Protection devices that are plug & play, last longer, and do multiple redundant functions resulting in less IEDs (7) • Fast interrupt/restore (apply DC concepts to AC systems and localize fault effects) (5) • Low-cost dielectric – e.g., replacements for SF6 (2) • Process bus enabled devices – CBs – PT/CTs – Hardened IEDs with EMP resilience – Open protocol • Arrester that can control transients over voltage at a live-line/worksite bare-hand

Equipment Sensors	**Other**	**Cross-Cutting**
• Embedded Prognostic and Health Management (PHM) of transformer, cables, power flow controllers, protection devices and switchgear—graceful shutdown or employ reduced output power-availability (7) • Low cost, on-line (real-time) multi-functional (helps lower cost) sensors for increased visibility, awareness, and predictability (2) • Simple self-diagnostic, self-reporting features that can diagnose and report problems as far ahead as possible • Embedded diagnostic capability – Real-time – Transformers – Breakers – CVT • Report when action is required • Wide area situational awareness with analytics for grid condition for renewables wind and solar	• Cyber security: "keep them out" as first defense; reconfigurable system that is robust if they do come in as second defense (2) • Algorithms optimization (resilience): need to understand most effective way to add new things • Improved dynamic modeling: forecasting and simulation • Flexible regulatory control (and preferable sane) – If regulators are fixed then component functionality will be fixed "other" other • Better technology transfer from researchers to manufacturers and users	• Resiliency: components that can take a licking. Engineer out criticality (5) • Simplify/decouple stable systems with fault tolerant that are flexible (1) • Resilient materials for multiple applications • Quality vs. cost: low maintenance cost especially from manufacturers viewpoint

Distribution Component Discussions

Red Group

Parallel Breakout Session 2: *Distribution Components R&D Gap Discussion*		
Focus Question #1: What are the key issues or challenges facing current distribution system components that impact or limit their utility/performance in a future grid (2020-2040)?		
Transformers	**Cables and Conductors**	**Power Flow Controllers**
• Better magnetic materials • Distribution transformers in high harmonic environment • No voltage & VAR control	• Discovery of high variability of voltage on secondary • Underground cable monitoring	• Integrating 1 phase PV (line balancing) • High penetration of DER in a small geographical area • Current source inverter (DER) need voltage source to follow • Lack of knowledge of design of multiple inverter system • PV/DER causing more device operations • FLISR systems require new construction • behind meter resilience: last mile essential circuit • Much of the distribution grid is radial – no networked opportunities are limited • Networked distribution feeders have higher reliability
Protection Devices and Switchgear	**Equipment Sensors**	**Other/Cross-Cutting**
• Protection strategy for bi directional power flow • Fault current contributions from distributed resources, microgrids • Power quality & voltage stability • Variable intermittent faults • Microgrid must provide V/f ride through if exporting power • Protective devices can't be tripped with power electronics • Anti-islanding for DER clusters • Alternative sensing technology can break "smart" systems (e.g. FLISRD) • Fixed/static protection schemes • Integration of grid support inverters (UL 1741 SA)	• Lack of visibility beyond distribution substation • 30% of Caps not working and don't know which ones • Lack of visibility downstream especially incipient failures of equipment, momentaries, etc. • Micro PMUs available, but not widely used • Distributed sensors tend to be of low fidelity/quality • Too many transformers to monitor, cost too high, value too low • Too many distribution assets, how do you monitor them? How do you aggregate & manage data?	• Poor system models prevent good fault location • Volt/VAR control with non-accurate load models • Fault locating in grid network (city center) • Lack of proprietary loads. DR at a finer level during microgrid contingency operation. • Distribution feeders – PV hosting very challenging • Higher peak loads and more variability • Standards gaps • Improve land management – energy storage • EV charging can strain distribution capacity • Variable pricing based on demand

Focus Question #2: What new requirements, capabilities, or functions will be needed or is desired for the range of distribution system components (see table below) to address the issues or challenges identified? (Numbers in parenthesis indicate the votes for top requirements, capabilities, or functions)

Transformers	**Cables and Conductors**	**Power Flow Controllers**
• Power electronics based load tap changer/LVR for fast voltage control on feeders (10) • Distribution transformers with volt/VAR control, flexible to select in field (9) • Higher efficiency solid state transformer • Distribution transformers with lower cost power electronics, fail normal capability •	• Line configurations with low tree exposure/wind drag (2)	• Fault handling capability enhancement of power electronic equipment (6) • Medium voltage asynchronous converter/switch to interconnection microgrid, tie feeder (2) • 1 phase phase balancers (2) • Controllers for closing normally open points on distribution (2) • 2 and 4 quad distribution STATCOM device • Wide band gap based solid state breakers that are lower cost and faster reacting • Lower loss solid state switches • AC/DC energy router • Static transfer switches, bidirectional built in power quality monitoring • A widget to enable the easy Networking of radial feeders • Volt VAR control on distribution feeders from LV side to delivery high PV hosting

Protection Devices and Switchgear	**Equipment Sensors**	**Other/Cross-Cutting**
• Full solid state DC breaker hybrid (5) • Solid state devices used to replace vacuum circuit breaker (5) • Solid state fault current limiter <= 100msec; active fine control of power flow; active power quality monitoring SCADA (3) • Low cost fault current limiter (2) • Wide bandgap based solid state breakers that are lower cost and faster reacting (2) • Adaptive/dynamic protection systems	• Distributed real time control/modeling sensor/data management (5) • Autonomous distributed asset control with slow coordination (3) • Line strain sensors to detect outages and breakages (2) • Integration from sensor to control center to line crew • Low cost sensor and communications to enable ubiquitous sensing – also data aggregation • Correlation of system event data with health monitoring	• New paradigm for operation (especially protection, but all devices) (3) • Distributed DC delivery systems (3) • Standard grid support characteristics for connected loads frequency, VAR, volt, inertia (3) • Fast restoration after a storm (3) • Cyber secure by design (and updated over time especially in low cost devices) (2) • Business case models for microgrids (2) • Standard microgrid to grid interface that allows proliferation (1) • Highly distributed and rapid adjusting VAR systems (1) • Dynamic distribution system modeling; modeling of autonomous distributed controllers • Simpler method of adding finer grained demand response to support reduced capacity microgrid "ask for power" • How can advanced manufacturing change the grid business model • Synthetic inertia provided by DG and require for connection

Green Group

Parallel Breakout Session 2: *Distribution Components R&D Gap Discussion*					
Focus Question #1: What are the key issues or challenges facing current distribution system components that impact or limit their utility/performance in a future grid (2020-2040)?					
Transformers	**Cables and Conductors**	**Power Flow Controllers**	**Protection Devices and Switchgear**	**Equipment Sensors**	**Power Quality**
• Limited lifetime of mechanically interfaced equipment (CAPs, LTCs, etc.) • Efficiency vs. cost for distribution transformers	• Online pre-fault failure detection for underground cables • Underground cable visibility	• Impact of harmonics on system operation	• Adaptive protection and reconfiguration • Protection challenges – speed vs. security, sensitivity vs. selectivity • How to detect faults in low short-circuit current conditions • Do we have correct switchgear to allow microgrids with seamless transfer?	• Low per unit value for distribution sensors • "Edge of system" monitoring	• High frequency load support (like WPT) • Increased amount of DC

Control	**Cross-Cutting**	**Other**
• How to black-start (restore) a system with high levels of renewable energy (non-synchronous generation) • Low visibility beyond the substation – Need more time synchronized measurements (V, I, f, phase) • Remote communications for control and sensor data • Massive DER- dispatchable, observable • Lack of automated model development and maintenance (cross-cutting) • Cascading events (modeling extreme events and restoration) • Lack of uniformity in equipment models • Lack of validated models • Fast controls for distribution and uncertain ev. With and without communications • Lack of time synchronization • Recovery/resiliency in design • Analytics at the edge	• Resiliency of the system during/after weather events – improve rather than restore • Resiliency during extreme weather conditions • Regulating the distribution markets with DER • How to manage voltage with distributed generation • Rate structure business case (equity; customers leaving, those left behind) • Lack of compatibility between municipalities/co-ops/utilities • Transition/movement to an IP6 network from an IP4 network (coordination and interoperability) • What are reasonable temperatures to extrapolate to for component applications (regional weather and extreme events) • Need more capacity from existing and new infrastructure (lower size, greater capacity) • Increased urban density is restricting infrastructure options • New markets enabling DER customers (variety of market mechanisms) • Cyber vulnerabilities	• Why not 220V? • Define standards for comparing materials (e.g., loss measurements) • Ability to feed "D"-DER into the grid • Communication and hierarchy of all devices • Consumer vs. monopoly supplier mentality • Vehicle electric (energy mobility?) • EV charging or flying car charging • Increase penetration of PEVs • Variability optimization with DER introduction • Unknown load due to distributed generation and EV • Two way flows in a traditionally one directional world

Focus Question #2: What new requirements, capabilities, or functions will be needed or is desired for the range of distribution system components (see table below) to address the issues or challenges identified? (Numbers in parenthesis indicate the votes for top requirements, capabilities, or functions)

Transformers	Cables and Conductors	Power Flow Controllers	Protection Devices and Switchgear
• Regulating transformers without mechanical switching (5) • Low cost manufacturing for higher frequency transformers (3) • Cost reduction of core materials with higher efficiency performance for distribution transformers (1) • Optimal transformer location	• High capacity cable at low cost (4) • Online state-of health of underground cables (3) • Medium voltage (MV) cable designed for DC (1) • Location communicating cable	• Medium voltage (MV) power flow controllers that can be used to manage voltage/reactive power (6)	• Cheap harmonic filters for fault current limiters (2) • Digital fuses (self-restoring; smart fuses; no manual reset) (1)
Equipment Sensors	**Control**	**Other**	**Cross-Cutting**
• Smarter sensors that can accumulate bi-directional energy flows (4) • Sensor platforms with higher value at distribution level (multi-function, wide area, low cost) (1) • Couple sensor data/control signals to power lines (signal propagation quality across transformers) for PLC	• Real-time "what if" contingency analysis (8) • Cyber: standards, mitigation, detection, repair (7) • Transient and sub-transient modelling of multi-node distribution networks (4) • Real-time automated DS-operation with 1000s of DER (1) • Robust communication at remote location (1)	• Upgrade U.S. distribution to 220V (3) • Improved detection isolation of intrusion (physical, cyber, EMP) (2)	• Standardized/modular component design (8) • Standardized communications and clear hierarchies (2) • Require transmission/distribution interface to be bi-directional (2) • DC connection to houses (1) • Improved capability to balance bi-direction power flow (DERs) • Self-commissioning automated installation of equipment (plug and play) • 30+ year lifetime for power electronics?

Blue Group

Parallel Breakout Session 2: *Distribution Components R&D Gap Discussion*			
Focus Question #1: What are the key issues or challenges facing current distribution system components that impact or limit their utility/performance in a future grid (2020-2040)?			
Transformers	**Cables and Conductors**	**Power Flow Controllers**	**Protection Devices and Switchgear**
• Losses in transformers: High efficiency materials for transformer cores are needed • Distribution (i.e. pole top) transformers lack health diagnostics, 2-way power flow, protection • Distribution transformers not installed for 100% loading, 24 hours per day • Increased LTC operation to address volt fluctuations caused by PV • Oil/PCBs (in Canada)/SF6	• Icing and varmints • Low resistance to natural disasters – Icing, lightning – Hurricanes – Fallen trees, etc. • Cables PILC (paper insulated lead cables) – Replacement – Duct size (proper insulated led cables) – Transition splice	• The doomsday scenario: electric vehicles are movable load and power flow • How to integrate order of magnitude more electric vehicles • PV lacks inertia; reverse power flow • Currently cannot localize faults quickly enough without dropping a lot of load because lacking more efficient feeder automation	• Protection not designed/installed for two-way power flow and distribution system is constantly reconfigured • Distributed generation power flow protection traditional sensing cannot see fault current • Protection systems seeing reverse power flows • High short circuit limits type of devices can be installed

Equipment Sensors	**Other**	**Cross-Cutting**
• DER integration issues going from top down flow to mesh sensors/analytics • System, control monitoring and energy management • Too much data and what to do with it • Extent of damage after major storm or any event. How bad is it? ETR?	• Lack of voltage/VAR devices and control • Auto appliances communication • Visibility and control beyond the meter • Distribution system models that incorporate generation • Data overload how to extraction of relevant data is needed • No AC and DC distribution integrated	• Voltage variability because of load fluctuations/PV • Little flexibility: it's complicated to update, change, or modify protection, control, and logistics • Loads are not presently controlled even by the consumer • Large PV (20 MW) on distribution • DER integration: markets or other unknown structures as net metering ends • Reduced inertia due to multiple inverters being deployed • Responsibility: – Microgrids vs. homes vs. commercial = GRID – Improperly installed distributed generation hurts utility ability to restart

Focus Question #2: What new requirements, capabilities, or functions will be needed or is desired for the range of distribution system components (see table below) to address the issues or challenges identified? (Numbers in parenthesis indicate the votes for top requirements, capabilities, or functions)

Transformers	Cables and Conductors	Power Flow Controllers	Protection Devices and Switchgear
• Multiport transformers that can accommodate multi sources such as PV, wind, etc. (DC & AC capability) VSB concept "plug & play" (10) • Power Router Hubs – agnostic to source(s) – AC/DC – LV/MV/HV – 3 phase/2 phase/multiphase • Flexible Transformer – Various voltages – Varying impedance – Low-cost – Fault detection • Solid state transformers – Provide power information – Control power flow – Fault current limiting • Controlled pole mount/pad mount transformers – volt/VAR control • Multi-purpose transformer that can do step up-step down, power flow control and protection in one • New chemicals and/or system designs to address event issues oil/PCBs/SF6	• Lower loss conductors that are cost-effective (2) • Ice-phobic coatings for conductors (1)	• Bi-directional power flow (10) • PE direct tie to MV and (HV)? Systems (7) • VVO on feeder level for additional generation power quality management (3) • Fast to diagnose and repair "hot swappable" (2) • Solid state capacitors VAR/voltage variable – Cost effective – Maybe use inverter/battery storage	• Different protection philosophy (7) – Setting-less – Not based on over-current – Dynamic protection needed because of changing load/generation mix • High impedance fault detection for wire down to detect low current (5) • Smart interface between grid and consumer (PV) to address increasing variation in power flows (2) • Relays Plug & Play (1) • Communication (widespread) between protection/control devices • Sync Distribution System with an island system

Equipment Sensors	Other	Cross-Cutting
• Self-powered sensors (4) – Fault indication – Current/voltage – Direction – Communication • Sensor systems to address changes and demand with controllers (3) • In situ small signal monitoring of equipment for prognostic and health management. (2)	• Treat renewables "more" as critical sources as penetration increases (2) • DER operating system (1) – Economic dispatch/incentives for load control; Flow control; Location sensitive • UAV fleets to investigate storm damage and report back (1) • Customer outreach and education – PV; Demand response; UPS; Generator installation; Elect. Vehicles • Automated load control – advanced components to accomplish this • Algorithms: load-models & better modeling for electric vehicles (charging)	• Advanced semiconductor devices, magnetics, capacitors and packaging and thermal management – new material for transformer, PF controlled protection (2)

Worksheets

Red Group

Top Priority Opportunity: *(i.e., component name and features)* Adaptive/Dynamic Protection		**Group Members:** Jeff Wischkaemper; Alan Mantooth; Tom Salem; Terry Oliver; Arthur Barnes
Desired Outcomes	*What are the new requirements, capabilities, or functions needed? Elaborate on the purpose of these new features.*	Enable reliable & secure protection • In systems with bi-directional power flow • Minimal human input • Gracefully handles system power flow
Current Status	*What is the current technical progress (e.g., TRL) of the opportunity and who (if any) is making investments?*	Not developed TRL 3-ish
Metrics	*What is the cost and/or performance baseline of the current technology or alternatives (if applicable)?*	No comparable product $7-10k per point
	What is the cost and/or performance targets (i.e., metrics and timeframes) for the opportunity?	No business case exist currently
Resources Needed	*What financial resources are needed to meet targets? ($XXX/year for YY years)*	$2M/year for 3 years
Benefits	*What is the potential value and benefits of realizing this opportunity at scale? (quantitative or qualitative)*	Required for networked distribution Enables flexible operation of distribution infrastructure
Critical Paths	*What are the critical paths associated with realizing this opportunity? Include technology, market, policy, or regulatory challenges.*	New imagination/assumptions about how to….

<table>
<tr><td colspan="3">Top Priority Opportunity: (i.e., component name and features)
Low cost sensors/analytics/health monitoring</td><td>Group Members:
Jeff Wischkaemper; Alan Mantooth; Tom Salem; Terry Oliver; Arthur Barnes</td></tr>
<tr><td>Desired Outcomes</td><td>What are the new requirements, capabilities, or functions needed? Elaborate on the purpose of these new features.</td><td colspan="2">• Low cost (total)
• Accuracy/fidelity
• Provide useful information accessible to enable improved O&M</td></tr>
<tr><td>Current Status</td><td>What is the current technical progress (e.g., TRL) of the opportunity and who (if any) is making investments?</td><td colspan="2">• Various depending upon sensor type
• Volt sensor may be mature, non-traditional CT's present opportunity</td></tr>
<tr><td rowspan="2">Metrics</td><td>What is the cost and/or performance baseline of the current technology or alternatives (if applicable)?</td><td colspan="2">Goal is to be less than $1k total</td></tr>
<tr><td>What is the cost and/or performance targets (i.e., metrics and timeframes) for the opportunity?</td><td colspan="2"></td></tr>
<tr><td>Resources Needed</td><td>What financial resources are needed to meet targets? ($XXX/year for YY years)</td><td colspan="2">Processing capability, communications systems, intelligence for incorporating new data/information</td></tr>
<tr><td>Benefits</td><td>What is the potential value and benefits of realizing this opportunity at scale? (quantitative or qualitative)</td><td colspan="2">• Improved condition based maintenance, prognosis, health monitoring
• Forensic data
• Operational improvement on system</td></tr>
<tr><td>Critical Paths</td><td>What are the critical paths associated with realizing this opportunity? Include technology, market, policy, or regulatory challenges.</td><td colspan="2">Conduct survey to study/report on present status of available technologies across all sensor types (1.5 to 2 year project ~ $200k)</td></tr>
</table>

Top Priority Opportunity: *(i.e., component name and features)* Power electronics based LTC for fast voltage control		**Group Members:** Dale Player; Kerry Cheung; Mario Sciulli, Dave Loucks
Desired Outcomes	*What are the new requirements, capabilities, or functions needed? Elaborate on the purpose of these new features.*	• Fast switching between taps (cycles) • +/- 20%
Current Status	*What is the current technical progress (e.g., TRL) of the opportunity and who (if any) is making investments?*	• Nonexistent for medium power TR • Advanced for smaller low voltage equipment that can be leveraged
Metrics	*What is the cost and/or performance baseline of the current technology or alternatives (if applicable)?*	• 10 MVA TR w/ LTC A $1.5M • Keep the price point the same • No more than 20 operations per day
	What is the cost and/or performance targets (i.e., metrics and timeframes) for the opportunity?	• Keep the same baseline price point • Smooth ramping control (infinite taps) • Be as reliable as mechanical
Resources Needed	*What financial resources are needed to meet targets? ($XXX/year for YY years)*	Need control logic development ($10M), need new power electronic design ($10M), possible transformer design to expand voltage compensation range to support wider voltage swings due to renewables (0-$50M)
Benefits	*What is the potential value and benefits of realizing this opportunity at scale? (quantitative or qualitative)*	• Minimized flicker • Faster switching • Support increased penetration of renewables
Critical Paths	*What are the critical paths associated with realizing this opportunity? Include technology, market, policy, or regulatory challenges.*	• Changing from mechanical control -> electronics • Increase from 10% TR to 20% TR

U.S. DEPARTMENT OF ENERGY | Office of Electricity Delivery and Energy Reliability

Top Priority Opportunity: *(i.e., component name and features)* Enhanced fault handling capability of power electronics		**Group Members:** David Syracuse, Al Hefner, Fred Wang
Desired Outcomes	*What are the new requirements, capabilities, or functions needed? Elaborate on the purpose of these new features.*	• Adapt to fault current and voltage variation (requirement) • Higher surge current for more synthetic inertia • Need higher max interrupt current capability • Enhance capability of fault current limiter and similar apps
Current Status	*What is the current technical progress (e.g., TRL) of the opportunity and who (if any) is making investments?*	• Wide bandgap Power America/DOE/DOD • Hybrid technologies / industry
Metrics	*What is the cost and/or performance baseline of the current technology or alternatives (if applicable)?*	• 2x for inverters • Breakers 10^4 x • BIL
	What is the cost and/or performance targets (i.e., metrics and timeframes) for the opportunity?	• Available 10% higher • 5 years +
Resources Needed	*What financial resources are needed to meet targets? ($XXX/year for YY years)*	• 100kW inverter $1-2 million • 2-3 years
Benefits	*What is the potential value and benefits of realizing this opportunity at scale? (quantitative or qualitative)*	• Pervasive power electronics meeting power surge performance • Higher penetration of renewables • Earlier use of emerging technologies working in harmony with existing technology • More adaptive fault handling
Critical Paths	*What are the critical paths associated with realizing this opportunity? Include technology, market, policy, or regulatory challenges.*	• Si -> Hybrid -> SiC -> Wide bandgap • Thyristor Crossbars • Leveraging existing technology with emerging technology

Top Priority Opportunity: *(i.e., component name and features)*		**Group Members:**
Power flow controller to maximize utilization		Vahan Gevorgian, Pawel Grudzki, Dominic Lee
Desired Outcomes	*What are the new requirements, capabilities, or functions needed? Elaborate on the purpose of these new features.*	• Lower cost, standardized modular, scalable, hybrid design • Optimized coordinated control, optimized placement • Reduced losses (WBG materials)
Current Status	*What is the current technical progress (e.g., TRL) of the opportunity and who (if any) is making investments?*	• Varies depending on FACTS device • TRL varies depending on device type • Transmission system operators make investments
Metrics	*What is the cost and/or performance baseline of the current technology or alternatives (if applicable)?*	• Varies depending on FACTS type • The family of devices is too large to define a range
	What is the cost and/or performance targets (i.e., metrics and timeframes) for the opportunity?	• More flexibility in standardized designs to match characteristics of different grids • No single cost target, it is a large family of devices
Resources Needed	*What financial resources are needed to meet targets? ($XXX/year for YY years)*	• $5M/year for 5 years
Benefits	*What is the potential value and benefits of realizing this opportunity at scale? (quantitative or qualitative)*	• Better utilization of transmission • Reduced integration cost for renewables • Curtailment reduction for wind and solar generation
Critical Paths	*What are the critical paths associated with realizing this opportunity? Include technology, market, policy, or regulatory challenges.*	• Cost reduction • New power electronics technologies (WBG), coordinated control • Better understanding of transient impacts and power quality

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<tr><td colspan="3">Top Priority Opportunity: (i.e., component name and features)
Distribution transformer w/ volt – VAR control at customer service transformer</td><td>Group Members:
Joe Schatz, Lillian Bruce</td></tr>
<tr><td>Desired Outcomes</td><td>What are the new requirements, capabilities, or functions needed? Elaborate on the purpose of these new features.</td><td colspan="2">• Local operation that provides volt/VAR/communications/integration
• Balanced deterministic voltage to premise</td></tr>
<tr><td>Current Status</td><td>What is the current technical progress (e.g., TRL) of the opportunity and who (if any) is making investments?</td><td colspan="2">• TRL 2 but could quickly migrate to TRL 8/9 with concerted efforts described in resources
• Voltage injection electronics (nonintegrated)
• Utilities/EPRI & DOE minimal investment at this time</td></tr>
<tr><td rowspan="2">Metrics</td><td>What is the cost and/or performance baseline of the current technology or alternatives (if applicable)?</td><td colspan="2">• Current technology does not exist in an integrated fashion
• unknown</td></tr>
<tr><td>What is the cost and/or performance targets (i.e., metrics and timeframes) for the opportunity?</td><td colspan="2">• Minimal rate impact</td></tr>
<tr><td>Resources Needed</td><td>What financial resources are needed to meet targets? ($XXX/year for YY years)</td><td colspan="2">• $3M/year for 3 years</td></tr>
<tr><td>Benefits</td><td>What is the potential value and benefits of realizing this opportunity at scale? (quantitative or qualitative)</td><td colspan="2">• Positions and enables a more flexible grid for PV or other grid integrated technologies
• Stepping stone to wider deployment of power electronics augmented power delivery solutions</td></tr>
<tr><td>Critical Paths</td><td>What are the critical paths associated with realizing this opportunity? Include technology, market, policy, or regulatory challenges.</td><td colspan="2">• Should be no policy or regulatory challenges other than costs
• This is needed immediately, so critical paths involved funding, not core technology at this point
• Integration and pilot deployments</td></tr>
</table>

Top Priority Opportunity: *(i.e., component name and features)* Easy transportable transformer for transmission w/ solid state transformers		**Group Members:** Pawel Gradzki, Joe Schatz, Klaehn Burkes, Vahan Gevorgian, Lilian Bruce, Dominic Lee
Desired Outcomes	*What are the new requirements, capabilities, or functions needed? Elaborate on the purpose of these new features.*	• WBG materials & devices • Standardized and scalable • Hybrid/power electronics augmented transformer • Power flow control • 10W loss magnetic material • Modular power electronics
Current Status	*What is the current technical progress (e.g., TRL) of the opportunity and who (if any) is making investments?*	• 15kV research semi conductive equipment • Private entities could structure deals along SST • Flexible designs don't exist • Modular design -> DHS • Interfacing with ISO satisfaction
Metrics	*What is the cost and/or performance baseline of the current technology or alternatives (if applicable)?*	• Current transformer status is \$2-7M or \$1M/100MVA
	What is the cost and/or performance targets (i.e., metrics and timeframes) for the opportunity?	• Competitive cost
Resources Needed	*What financial resources are needed to meet targets? (\$XXX/year for YY years)*	• \$10M/year for 10 years for SST
Benefits	*What is the potential value and benefits of realizing this opportunity at scale? (quantitative or qualitative)*	• If modular and scale can handle load growth • Added functionality can deploy during national disasters • Variable impedance
Critical Paths	*What are the critical paths associated with realizing this opportunity? Include technology, market, policy, or regulatory challenges.*	• For transmission level solid state needed advanced switches • Market acceptance is size, reasonable footprint • For hybrid, need the magnetics • Interface with TRO & ISO • Vertical stack-ability

Green Group

Transmission Worksheets

Top Priority Opportunity: *(i.e., component name and features)* Faster protection? - Solid stage breakers; Fault characterization - what will we be dealing with? New protection relays/ algorithms for low fault current systems (high non-synchronous generation)		
Desired Outcomes	*What are the new requirements, capabilities, or functions needed? Elaborate on the purpose of these new features.*	• Ability to detect and clear low-current faults • Ability to determine between load current and fault currents • Speed – be able to act very quickly (less than 1 cycle) • Capable of interrupting very high fault currents (over 50 kW) • Low losses for normal operation
Current Status	*What is the current technical progress (e.g., TRL) of the opportunity and who (if any) is making investments?*	• Research in microgrid switches and protective relay algorithms (mostly LV and MV, not HV) • DoD (Navy) – shipboard power systems
Metrics	*What is the cost and/or performance baseline of the current technology or alternatives (if applicable)?*	• Current technology is mechanical breakers and programmable digital relays and communication
	What is the cost and/or performance targets (i.e., metrics and timeframes) for the opportunity?	• Need new solid-state breakers and controls to be cost competitive with today's technologies
Resources Needed	*What financial resources are needed to meet targets? ($XXX/year for YY years)*	• $5 million/year for 6 years for hardware development • $2 million/year for 3 years for algorithm development
Benefits	*What is the potential value and benefits of realizing this opportunity at scale? (quantitative or qualitative)*	• Needed for power systems with high amount of non-synchronous generation • Ability to withstand interruption in the main grid, turn into islands/microgrids for resiliency
Critical Paths	*What are the critical paths associated with realizing this opportunity? Include technology, market, policy, or regulatory challenges.*	• Ability of solid-state devices to withstand large fault currents • Leverage fault current limitations • Moving beyond over current protection. Evaluate other techniques to detect faults. • Develop fault signatures for power systems with high amounts of non-synchronous generation

Top Priority Opportunity: *(i.e., component name and features)* High energy storage system		
Desired Outcomes	*What are the new requirements, capabilities, or functions needed? Elaborate on the purpose of these new features.*	• MWh, peak MW, reduced cost • Increased efficiency, increased load cycling, and service life • Environmentally friendly, frequency regulation, incentives
Current Status	*What is the current technical progress (e.g., TRL) of the opportunity and who (if any) is making investments?*	• Use of lithium car batteries • Manufacturers for batteries, universities, and government for materials
Metrics	*What is the cost and/or performance baseline of the current technology or alternatives (if applicable)?*	• Overall cost verses cost of alternatives
	What is the cost and/or performance targets (i.e., metrics and timeframes) for the opportunity?	• Payback period of less than five years • 20 year lifetime
Resources Needed	*What financial resources are needed to meet targets? ($XXX/year for YY years)*	• $20 million/year for 10 years
Benefits	*What is the potential value and benefits of realizing this opportunity at scale? (quantitative or qualitative)*	• Increased renewable effectiveness • Reduced carbon footprint • Improved network resiliency
Critical Paths	*What are the critical paths associated with realizing this opportunity? Include technology, market, policy, or regulatory challenges.*	• Manufacturing/materials • Field demonstration of performance and reliability • Consequence for network inertia

Top Priority Opportunity: *(i.e., component name and features)* Higher heat withstanding capability of dielectric materials		
Desired Outcomes	*What are the new requirements, capabilities, or functions needed? Elaborate on the purpose of these new features.*	• Continuous operating temperature above 105°C and emerging operation above 140°C • Increased capacity and added robustness of the system (N-1 operation) • Scope – transformers, cables, bushings, accessories, solid dielectric switchgear
Current Status	*What is the current technical progress (e.g., TRL) of the opportunity and who (if any) is making investments?*	• Higher temperature materials are available but involve tradeoffs of cost, performance, longevity • Target objectives are minimum 40 year lifetime, low dielectric constant (low loss), moisture resistant
Metrics	*What is the cost and/or performance baseline of the current technology or alternatives (if applicable)?*	• Current market price • Current performance is 90°C-105°C • Alternative –Nomex® for TX's • Electrical properties – low dielectric constant, stability – heat, time wet aging, losses for TX's (A and D factors)
	What is the cost and/or performance targets (i.e., metrics and timeframes) for the opportunity?	• Temperature – continuous operation - 130°C • Temperature – emergency operation - 180°C
Resources Needed	*What financial resources are needed to meet targets? ($XXX/year for YY years)*	• $10 million/year for 10 years
Benefits	*What is the potential value and benefits of realizing this opportunity at scale? (quantitative or qualitative)*	• Smaller size/footprint • Greater load capacity • C/o within existing infrastructure – cable replacement • Added resilience of the system to withstand failure (N-1)
Critical Paths	*What are the critical paths associated with realizing this opportunity? Include technology, market, policy, or regulatory challenges.*	• Must look at all components within a system – bushings, connectors, accessories, etc. • Formulation, test to current standards, potentially change current standards of materials • Building codes to allow for higher temperatures

Top Priority Opportunity: *(i.e., component name and features)* New material development at pilot scale		
Desired Outcomes	*What are the new requirements, capabilities, or functions needed? Elaborate on the purpose of these new features.*	• Higher efficiency and capacity (conductors) • Higher temperature, higher voltage, and higher frequency dielectric performance • Higher frequency, higher temperature, lower cost (magnetics)
Current Status	*What is the current technical progress (e.g., TRL) of the opportunity and who (if any) is making investments?*	• Conductors – superconductors (higher TRL 6 or 7), carbon nanotube copper (laboratory scale) • Dielectric (glass capacitors, TRL 2 or 3) • Magnetics (TRL 4)
Metrics	*What is the cost and/or performance baseline of the current technology or alternatives (if applicable)?*	• Copper/aluminum – copper ($20/lb, 60 ms/m), aluminum (less than $1/lb, 30 ms/m) • Mica → Polyethylene → Nomex® • Si steel and ferrite
	What is the cost and/or performance targets (i.e., metrics and timeframes) for the opportunity?	• ($30-$50 KA/m) lower than this for transmission timeframe → 2030 (10 years) • Is should be competitive in $/kW with Si steel and ferrites, with similar efficiency as ferrites
Resources Needed	*What financial resources are needed to meet targets? ($XXX/year for YY years)*	• CNT → $2 million/year for 30 years • Magnetics → $2 million/year for 10 years (on successful project)
Benefits	*What is the potential value and benefits of realizing this opportunity at scale? (quantitative or qualitative)*	• Transmission, motors, distribution, power electronics circuits (dielectrics and magnetics) • Conductors → factor of 2 reduction in losses • HTS → factor of 10 increase in capacity
Critical Paths	*What are the critical paths associated with realizing this opportunity? Include technology, market, policy, or regulatory challenges.*	• Magnetics (cost of high frequency transformers and value proposition) • Dielectrics (cost, manufacturing, and technology) • Conductors (cost, manufacturing) • Cryogenics → superconductors

Top Priority Opportunity: *(i.e., component name and features)* Real-time "what if" contingency analysis		
Desired Outcomes	*What are the new requirements, capabilities, or functions needed? Elaborate on the purpose of these new features.*	• Higher computing power/standardized distribution model software • Develop equipment models for accuracy • Standardized I/O interfaces with adjacent network
Current Status	*What is the current technical progress (e.g., TRL) of the opportunity and who (if any) is making investments?*	• Exists at transmission level • Software companies/network management systems • University
Metrics	*What is the cost and/or performance baseline of the current technology or alternatives (if applicable)?*	• No performance baseline
	What is the cost and/or performance targets (i.e., metrics and timeframes) for the opportunity?	• Unknown
Resources Needed	*What financial resources are needed to meet targets? ($XXX/year for YY years)*	• $5 million/10 years
Benefits	*What is the potential value and benefits of realizing this opportunity at scale? (quantitative or qualitative)*	• Resiliency of the distribution network • Predict load and generation requirements
Critical Paths	*What are the critical paths associated with realizing this opportunity? Include technology, market, policy, or regulatory challenges.*	• Research time • Implementation time • Cybersecurity

Top Priority Opportunity: *(i.e., component name and features)* Standardized/modular component design		
Desired Outcomes	*What are the new requirements, capabilities, or functions needed? Elaborate on the purpose of these new features.*	• High power density – ease of transportation • Off-the-shelf/scalable • Standardization of design
Current Status	*What is the current technical progress (e.g., TRL) of the opportunity and who (if any) is making investments?*	• TRL 4 → some efforts and an application proof of concept • Large manufacturers that have R&D budgets • FOA – office of OE – small amount
Metrics	*What is the cost and/or performance baseline of the current technology or alternatives (if applicable)?*	• $/kW is cheap, but power density is extremely poor
	What is the cost and/or performance targets (i.e., metrics and timeframes) for the opportunity?	• $/kW, MW/in^3 → > 20 years (transmission transformers)
Resources Needed	*What financial resources are needed to meet targets? ($XXX/year for YY years)*	• $10 million/year for 20 years
Benefits	*What is the potential value and benefits of realizing this opportunity at scale? (quantitative or qualitative)*	• Increased resiliency
Critical Paths	*What are the critical paths associated with realizing this opportunity? Include technology, market, policy, or regulatory challenges.*	• Testing facilities • Switching devices and other enabling components

Top Priority Opportunity: *(i.e., component name and features)* Cyber: standards, mitigation, detection, repair		
Desired Outcomes	*What are the new requirements, capabilities, or functions needed? Elaborate on the purpose of these new features.*	• Cybersecurity defenses that do not allow attack • Algorithms to detect and report attack attempts • Cyber requirements and standards • Authentication methods that allow only "credible" communications • On-device cybersecurity intelligence
Current Status	*What is the current technical progress (e.g., TRL) of the opportunity and who (if any) is making investments?*	• Cyber defenses continually advancing; however, must be implemented and updated • Cybersecurity may not always be properly implemented in practice • On-device cybersecurity intelligence (TRL ?)
Metrics	*What is the cost and/or performance baseline of the current technology or alternatives (if applicable)?*	• FOB/RSA-type tokens for access • Black Hat hackers for "in-house" attacks • Higher cyber vulnerability requires more defensive physical security
	What is the cost and/or performance targets (i.e., metrics and timeframes) for the opportunity?	• Practical implementation vs. need • Keeping all devices updated with patches → "smart" cyber devices
Resources Needed	*What financial resources are needed to meet targets? ($XXX/year for YY years)*	• $10 million/year for 10 years
Benefits	*What is the potential value and benefits of realizing this opportunity at scale? (quantitative or qualitative)*	• National security based on cyberattack resistant devices • Grid is vulnerable at each node and will become more vulnerable as more connected devices are deployed • Robust cyber defense *must* be implemented for national security and reliability purposes
Critical Paths	*What are the critical paths associated with realizing this opportunity? Include technology, market, policy, or regulatory challenges.*	• Workforce development • Understanding the risks • Regulatory challenges

Top Priority Opportunity: *(i.e., component name and features)* Medium voltage (MV) power flow controllers that can be used to manage voltage/reactive power		
Desired Outcomes	*What are the new requirements, capabilities, or functions needed? Elaborate on the purpose of these new features.*	• Active and reactive power control – manage voltage for all DER and load profiles including higher penetration PV and EVs • Outdoor rated, pole mountable • Resilient to weather, storms, electrical surges
Current Status	*What is the current technical progress (e.g., TRL) of the opportunity and who (if any) is making investments?*	• Varetec, Gridco → prototypes being developed (TRL 5) (unclear if they meet all the technical specifications) • Solid-state transformers (prototypes in laboratories) (IREOM Center, GE?) • Maybe ARPA-E, Varetec, ORNL
Metrics	*What is the cost and/or performance baseline of the current technology or alternatives (if applicable)?*	• \$10/KVA (in the range of current transformers) • Cost of transformers with tops for V/R and CAP bank
	What is the cost and/or performance targets (i.e., metrics and timeframes) for the opportunity?	• \$10/KVA • 10 years (try to complete and make widely available)
Resources Needed	*What financial resources are needed to meet targets? (\$XXX/year for YY years)*	• \$2-3 million for 5 years for development • \$1 million for 3 years – commercialization and market development
Benefits	*What is the potential value and benefits of realizing this opportunity at scale? (quantitative or qualitative)*	• Benefit → alleviate voltage issues associated with high penetration PV and EV deployment • Benefit → voltage optimization and CVR, general power optimization (Optimal Power Flow on distribution circuit)
Critical Paths	*What are the critical paths associated with realizing this opportunity? Include technology, market, policy, or regulatory challenges.*	• Reliability – can this be made with the same reliability as a voltage regulator and capacitor bank? • Cost effectiveness • How to pay (or rate-base) for devices

Blue Group

Top Priority Opportunity: *(i.e., component name and features)* Flexible Multiport Transformers (Distribution) • SST • Traditional		**Group Members:** Tom Keister, Steve Whisenant, V.R. Ramanan
Desired Outcomes	*What are the new requirements, capabilities, or functions needed? Elaborate on the purpose of these new features.*	• Variable voltage, varying impedance, ride through, low cost fault detection • AC/DC flexibility, multiport, agnostic source (multi-sources) • Multi-functional: line balancing, VAR control, power flow control
Current Status	*What is the current technical progress (e.g., TRL) of the opportunity and who (if any) is making investments?*	• Traditional transformer = TRL 3 • SST: Europe (consortium is making plans for launching product) … research projects • Alstrom, GE, Siemens, ABB have traction with SST
Metrics	*What is the cost and/or performance baseline of the current technology or alternatives (if applicable)?*	• Technology evolving — SST cost is high ($100/KVA) • $35-50 traditional upgraded
	What is the cost and/or performance targets (i.e., metrics and timeframes) for the opportunity?	•
Resources Needed	*What financial resources are needed to meet targets? ($XXX/year for YY years)*	•
Benefits	*What is the potential value and benefits of realizing this opportunity at scale? (quantitative or qualitative)*	• Efficiency, flexibility, lower system cost, operate better • VAR control, mix systems, simplify protection
Critical Paths	*What are the critical paths associated with realizing this opportunity? Include technology, market, policy, or regulatory challenges.*	• SST: cost competitive to traditional or return on investment • SST: better resiliency than traditional

Top Priority Opportunity: *(i.e., component name and features)* Flexible Multiport Transformers (Transmission) • SST • Traditional		**Group Members:** Tom Keister, Steve Whisenant, V.R. Ramanan
Desired Outcomes	*What are the new requirements, capabilities, or functions needed? Elaborate on the purpose of these new features.*	• Standardize LTP → • Variable voltage, variable importance, ride through, low cost, fault detect • Fault tolerant, VAR control, protection: all in one device • AC/DC, Low voltage/medium voltage/high voltage, 3 phase/2 phase/multi-phase
Current Status	*What is the current technical progress (e.g., TRL) of the opportunity and who (if any) is making investments?*	• Traditional modified → lots of experience → TRL = 3 • SST → closest thing is HVDC (conventional transformer with electronics)
Metrics	*What is the cost and/or performance baseline of the current technology or alternatives (if applicable)?*	• Technology evolving, SST cost is high ($100/kVA) • $12-15 traditional upgrade
	What is the cost and/or performance targets (i.e., metrics and timeframes) for the opportunity?	• $12-15; Cost goal to make SST = traditional upgrade
Resources Needed	*What financial resources are needed to meet targets? ($XXX/year for YY years)*	
Benefits	*What is the potential value and benefits of realizing this opportunity at scale? (quantitative or qualitative)*	• Efficiency, flexibility, lower system cost, operate better • VAR control, mix systems, simplify protection
Critical Paths	*What are the critical paths associated with realizing this opportunity? Include technology, market, policy, or regulatory challenges.*	• SST: voltage and power ratings • SST: better resiliency than traditional

Top Priority Opportunity: *(i.e., component name and features)* Bidirectional Power Flow and Power Electronics Direct Tie MV		**Group Members:** Tom King, Milovan Grbic, Prasad Kandula, Ray Johnson
Desired Outcomes	*What are the new requirements, capabilities, or functions needed? Elaborate on the purpose of these new features.*	• Low cost converter; 4 Quad Volt-VAR control • Development of standards – who owns, who controls, customer, utility, 3rd party • Load balancing
Current Status	*What is the current technical progress (e.g., TRL) of the opportunity and who (if any) is making investments?*	• Yes, there is vendor progress • TRL level 6-7, DOE can help reduce cost
Metrics	*What is the cost and/or performance baseline of the current technology or alternatives (if applicable)?*	• Cost and reliability improvements • Increase voltage and current ratings for power electronics
	What is the cost and/or performance targets (i.e., metrics and timeframes) for the opportunity?	• Must handle lightning • 10+ years with transients
Resources Needed	*What financial resources are needed to meet targets? ($XXX/year for YY years)*	• $15M/5 years
Benefits	*What is the potential value and benefits of realizing this opportunity at scale? (quantitative or qualitative)*	• Accelerate renewals • Environmental • Engage consumer • Consumer reactive vs. passive
Critical Paths	*What are the critical paths associated with realizing this opportunity? Include technology, market, policy, or regulatory challenges.*	• Safety and security – policies need to be in place • Standards • $/kW

Top Priority Opportunity: *(i.e., component name and features)* Protection Devices that are Plug and Play			**Group Members:** Allen Thiel, Maciej Kumosa, Michael Rivera
Desired Outcomes	*What are the new requirements, capabilities, or functions needed? Elaborate on the purpose of these new features.*	• Protection devices that are plug and play • Protection devices that last longer • Protection devices that do multiple redundant functions • Protection devices that result in less but more flexible intelligent electronic devices	
Current Status	*What is the current technical progress (e.g., TRL) of the opportunity and who (if any) is making investments?*	• GE, Schweitzer, other manufacturers • Unknown state of current research (manufacturer priority knowledge) • Industry likely working on it, but need to be pushed harder • DOD might be doing this	
Metrics	*What is the cost and/or performance baseline of the current technology or alternatives (if applicable)?*	• Current tech is expensive, not flexible, and does not last long enough • Difficult and takes a long time to replace (also dangerous)	
	What is the cost and/or performance targets (i.e., metrics and timeframes) for the opportunity?	• Cost equal to or less than current devices in purchase and implementation • Cost effective life cycle (i.e., short life cycle = cheap device; long cycle = more expensive)	
Resources Needed	*What financial resources are needed to meet targets? ($XXX/year for YY years)*	• $1 million per year	
Benefits	*What is the potential value and benefits of realizing this opportunity at scale? (quantitative or qualitative)*	• Reduce maintenance, capital costs, and increased reliability • Reduce response time to abnormal events/failure • Increased redundancy	
Critical Paths	*What are the critical paths associated with realizing this opportunity? Include technology, market, policy, or regulatory challenges.*	• Cybersecurity needs to ensure security of components • Ease of Use: relays with too many switches are difficult and costly to use • Data Management: more complicated devices might create too much data	

Top Priority Opportunity: *(i.e., component name and features)* Different Protection Philosophy		**Group Members:** Michael Rivera, Maciej Kumosa, Allen Thiel
Desired Outcomes	*What are the new requirements, capabilities, or functions needed? Elaborate on the purpose of these new features.*	• Setting-less – Not based on over current – Dynamic protection
Current Status	*What is the current technical progress (e.g., TRL) of the opportunity and who (if any) is making investments?*	• EPRI – maybe • Academia
Metrics	*What is the cost and/or performance baseline of the current technology or alternatives (if applicable)?*	• Monitoring current and voltage only • Active response only
	What is the cost and/or performance targets (i.e., metrics and timeframes) for the opportunity?	• Increased reliability • Accommodate DER – two way power flow • Proactive approach to protection instead of reactive • Intelligent self-assessing protection system
Resources Needed	*What financial resources are needed to meet targets? ($XXX/year for YY years)*	• $1M/year
Benefits	*What is the potential value and benefits of realizing this opportunity at scale? (quantitative or qualitative)*	• Increased reliability • Accommodate DER – two way power flow • Proactive approach to protection instead of reactive • Intelligent self-assessing protection system
Critical Paths	*What are the critical paths associated with realizing this opportunity? Include technology, market, policy, or regulatory challenges.*	• Technology – Sensing limitations – Electromechanical • Secure and efficient communication technology • Cyber security

Top Priority Opportunity: *(i.e., component name and features)* Multi-function Power Transformation Device		**Group Members:** Jeff Hildreth, Milke McElfresh, Stan Atcitty, Kevin Berent
Desired Outcomes	*What are the new requirements, capabilities, or functions needed? Elaborate on the purpose of these new features.*	• One device with the following functions: voltage transformation, power flow control, fault current limit, VAR support, GIC protection, physically secure • Avoid one-of-a-kind custom devices
Current Status	*What is the current technical progress (e.g., TRL) of the opportunity and who (if any) is making investments?*	• These functions exist in separate devices
Metrics	*What is the cost and/or performance baseline of the current technology or alternatives (if applicable)?*	• Conventional transformers are cost effective but inflexible • Existing power electronic (FACTS) devices are flexible but not always cost effective or reliable enough
	What is the cost and/or performance targets (i.e., metrics and timeframes) for the opportunity?	• Cheaper than the sum of the costs of existing devices • At least as reliable as existing LPT • Transportation must be practical
Resources Needed	*What financial resources are needed to meet targets? ($XXX/year for YY years)*	• Big $ • Start at distribution level first
Benefits	*What is the potential value and benefits of realizing this opportunity at scale? (quantitative or qualitative)*	• Maximize/optimize use of existing transmission corridors • More resilient power system operation • Simplified spare strategy
Critical Paths	*What are the critical paths associated with realizing this opportunity? Include technology, market, policy, or regulatory challenges.*	• Advanced power semiconductors • Control systems

Top Priority Opportunity: *(i.e., component name and features)* Embedded Prognostic and Health Management Systems for Transmission Components		**Group Members:** Jeff Hildreth, Mike McElfresh, Stan Atcitty, Kevin Berent
Desired Outcomes	*What are the new requirements, capabilities, or functions needed? Elaborate on the purpose of these new features.*	• Provides actionable information • Anticipate or predict component failure or remaining life • Manage/optimize component life by recommending maintenance or change in operating conditions
Current Status	*What is the current technical progress (e.g., TRL) of the opportunity and who (if any) is making investments?*	• Some sensors are embedded, there are opportunities to add more • Analytics are primitive
Metrics	*What is the cost and/or performance baseline of the current technology or alternatives (if applicable)?*	• Data is collected without a means for analyzing it
	What is the cost and/or performance targets (i.e., metrics and timeframes) for the opportunity?	• Accuracy of prediction (remaining life, pending failures) • Extend equipment life, avoid outage, avoid unnecessary maintenance
Resources Needed	*What financial resources are needed to meet targets? ($XXX/year for YY years)*	• 0 < $ needed < $1B
Benefits	*What is the potential value and benefits of realizing this opportunity at scale? (quantitative or qualitative)*	• Extend equipment life, avoid outage, avoid unnecessary maintenance
Critical Paths	*What are the critical paths associated with realizing this opportunity? Include technology, market, policy, or regulatory challenges.*	• This is primarily a technical challenge • Help regulated utilities justify need to replace transmission assets

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