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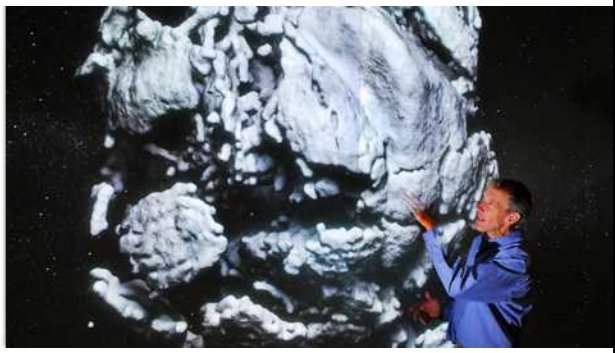

Employing Advanced Inverter Functionality to Create Smarter Electricity Grids

2013 Energy Tech Insight
Seoul, Korea
28 Aug, 2013

Jay Johnson

Photovoltaic and Distributed Systems Integration, Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

- The Interoperability Vision
- Example Advanced Functions
- Interoperability and Advanced Function Testing
  - Sandia Test Protocols
  - Testbeds at Sandia and KERI
  - Preliminary Interoperability Test Results at Sandia
- Importance of Collaboration
  - Korea Electrotechnology Research Institute (KERI)
  - Smart Grid International Research Facility Network (SIRFN)
  - California Public Utilities Commission (CPUC)
- Future work
  - Goal: Create robust consensus-based testing standard for adoption by standards and certification authorities.

Current Electricity Grid

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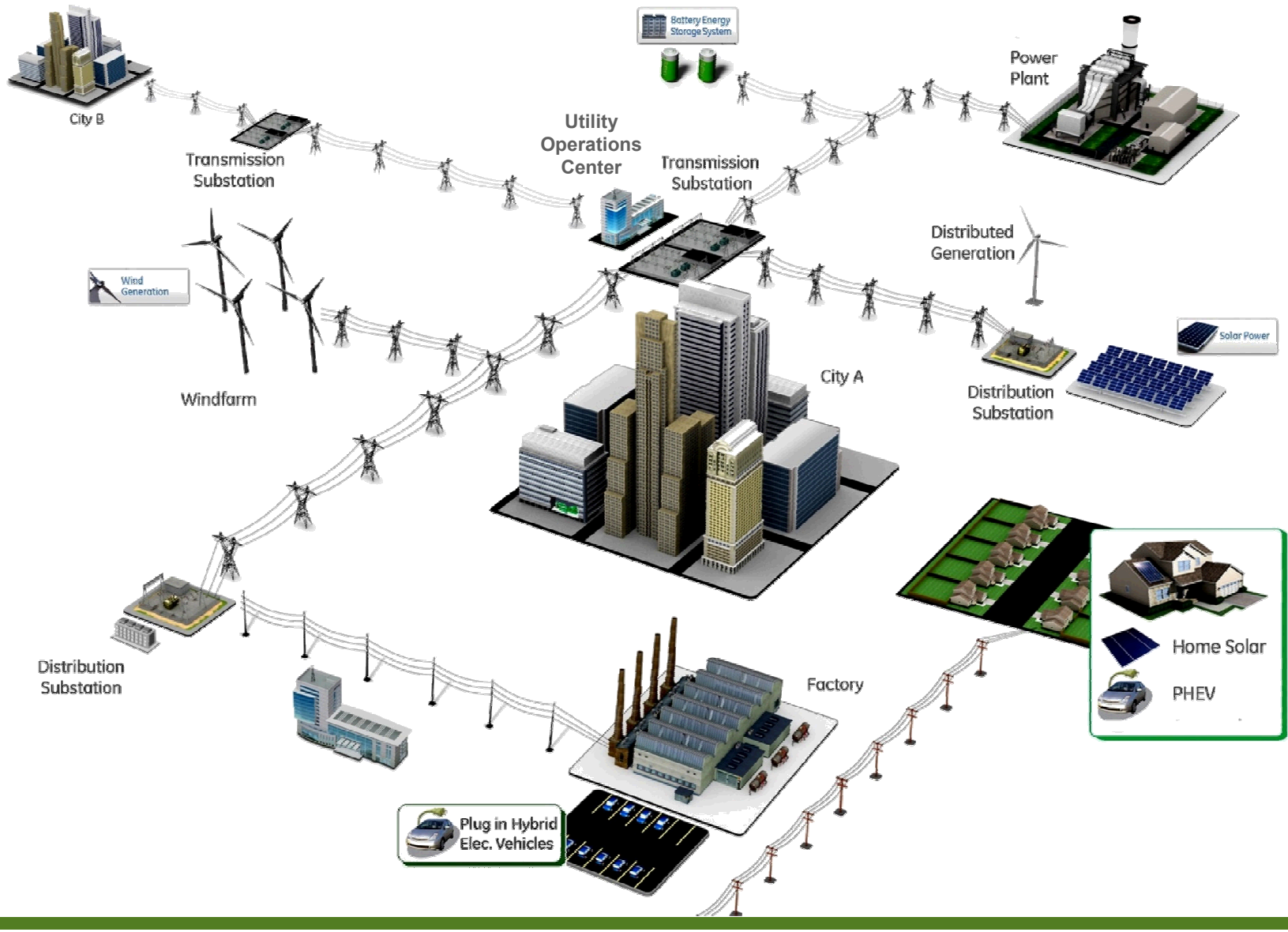

Image: Forbes India

Current Electricity Grid Communications

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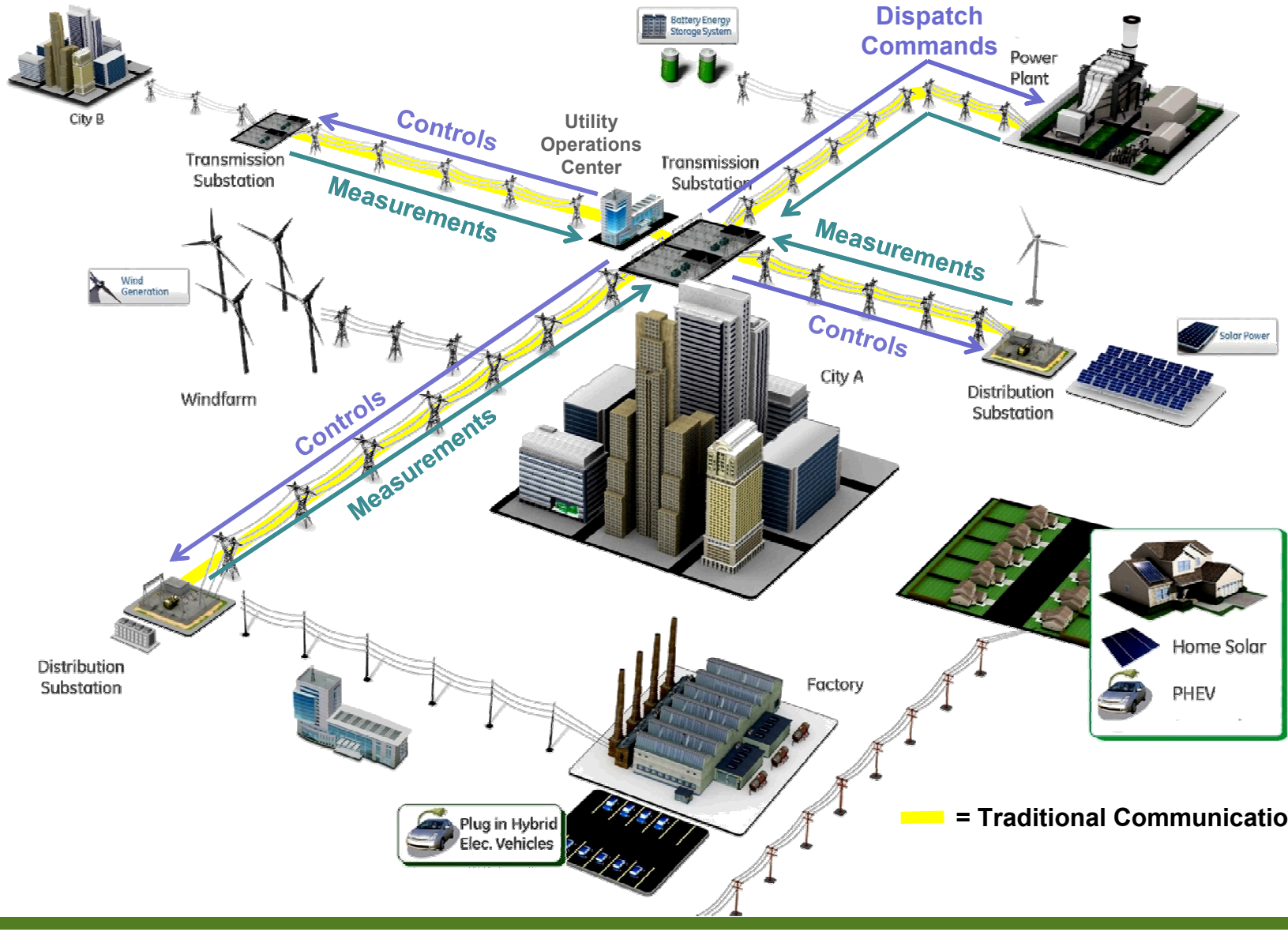

Image: Forbes India

Smart Electricity Grid

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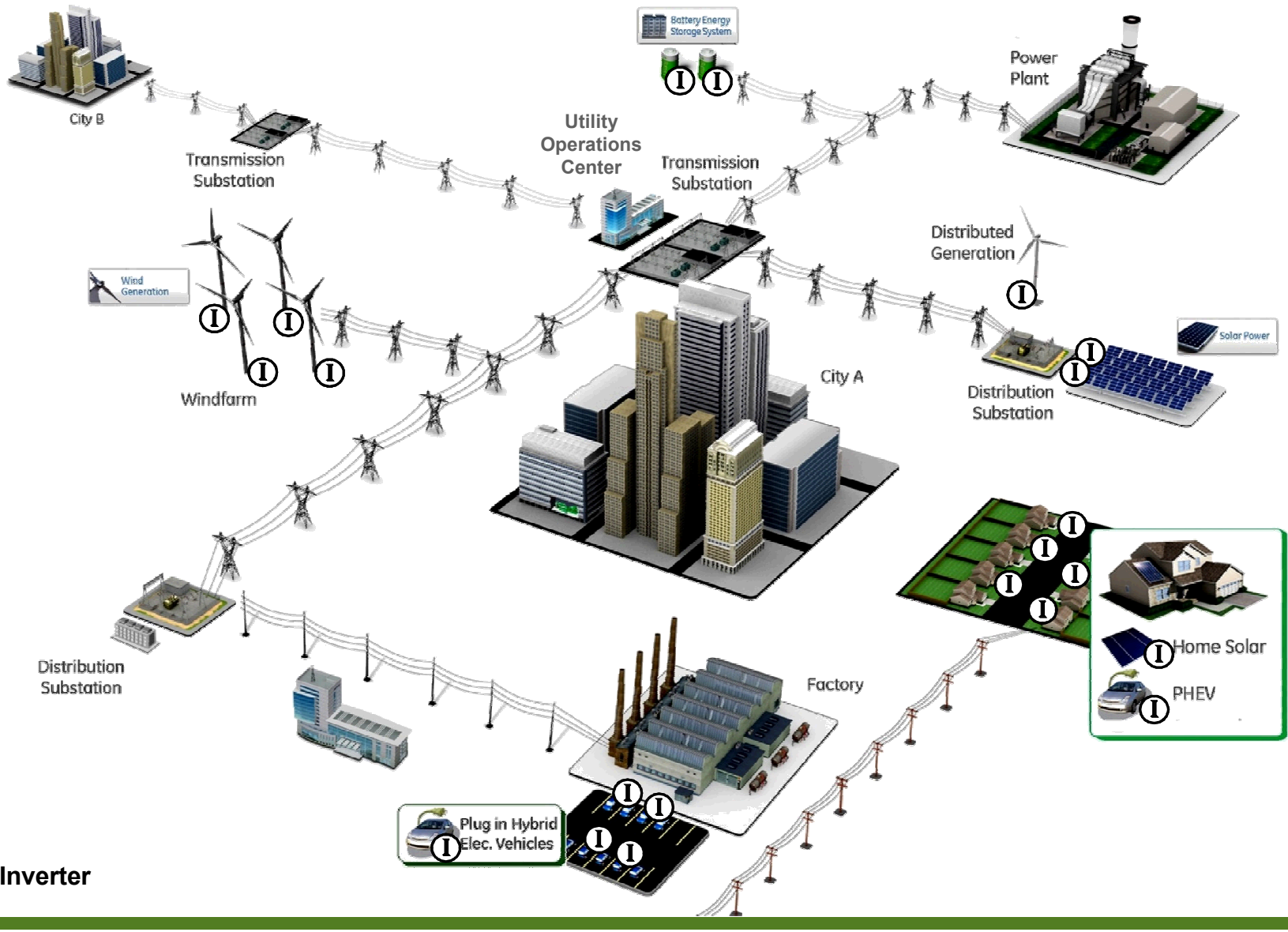

Ⓘ = Inverter

Image: Forbes India

Smart Electricity Grid Communications

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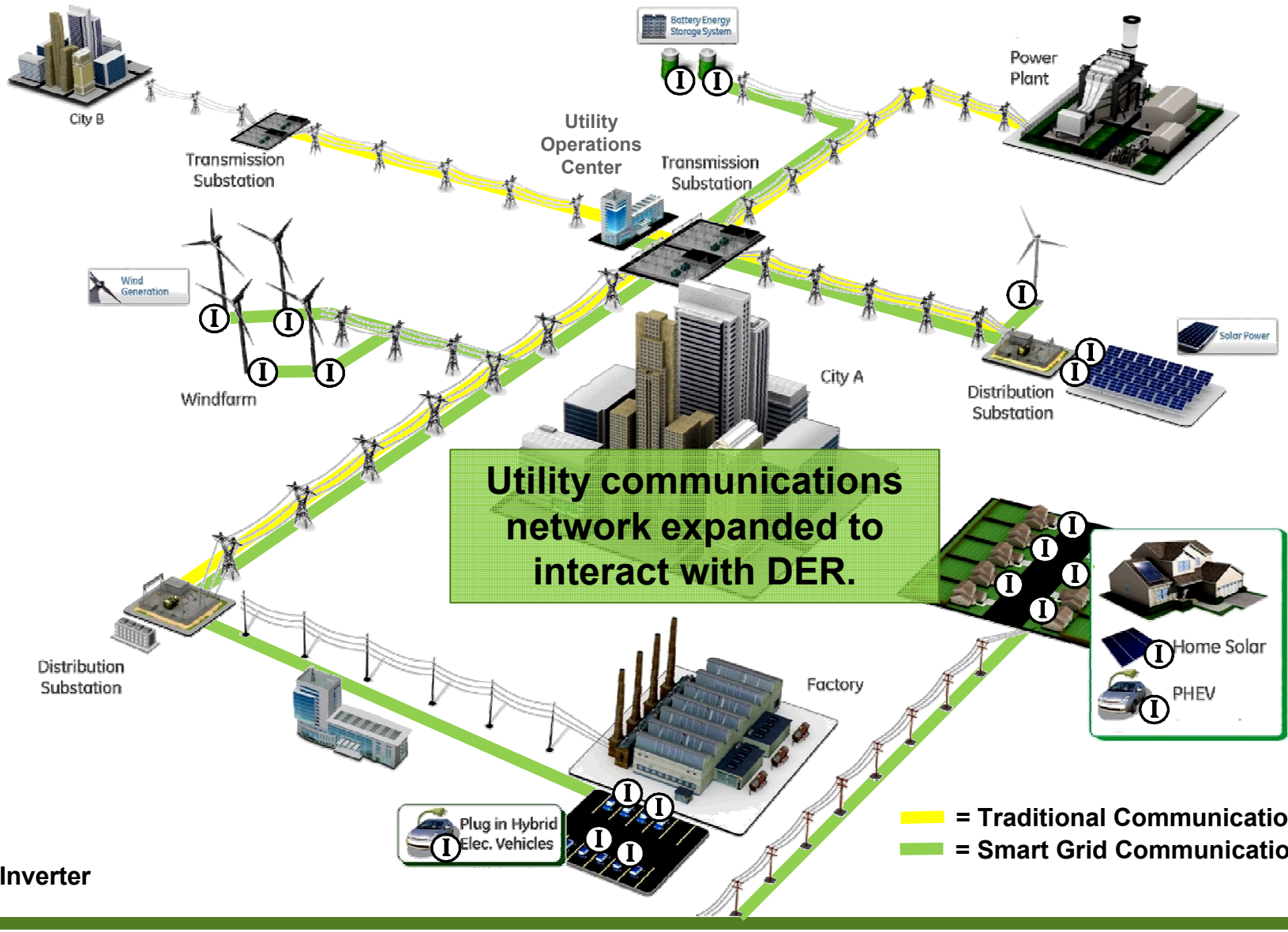

Image: Forbes India

Smart Electricity Grid Communications

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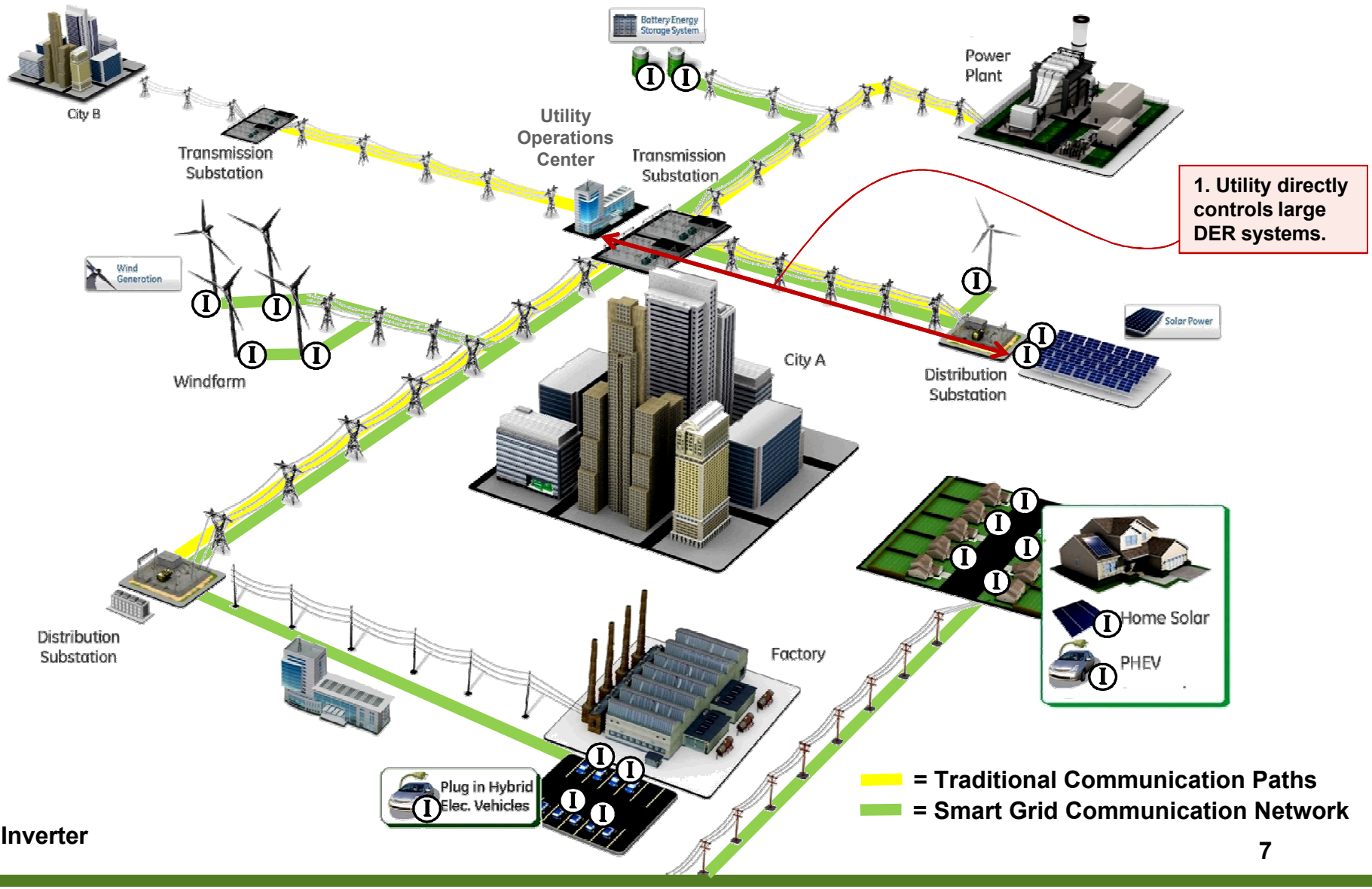

Image: Forbes India

Smart Electricity Grid Communications

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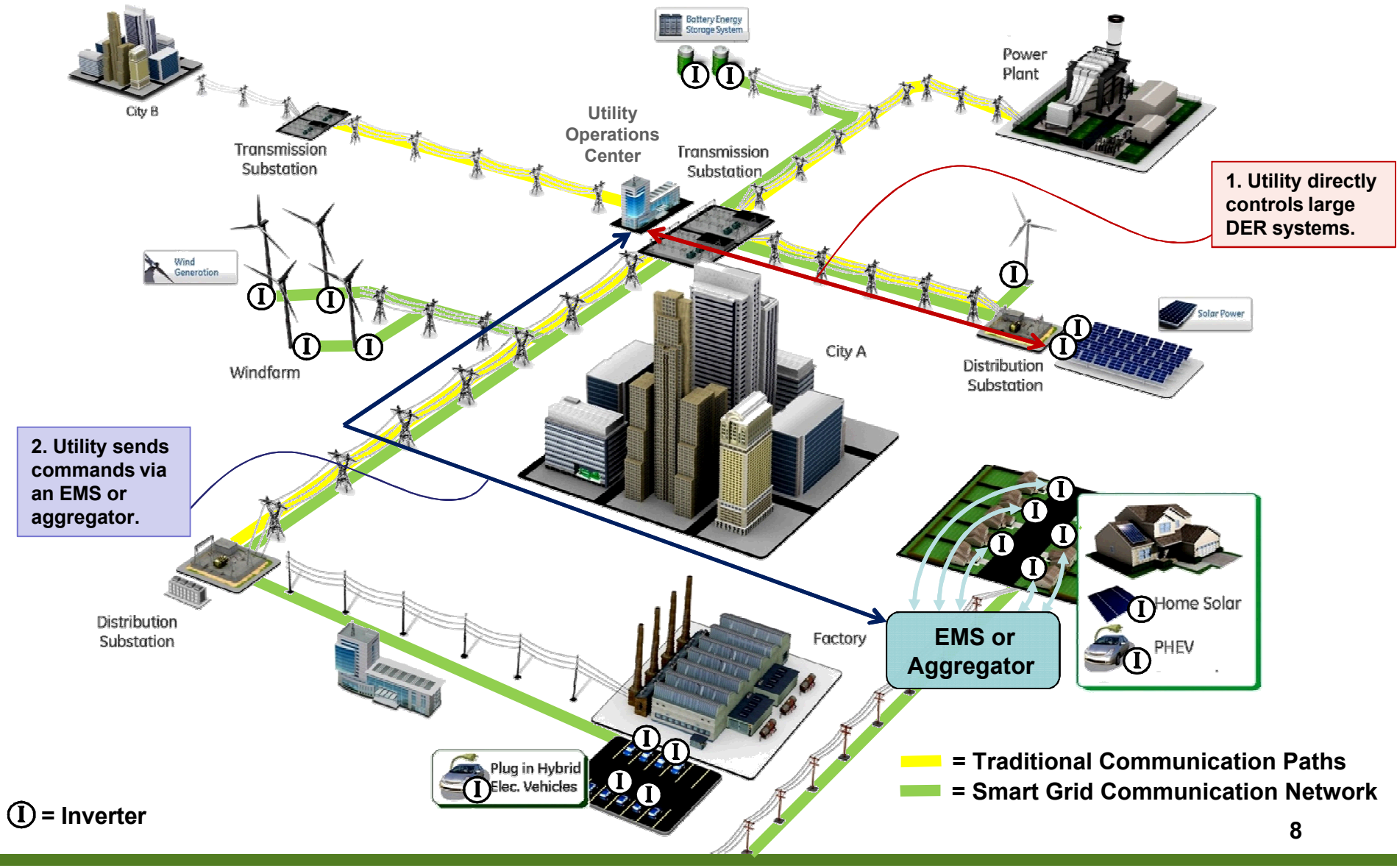
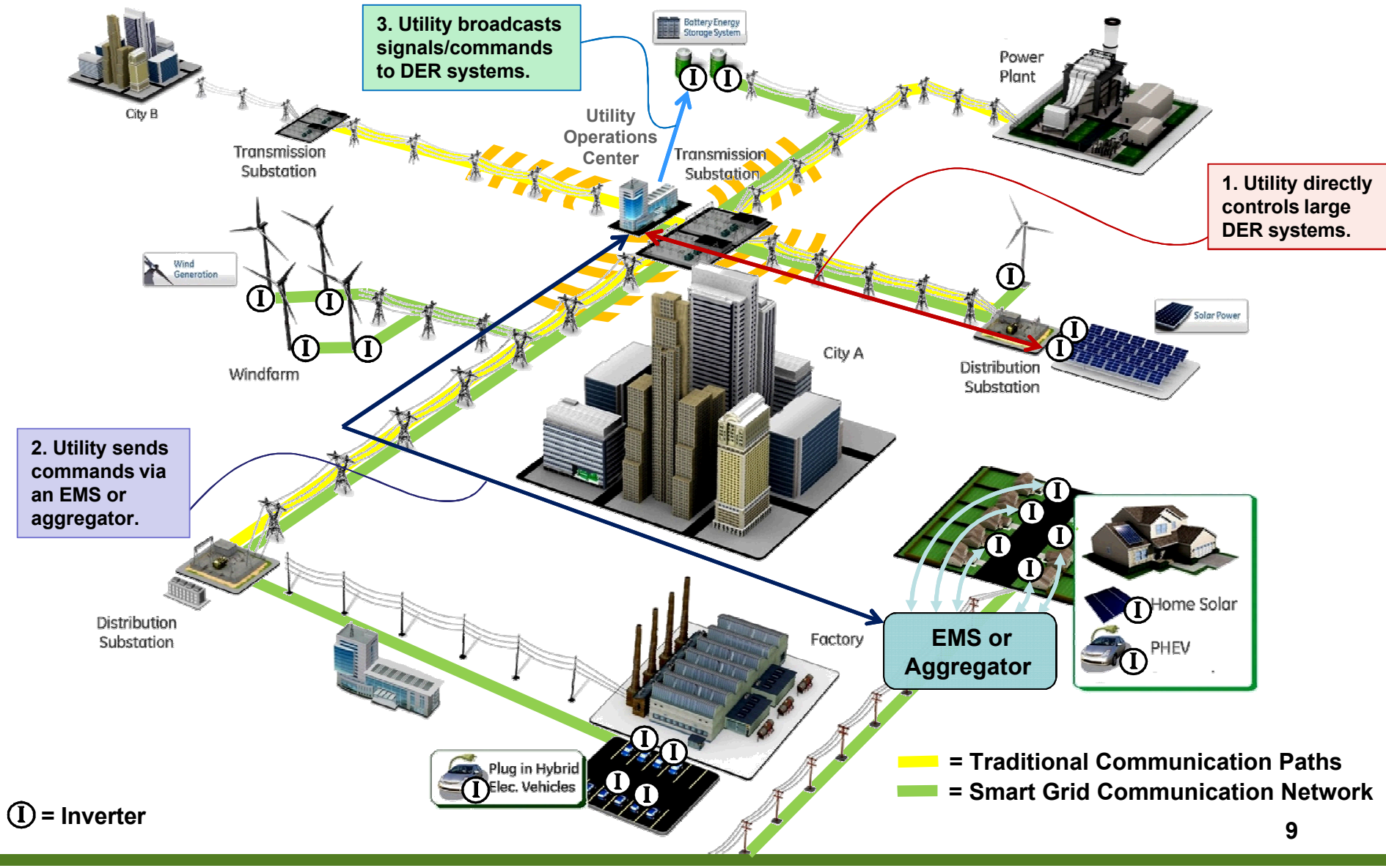


Image: Forbes India

Smart Electricity Grid Communications

Sandia National Laboratories



Source: Forbes India

Type of Advanced Inverter Functions

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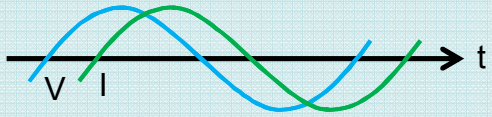
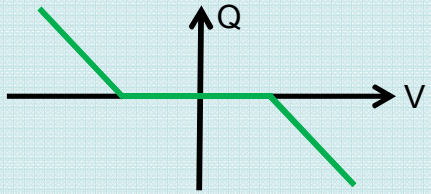
Advanced functions defined in IEC Technical Report 61850-90-7:

Voltage Support

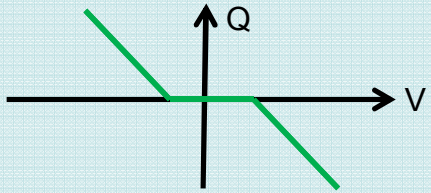
- **Adjust Power Factor (INV3)**



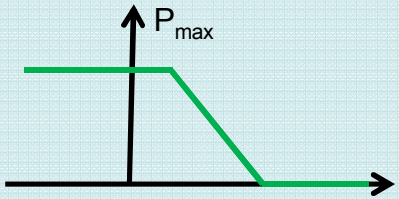
- **Volt-Var Mode (VV11, VV12, VV13)**



- **Dynamic Reactive Power (TV31)**

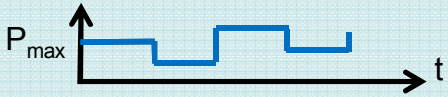


- **Volt-Watt Mode (VW51; VW52)**

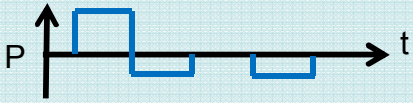


Frequency Support

- **Adjust Maximum Active Power (INV2)**

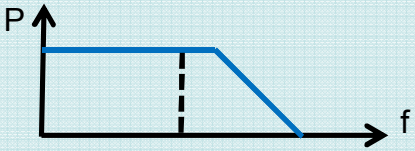


- **Request Active Power from Storage (INV4)**

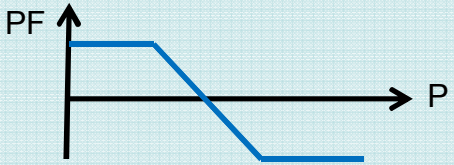


- **Signal for Charge/Discharge (INV5)**

- **Frequency-Watt Mode (FW21, FW22)**

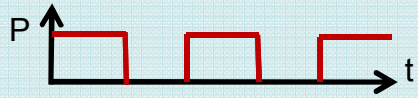


- **Watt-Power Factor (WP41, WP42)**

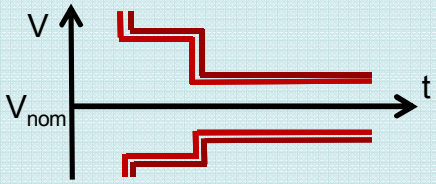


Grid Protection (Response to Disturbances)

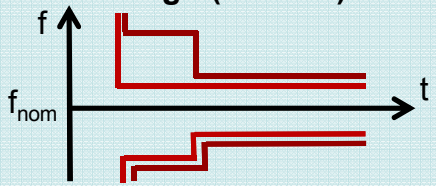
- **Connect/Disconnect (INV1)**



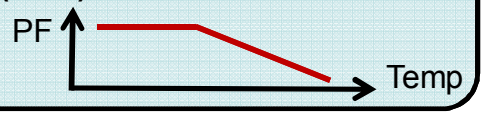
- **Low and High Voltage Ride Through (L/HVRT)**



- **Low and High Frequency Ride Through (L/HFRT)***



- **Temperature mode Behavior (TMP)**

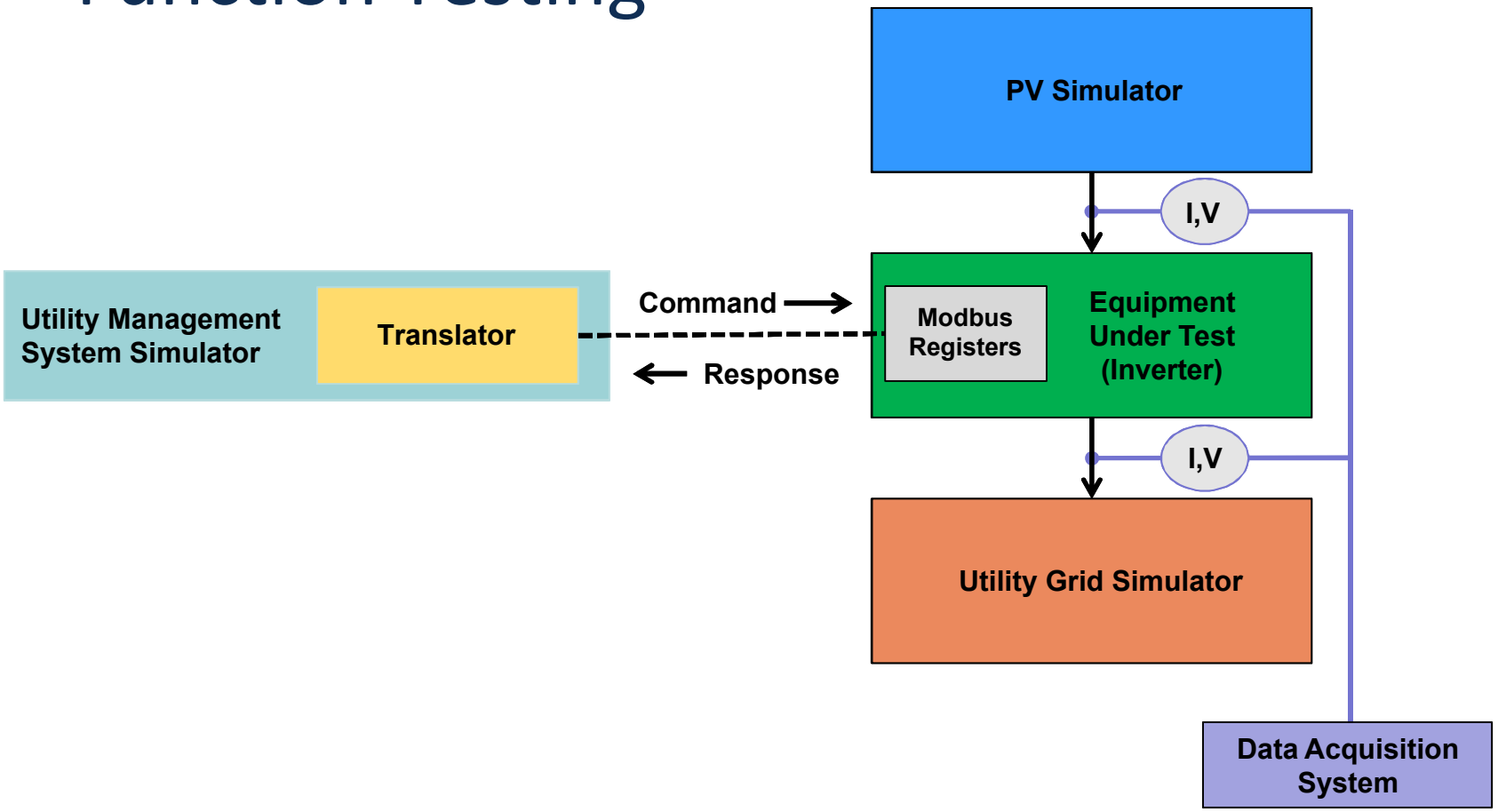


*FRT not included in IEC 61850-90-7, but is included in Sandia Test Protocols.

Moving toward a smarter grid

- **In the not-so-distant future…**
  - Inverters will include **advanced functions** which **autonomously support the grid frequency and voltage** by adjusting their behavior in response to **local grid measurements**
  - Utilities will update DER behavior using **interoperability communications**
- **Emerging industry need to have certification tests for these functions**
  - Sandia created an interoperability test protocol as a precursor to specific international or national standards
  - Sandia, KERI, and many others are working to:
    - Build interoperability testbeds to exercise the test protocols
    - Compare interoperability test results to revise/improve test protocols and suggest performance requirements
- **Many working groups are involved in bringing this smart grid vision to life:**
  - Codes/standards bodies allowing DERs to support grid frequency and voltage (e.g., IEEE 1547a)
  - Groups establishing consistent definitions for inverters functions (e.g., IEC TR 61850-90-7)
  - Consortia standardizing communications (e.g., SunSpec Alliance inverter models)
  - Inverter and DER manufacturers updating product designs
  - Laboratories and scientists creating testing procedures for verifying the interoperability communications and electrical functionality of these functions (e.g., Sandia Test Protocols)
  - Testing, revising, and improving test protocols (e.g., SNL, KERI, SIRFN members, etc.)
  - Collaborations establishing interoperability function performance criteria (e.g., UL, IEC)

DER Interoperability and Advanced Function Testing



DER Interoperability and Advanced Function Testing

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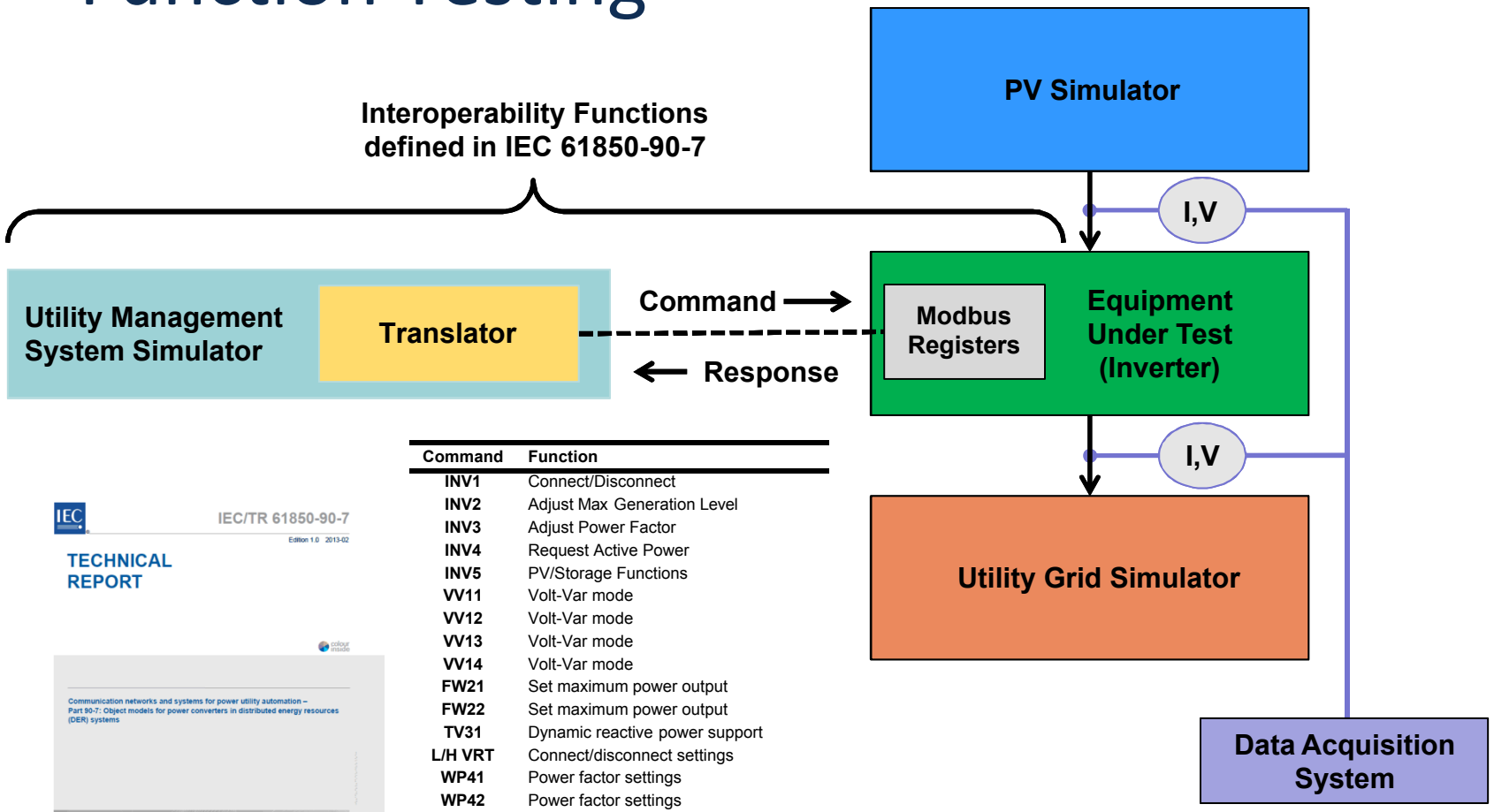

Command	Function
INV1	Connect/Disconnect
INV2	Adjust Max Generation Level
INV3	Adjust Power Factor
INV4	Request Active Power
INV5	PV/Storage Functions
VV11	Volt-Var mode
VV12	Volt-Var mode
VV13	Volt-Var mode
VV14	Volt-Var mode
FW21	Set maximum power output
FW22	Set maximum power output
TV31	Dynamic reactive power support
L/H VRT	Connect/disconnect settings
WP41	Power factor settings
WP42	Power factor settings
VW51	Set output to smooth voltage
VW52	Set output to smooth voltage
TMP	Temperature mode behavior
PS	Signal mode behavior
DS91	Modify DER Inverter Settings
DS92	Event/History Logging
DS93	Status Reporting
DS94	Time Synchronization

DER Interoperability and Advanced Function Testing

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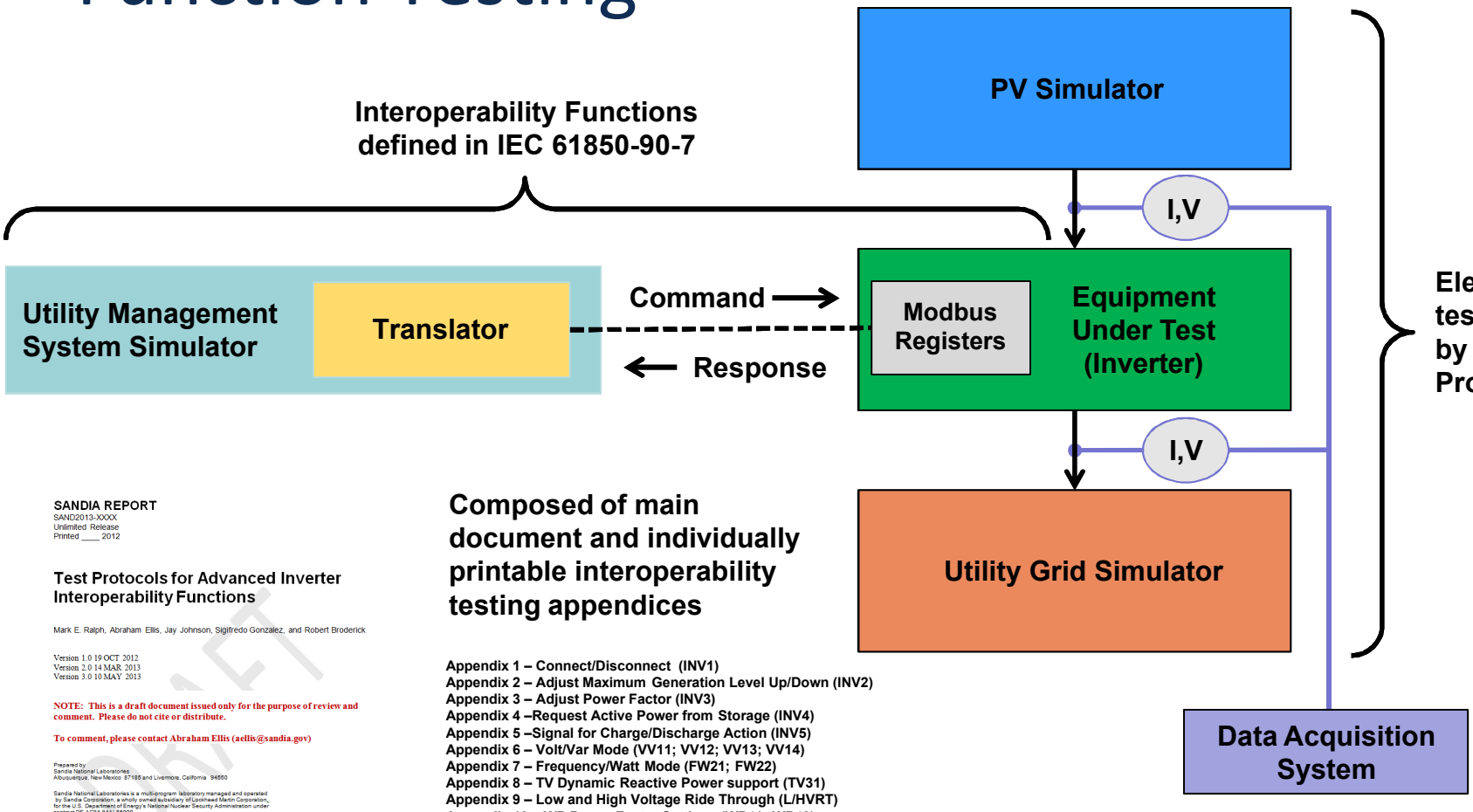

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SAND2013-XXXX
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Printed ____ 2012

Test Protocols for Advanced Inverter Interoperability Functions

Mark E. Ralph, Abraham Ellis, Jay Johnson, Sigifredo Gonzalez, and Robert Broderick

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Version 2.0 14 MAR 2013
Version 3.0 10 MAY 2013

NOTE: This is a draft document issued only for the purpose of review and comment. Please do not cite or distribute.

To comment, please contact Abraham Ellis (aellis@sandia.gov)

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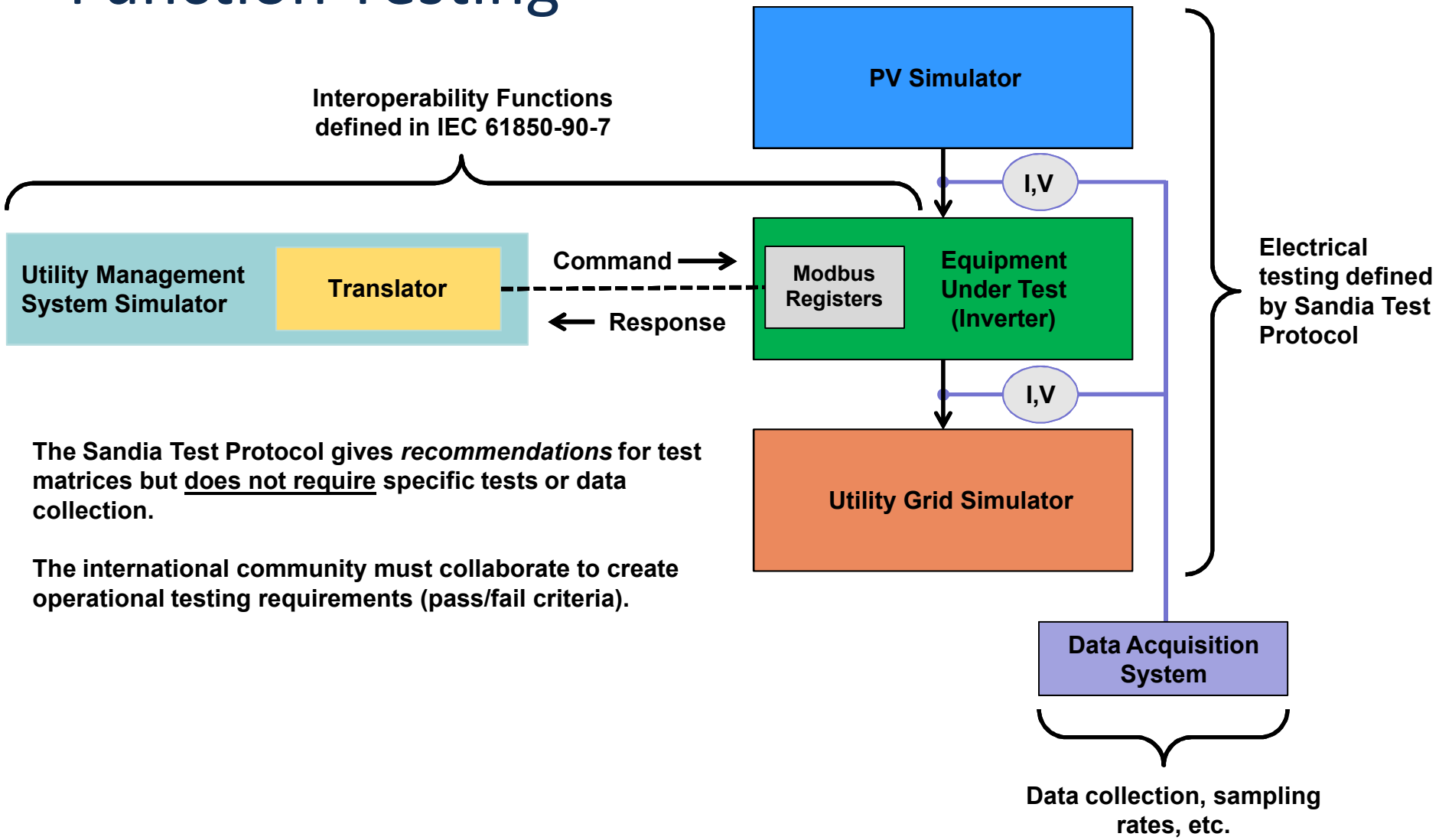
Composed of main document and individually printable interoperability testing appendices

Appendix 1 – Connect/Disconnect (INV1)
Appendix 2 – Adjust Maximum Generation Level Up/Down (INV2)
Appendix 3 – Adjust Power Factor (INV3)
Appendix 4 –Request Active Power from Storage (INV4)
Appendix 5 –Signal for Charge/Discharge Action (INV5)
Appendix 6 – Volt/Var Mode (VV11; VV12; VV13; VV14)
Appendix 7 – Frequency/Watt Mode (FW21; FW22)
Appendix 8 – TV Dynamic Reactive Power support (TV31)
Appendix 9 – Low and High Voltage Ride Through (L/HVRT)
Appendix 10 – WP Power Factor Settings (WP41; WP42)
Appendix 11 – VW Set Output to Smooth Voltage Variations (VW51; VW52)
Appendix 12 –Temperature mode Behavior (TMP)
Appendix 13 – Utility Signal Mode (PS)
Appendix 14 – Event History/Logging (DS92)
Appendix 15 – Status Reporting (DS93)
Appendix 16 –Time Synchronization (DS94)
Appendix 17 – Time Window & Random Time Delay
Appendix 18 – Ramp Rate
Appendix 19 – Command Timeout

DER Interoperability and Advanced Function Testing



The Sandia Test Protocol gives *recommendations* for test matrices but does not require specific tests or data collection.

The international community must collaborate to create operational testing requirements (pass/fail criteria).

DER Interoperability and Advanced Function Testing

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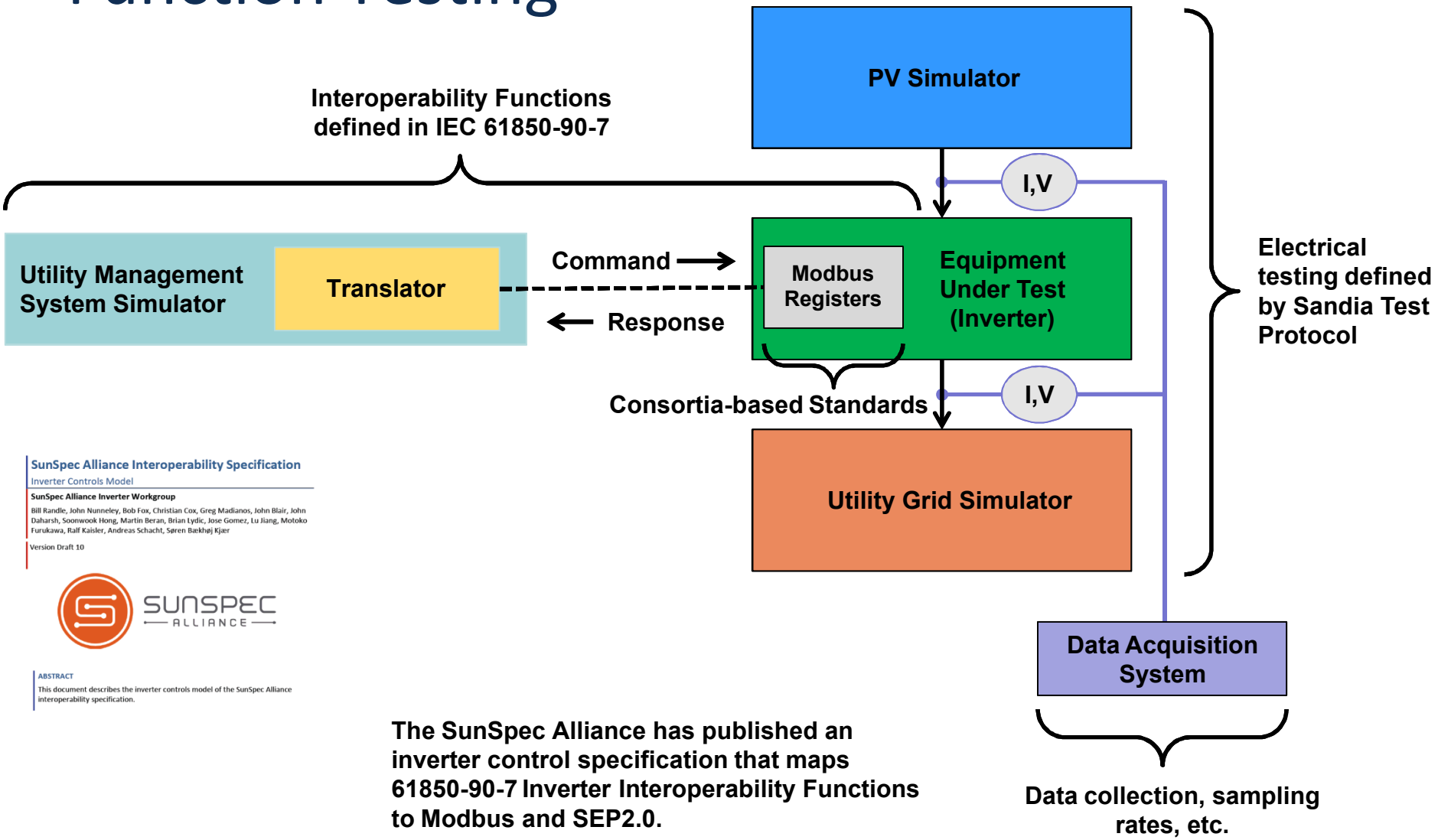


SunSpec Alliance Interoperability Specification

Inverter Controls Model

SunSpec Alliance Inverter Workgroup

Bill Randle, John Nunneley, Bob Fox, Christian Cox, Greg Madianos, John Blair, John Daharsh, Soonwook Hong, Martin Beran, Brian Lydic, Jose Gomez, Lu Jiang, Motoko Furukawa, Ralf Kaisler, Andreas Schacht, Søren Bækhøj Kjær

Version Draft 10

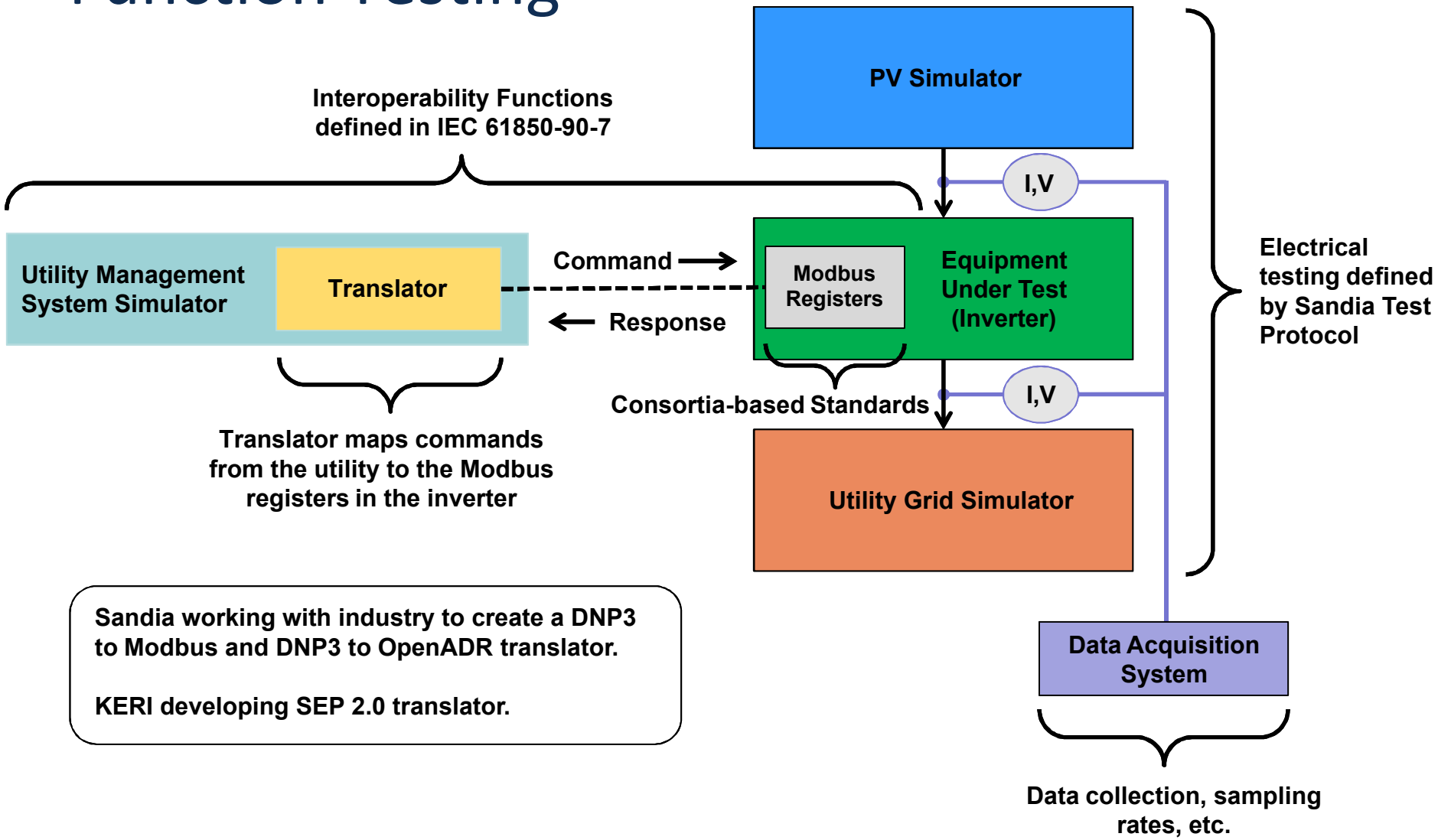
SUNSPEC ALLIANCE

ABSTRACT

This document describes the inverter controls model of the SunSpec Alliance interoperability specification.

The SunSpec Alliance has published an inverter control specification that maps 61850-90-7 Inverter Interoperability Functions to Modbus and SEP2.0.

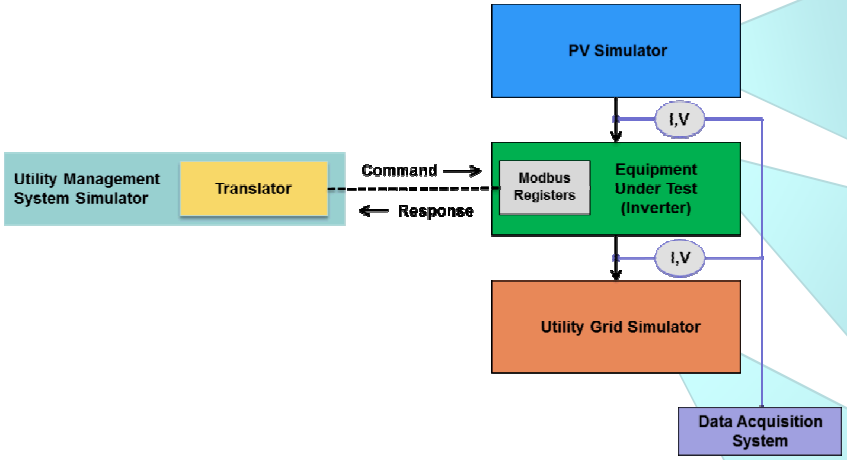
DER Interoperability and Advanced Function Testing



Inverter Interoperability Testing at Sandia and KERI

Sandia National Laboratories

Both Sandia and KERI have designed interoperability testbeds. These facilities will run tests in parallel and compare results. Challenges with testing will be used to improve the interoperability tests protocols.



PV Simulator
Power: 200 kW
Voltage: 0-1000 Vdc/output
Current: 10 A/output

PV Simulator
Power: 10 kW
Voltage: 0-500 Vdc
Current: 50 A

Inverter: Austrian Partner
Power: 3kW
Communications: Modbus, RS485
- Available worldwide
- Inexpensive
- SunSpec compliant

Inverter: Korean Partner
Power: 3kW
Communications: SEP 2.0

Grid Simulator
Power: 180 kVA
Voltage: 480 V 3ϕ
Current: 700 A/Phase

Grid Simulator
Power: 10kVA
Voltage: 380 V_{L-L}
3ϕ, 4-wire

Differences in hardware and grid voltage and frequency demonstrate the capabilities of the testing protocols.

US grid: 120/240 V, 60 Hz

Korean grid: 240 V, 60 Hz

Sandia Test Protocol

- General guidelines for harmonized equipment testing across different laboratories.
- Precursor to future equipment certification procedures.
- Two distinct phases for most functions:
  - Communication
    - Send the signal from the Utility Management System Simulator
    - Verify the communications reached the EUT
  - Electrical behavior characterization
    - Measurement of the DC and AC characteristics to verify the inverter updated its operation
- Communication phase of the test protocol sequence may be skipped for some inverters if there is no translator.

Example Test Protocol Sequence (Volt/Var VV11)

Step	Task	Function	Notes
Communication (Tell the inverter what to do. Listen for a response from the inverter.)			
Electrical Behavior Characterization (Electrically test the inverter to ensure the new functionality is enabled.)			
Analysis (Verify inverter behavior.)			

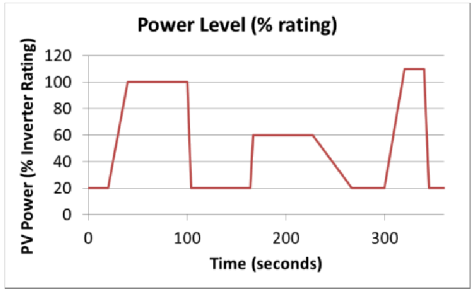
INV3: Set Constant PF – Electrical Characterization Results

Sandia National Laboratories

Step 1: Update inverter functionality according based on the Test Matrix.

Power Factor (INV3)	Ramp Rate (%/sec)	Timeout Period (sec)	Time Delay (sec)
1.00 (default)	Default	Default	0 sec
MaxPFAval (overexcited)	Default	600	60
MaxPFAval (underexcited)	Default	Default	300
0.5+MaxPFAval/2 (overexcited)	10	Default	Default
0.5+MaxPFAval/2 (underexcited)	Default	1800	Default

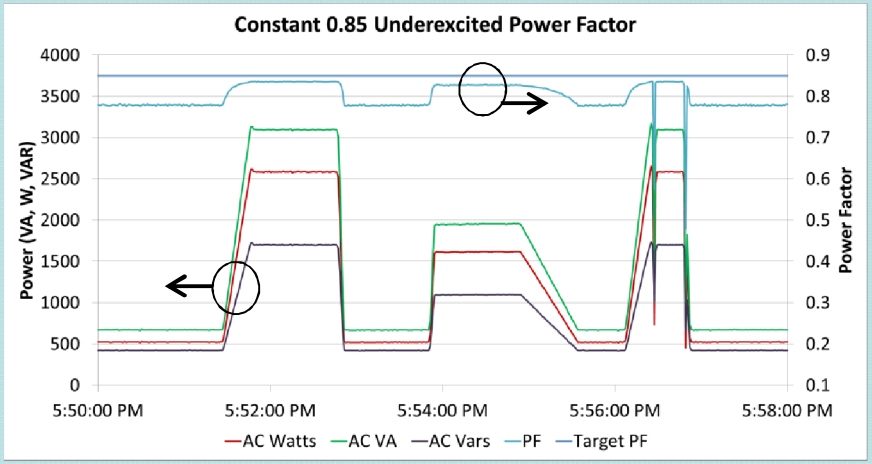
Step 2: Test Inverter by running the PV Simulator using a characteristic irradiance curve.



Step 3: Record electrical behavior of the inverter.

0.85 Underexcited Power Factor

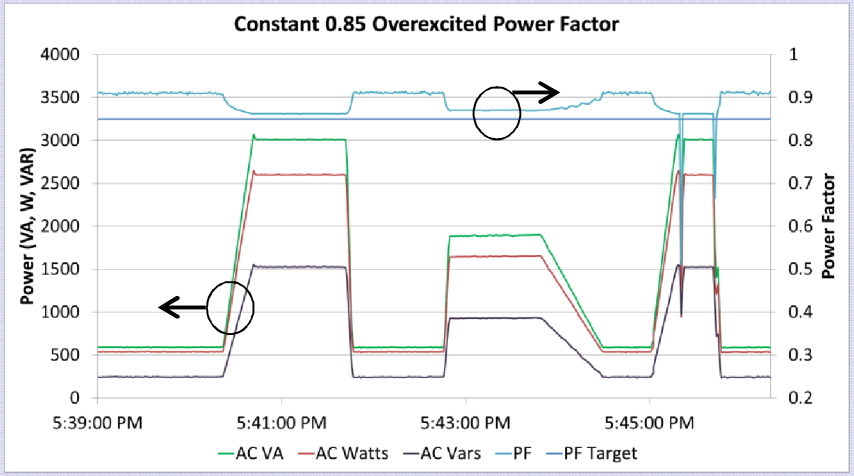
- Undershoots the target power factor.
- Inverter loses the MPPT when the PV simulator provides more power than the inverter rating: 3300 W_{dc} at the 1100 W/m^2 level.



Step 3: Record electrical behavior of the inverter.

0.85 Overexcited Power Factor

- Overshoots the target power factor.
- Same trouble with MPPT at 3300 W_{dc}.

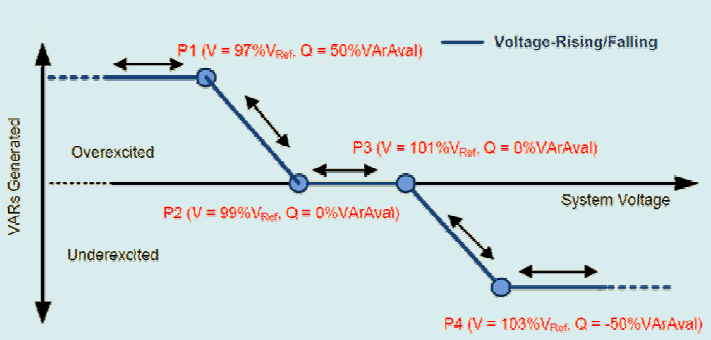


Example Results: Volt/Var (VV11)

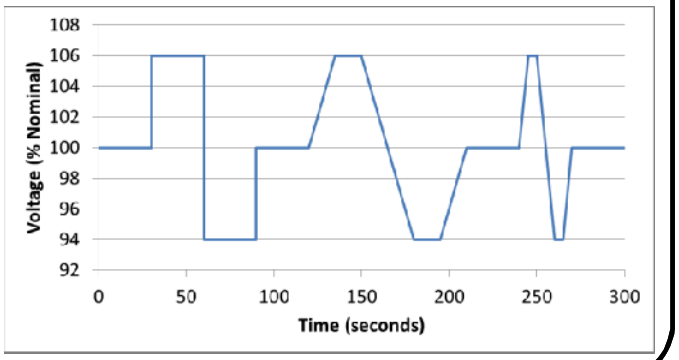
Sandia National Laboratories

Step 1: Update inverter functionality according based on the Test Matrix.

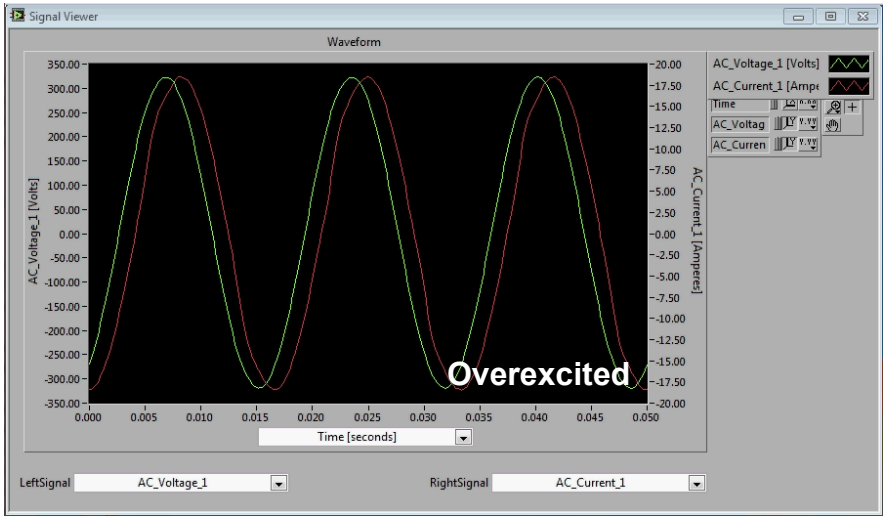
Volt/Var Initiation	Volt/Var [V,Q] Array				Requested Ramp Time (% VArAval/s)	Time Window for Randomization (seconds)	Timeout Period to Reach 95% of Target (seconds)
Binary, 1	V1	97	Q1	50	-		
	V2	99	Q2	0			
	V3	101	Q3	0			
	V4	103	Q4	-50			
Binary, 1	V1	97	Q1	50	25		
	V2	99	Q2	0			
	V3	101	Q3	0			
	V4	103	Q4	-50			
Binary, 1	V1	97	Q1	50	50		
	V2	99	Q2	0			
	V3	101	Q3	0			
	V4	103	Q4	-50			
Binary, 1	V1	97	Q1	50	-		
	V2	99	Q2	0			
	V3	101	Q3	0			
	V4	103	Q4	-50			

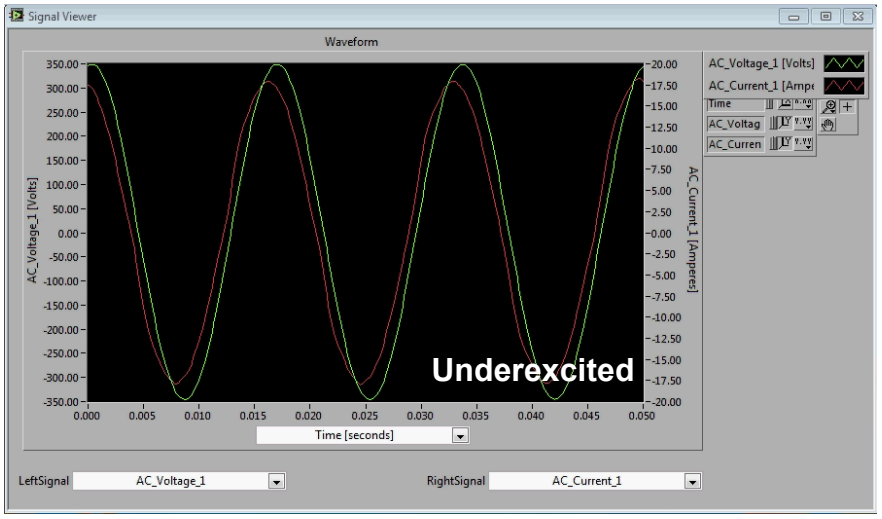


Step 2: Test Inverter by running the grid simulator using a characteristic voltage curve.



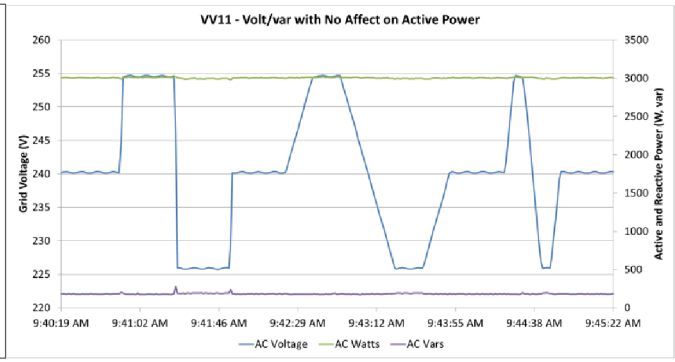
Step 3: Record electrical behavior





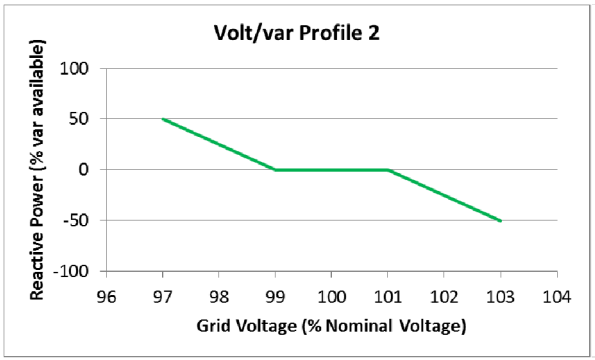
VV11 – Electrical Characterization Results

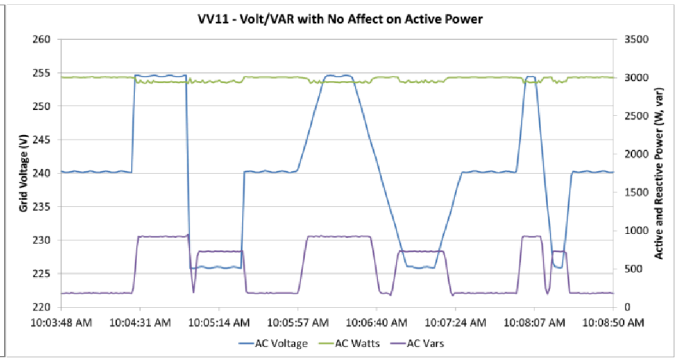
Constant PF = 1.00



Baseline Test Case

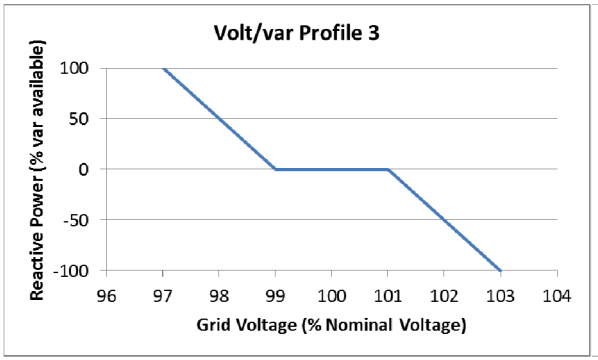
- No change in vars to compensate for grid voltage changes.

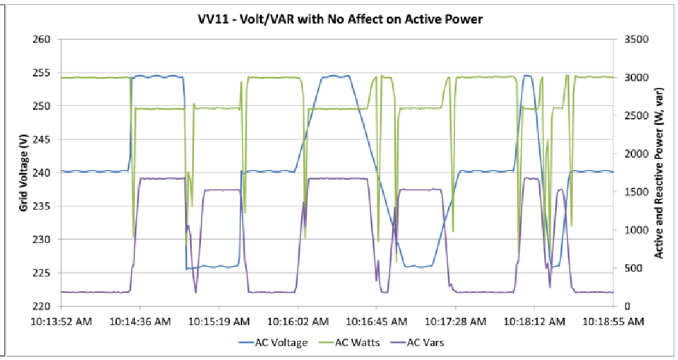




±50% VarAval

- Smooth transitions between over/underexctied regions in the volt/var curve.





±100% VarAval

- Larger reactive power injection/absorption
- Inverter turns off (reduces output current to 0) frequently.
- Outcome: Sandia recommends testing at the inverter limits to find these issues.

Example Collaborations: A Flurry of Activity

- Smart Grid International Research Facility Network (SIRFN)
  - Sandia collaborating with AIT, RSE, DERLab members, and other SIRFN laboratories to compare (and ultimately finalize) the test protocols using different translators, PV and grid simulation hardware, grid voltages and frequencies.
  - International partners help refine Sandia Test Protocol by providing feedback about the test procedures.
  - Laboratories using 3.0 kW inverters for the comparison.
- Sandia-KERI (Korea Electrotechnology Research Institute)
- NREL
  - Sandia visited NREL in May 2013 to begin advanced inverter function testing with a 500 kW inverter.
- California Public Utilities Commission (CPUC)
  - California adding 20 GW of new renewable capacity by 2020 (8 GW utility scale, 12 GW distributed)
  - California considering requiring advanced functions for all CA inverters, starting in 2014.
  - Providing some guidance on which functions to list as *Mandated*, *Recommended*, and *Optional* DER functions for California's interconnect requirements document.
- NIST Smart Grid Interoperability Panel (SGIP)
  - Providing updates on the implementation of test protocols for advanced inverter functions—ensuring good coverage of smart grid interoperability standardization.

Future Work

- Develop communications tools to translate between the utilities and inverters.
  - In the US, this will be DNP3 to Modbus, SEP 2.0, or OpenADR
- Exercise the Sandia Test Protocols to improve the test procedures, test matrices, PV and grid profiles, recording requirements, etc.
- Compare results from different laboratories to verify the test protocols produce the same/similar results regardless of the test equipment, grid frequency/voltage, etc.
- Revise the test protocols and seek adoption of the test procedures by IEC and Underwriters Laboratories (UL).

Thank you. 감사합니다.

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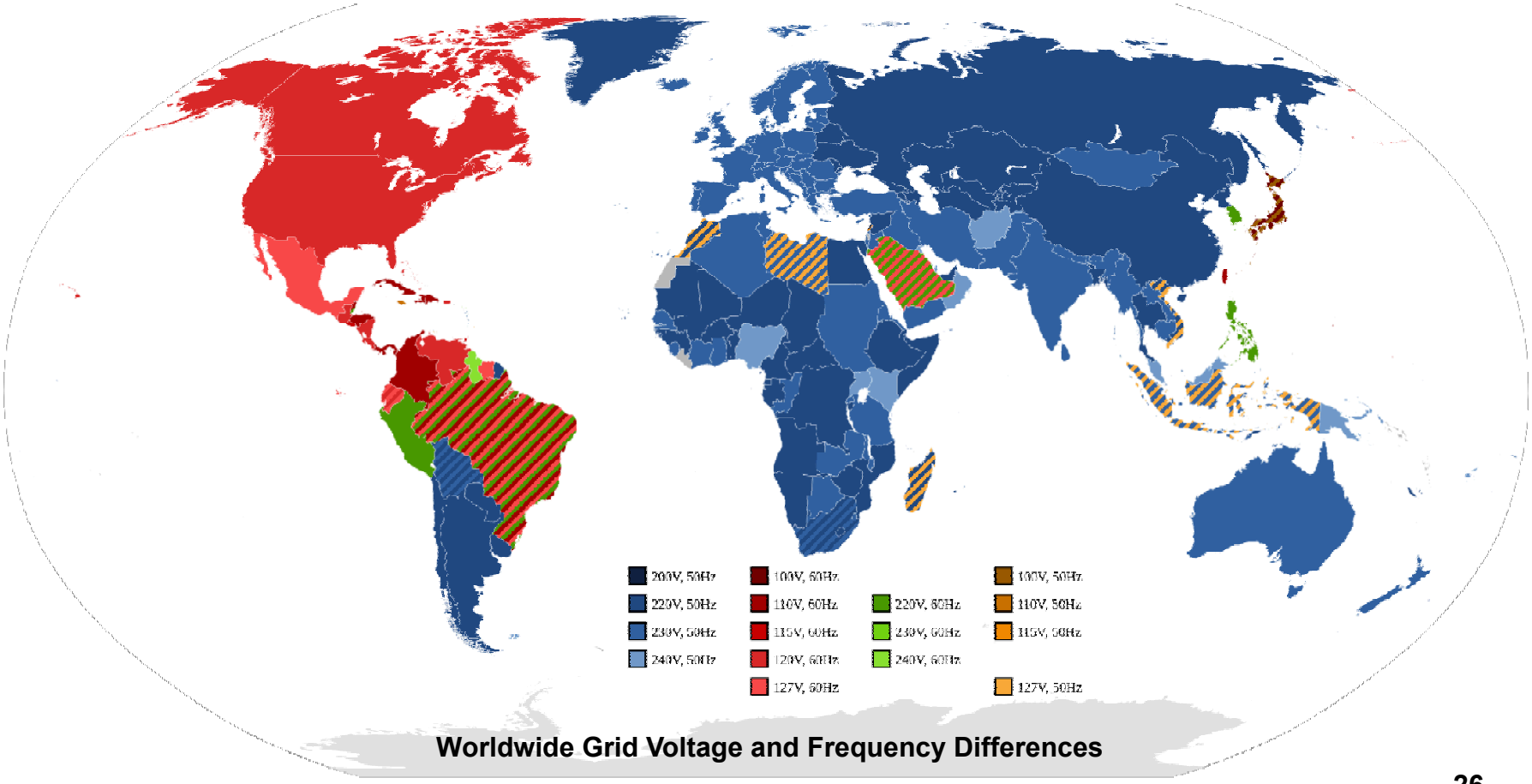
Value of International Collaboration

- Creating inverter test protocols for the international community requires careful selection of test parameters and international verification testing.



Worldwide Grid Voltage and Frequency Differences