End-to-end Architecture for DER Situational Awareness and Coordinated Control

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Challenges of high DER penetration

Challenges and project goals

- Overvoltage, thermal violations, shortcomings of conventional mitigation
- Large reverse power flows and potential protection miscoordination
- Potential for adverse control interaction among inverters, legacy devices
- Lack of situational awareness especially behind-the-meter DERs, and T&D interactions
- Project goal is to enable extreme levels of DER in distribution systems, while enhancing its reliability, resiliency, cyber security and power quality
- By a data-driven approach with **total situational awareness** afforded by a network of sensors, edge intelligent devices (EIDs), cloud-based analytical platform, and secure communications.

Solar situational awareness and control

Advanced DER inverter

- Programmable control parameters, modes and settings
- Robust control exploiting real-time information from EIDs

Edge intelligent device (EID)

- Two-way interface between DERs & cloud
- Move data and processing closer to DER, optimize latency and autonomy

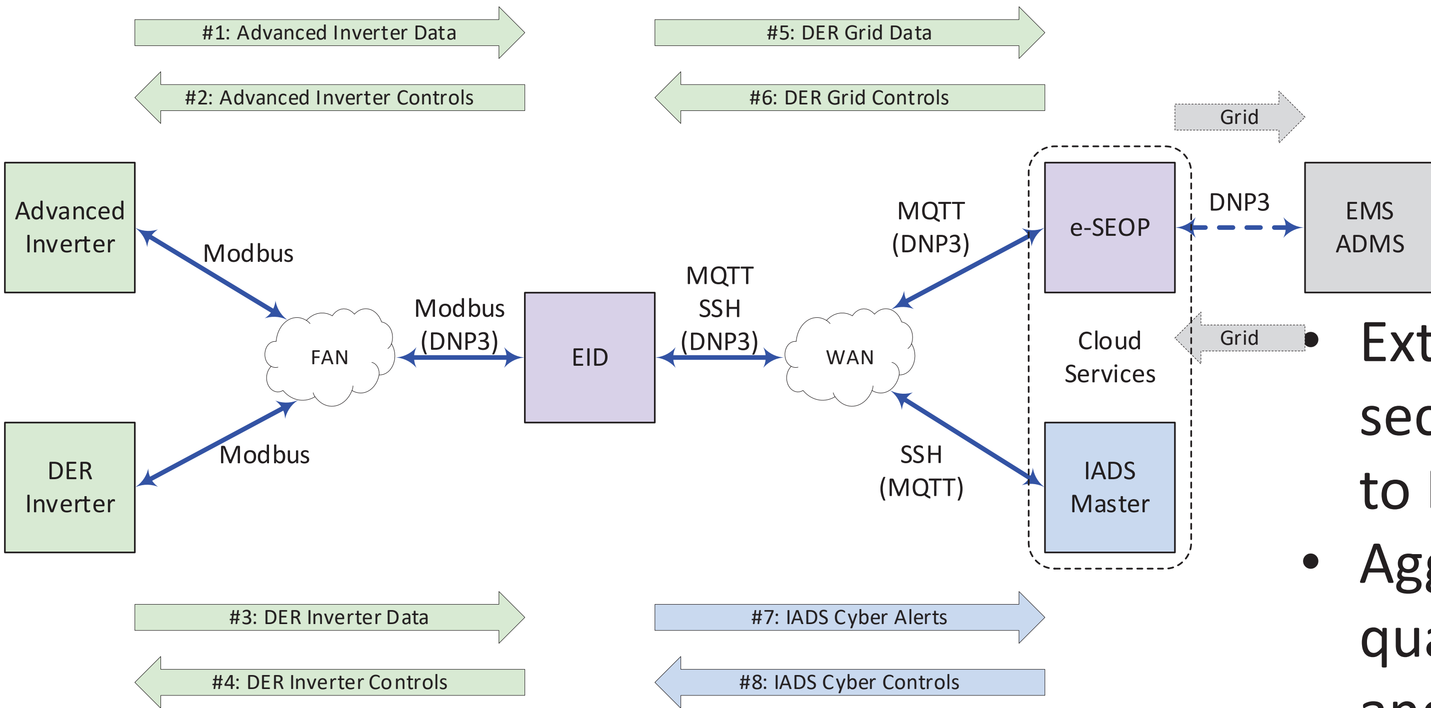
eSEOP cloud platform

- Integration point of DER providing holistic view to grid operators
- Provides near real time visibility into DER, loads, and utility equipment
- Commands large numbers of DERs for feeder voltage, fault management

Cybersecurity

- Continuous monitoring, real-time anomaly detection

End-to-end architecture



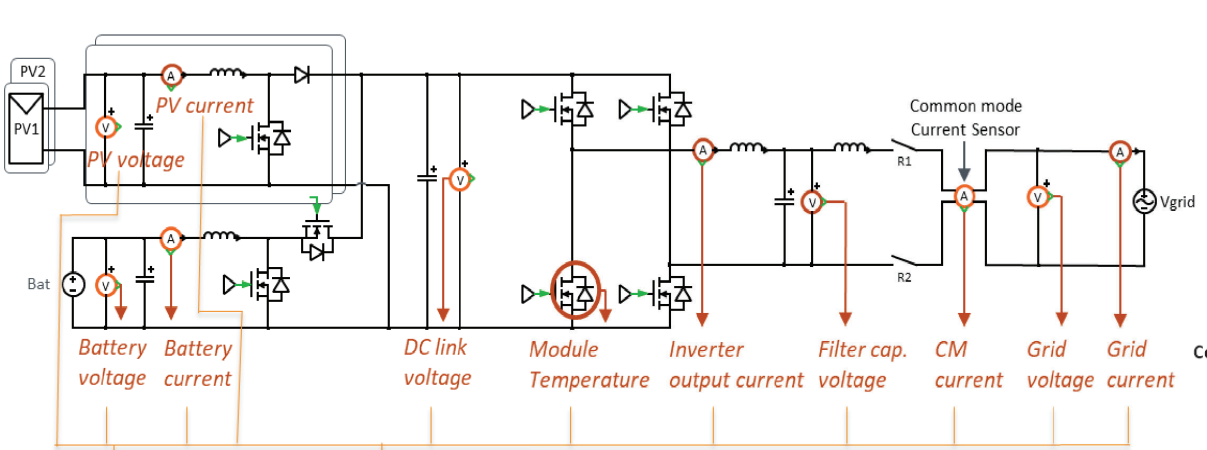
Some analytical modules in eSEOP cloud

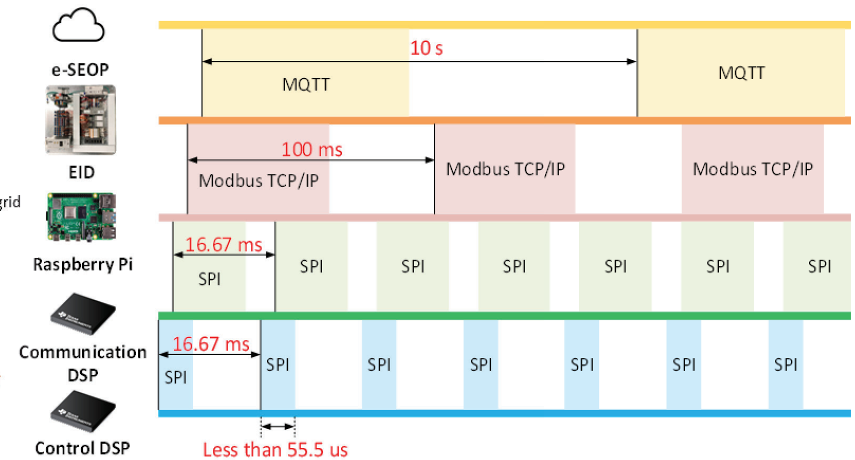
Integrated T&D analysis	Dynamic hosting capacity	Integrated feeder voltage management	Integrated fault management

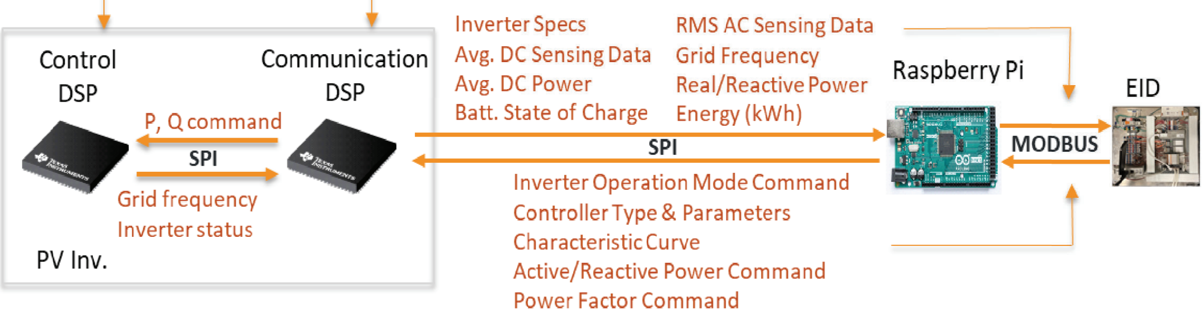
eSEOP: end-to-end solar energy optimization platform

- Extend the reach of secure utility systems to BTM DERs
- Aggregated, high-quality data to utility and all stakeholders
- Implement OT cyber-physical security

DER inverter and communication



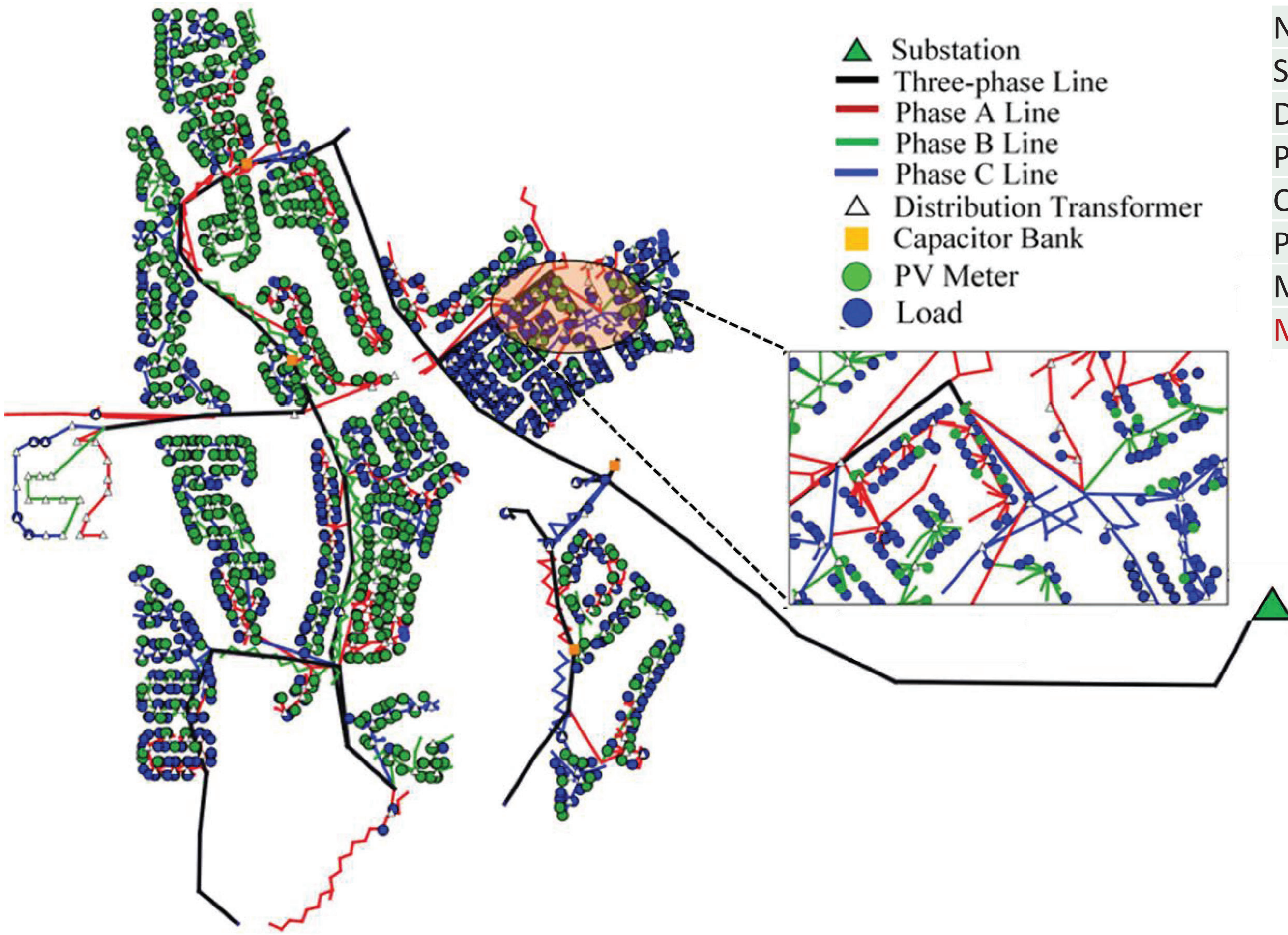




- One data exchange in DSPs in a switching cycle (55.5 us)
- Data resolution of 1 set of data per 60 Hz cycle
- Update rate: 1 cycle for low layers and 6 cycles (100 ms) for EID

Y. Si, N. Korada, R. Ayyanar and Q. Lei, "A High Performance Communication Architecture for a Smart Micro-Grid Testbed Using Customized Edge Intelligent Devices with SPI and Modbus TCP/IP Communication Protocols," in *IEEE Open Journal of Power Electronics*, vol. 2, pp. 2-17, 2021

Modeled high PV distribution feeder

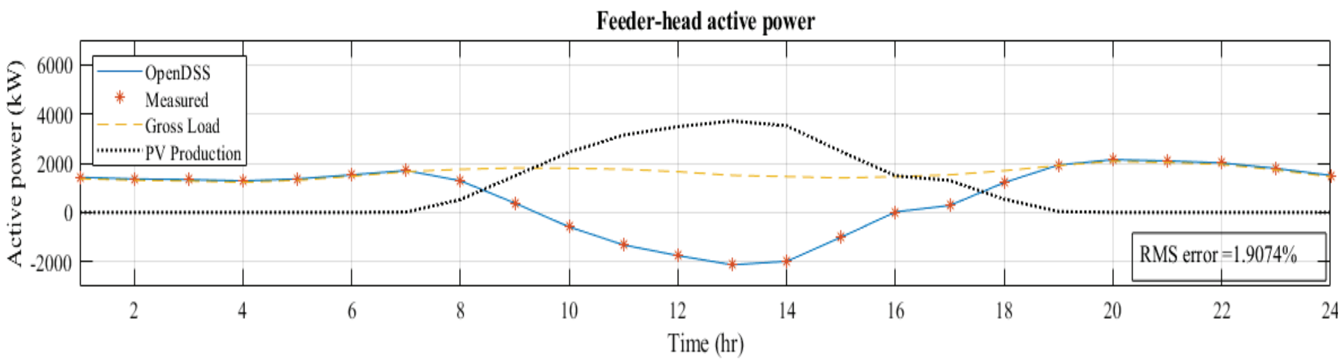


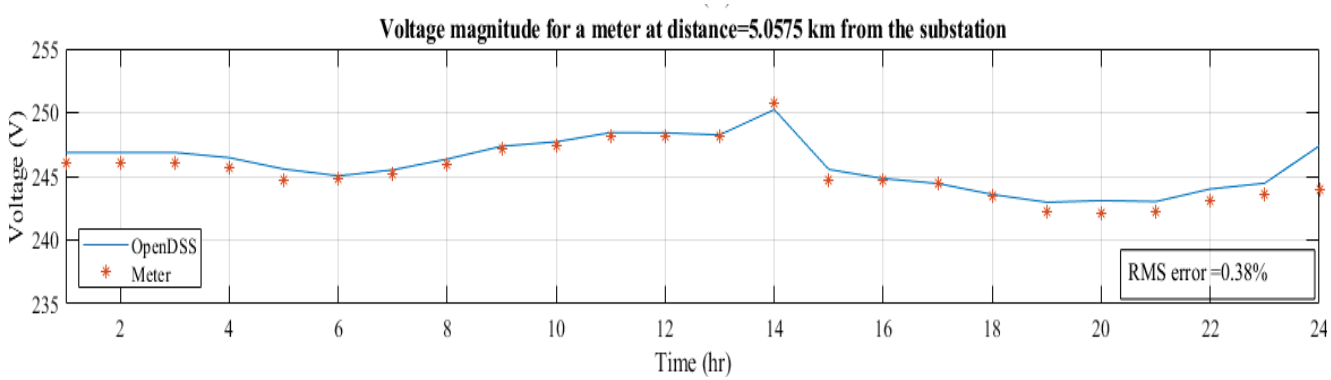
Nodes	7862
Sections (primary +secondary)	1790 + 5700
Distribution transformers	371
PV systems	767
Capacitor banks	4 x 1.2 MVAr
Peak load	7.35 MW
Max. PV generation	3.8 MW
Max. instant. PV penetration	**236.84%**

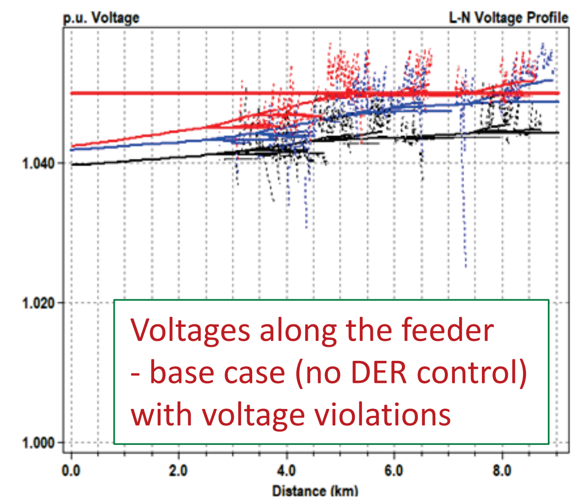
- Detailed model including the secondary network
- Extensive data collection from AMI meters, PV meters and SCADA
- Significant reverse power flows and overvoltages

Model validation at high penetration

Measured vs. time series OpenDSS results for March 15th case



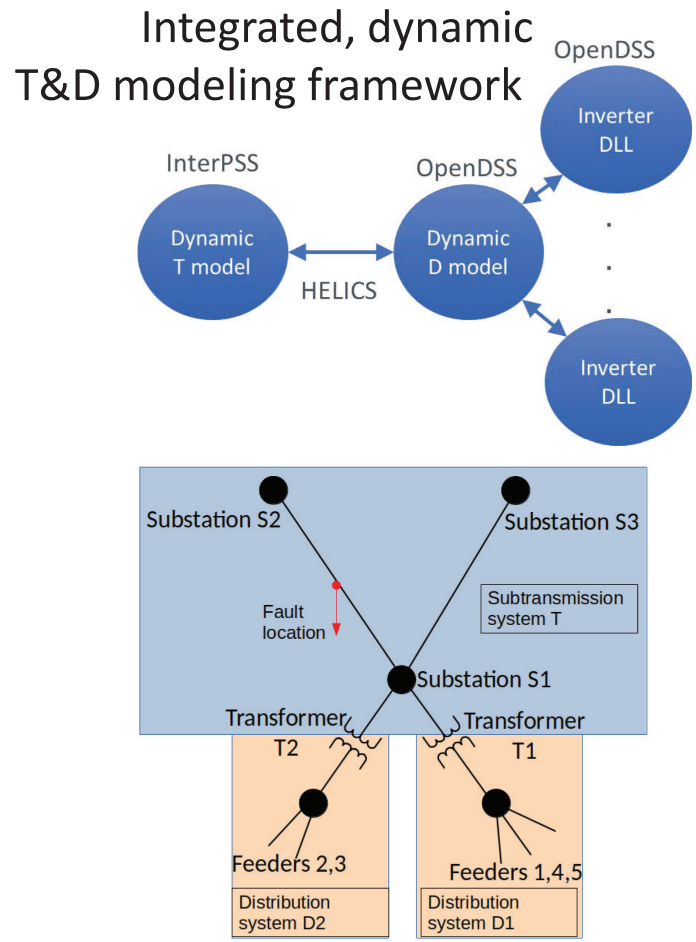




K. Montano-Martinez et al., "Detailed Primary and Secondary Distribution System Model Enhancement Using AMI Data," in IEEE Open Access Journal of Power and Energy, vol. 9, pp. 2-15, 2022, doi: 10.1109/OAJPE.2021.3125900.

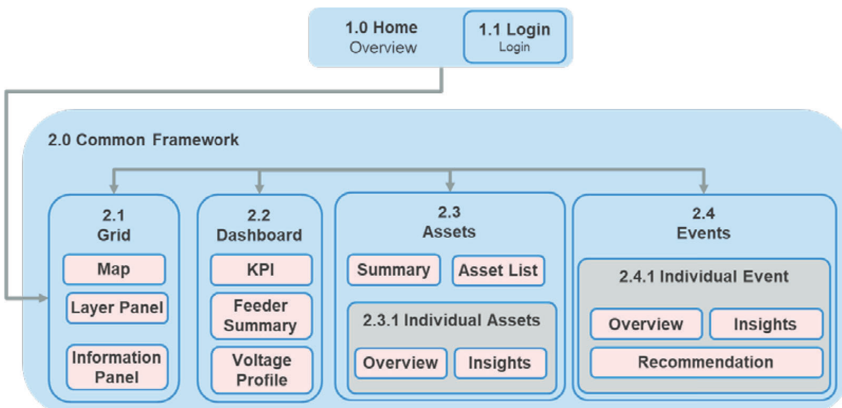
Integrated T&D dynamic co-simulation

- Critical to understand the mutual impact, protection, and hosting capacity
- Transmission system:
  - Three-sequence model of network in InterPSS
  - Dynamics of generators and any controls
- Distribution system
  - Unbalanced, three-phase model in OpenDSS
  - DER inverter dynamic, advanced control modeled in user defined DLL
- HELICS for data coordination, conversion between 3-sequence and 3-phase

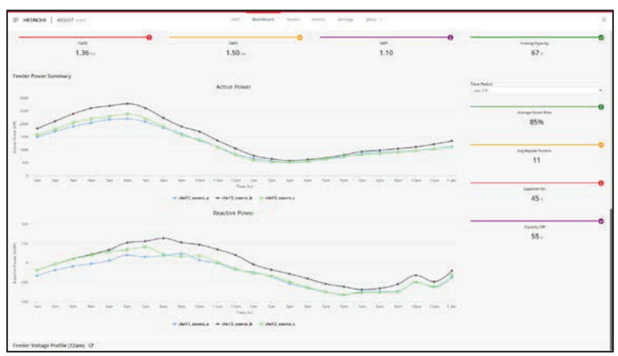


End-to-end Solar Energy Optimization Platform (eSEOP)

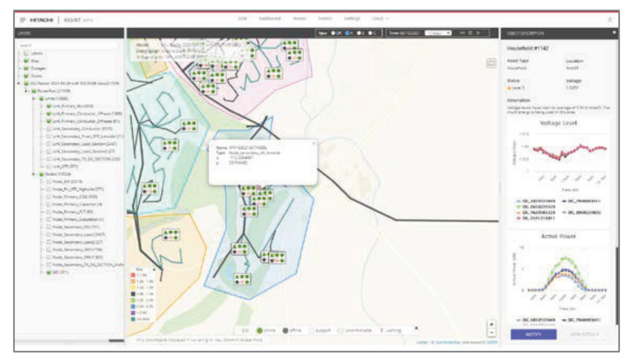
Information Architecture



Feeder with voltage levels



Time-series active and reactive power at feederhead



EID, inverters status, and time-series voltage and PV power

Use case: Voltage management with dynamic VQSM and system-wide data

Constraint 1
$\forall\, V_{node}[i] < 1.05$

Constraint 2
$V_{node}[i] = -VQSM[i][j] \times \Delta Q[j] + V0_{node}[i]$

Constraint 3
$Q[j] \leq 0.66 \times S_{rating}[j]$

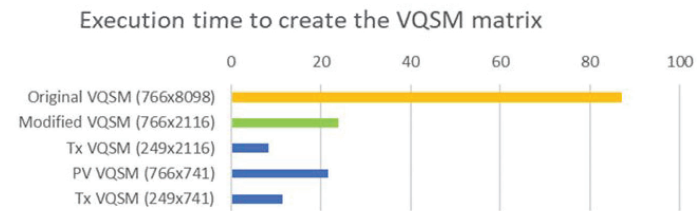
→ *Objective Function*
$minimize \sum Q[j]$

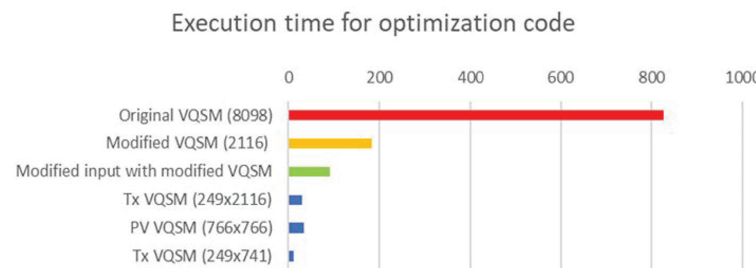
→ $Q[i]$

$V_{node}[i]$ – *node voltage*
$Q[j]$ – *inverter reqctive power*
$VQSM[i][j]$ – *VQSM matrix*
$S_{rating}[j]$ – *Inverter rating*
$V0_{node}[i]$ – *intial node voltage*

VQSM – Voltage-reactive power sensitivity matrix

- VQSM matrix developed for each operating condition in real-time
- Considering only the critical nodes (loads, PVs, transformer nodes) in VQSM calculation, optimization time is made suitable for real-time implementation (10.7 seconds)



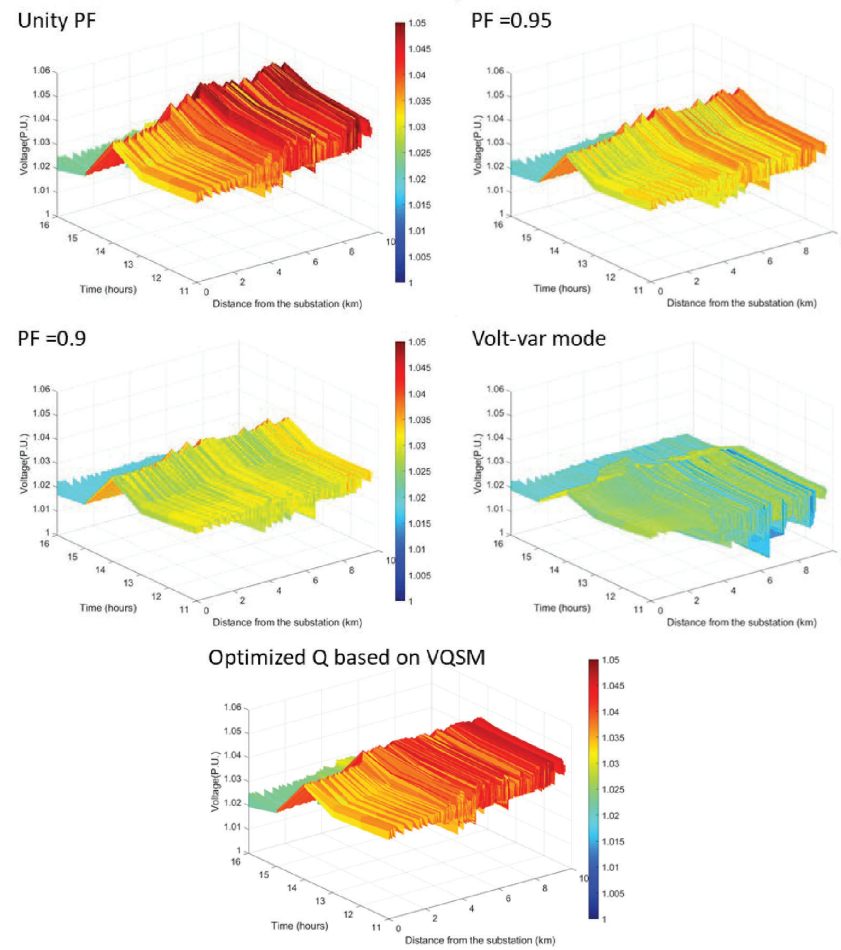


Time consumption for the optimization

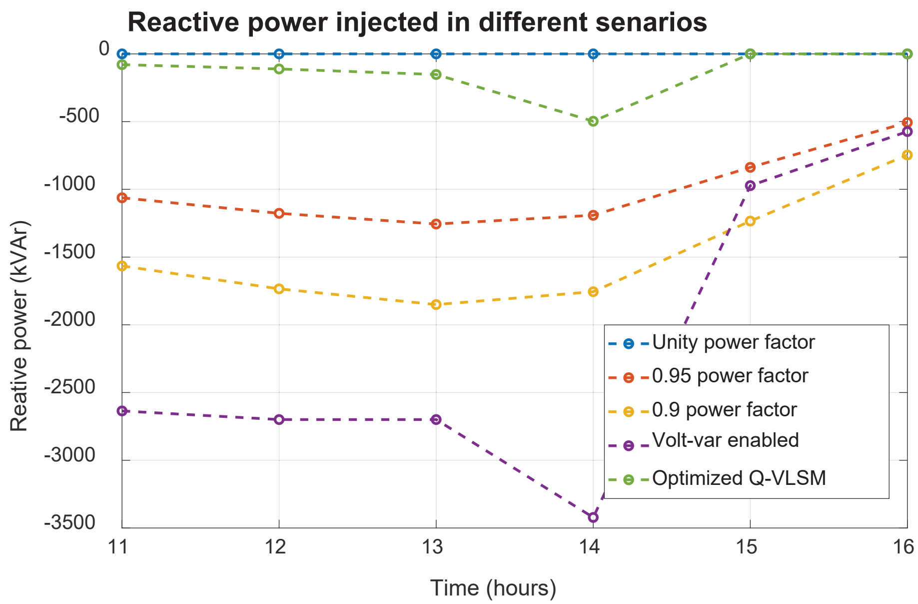
0m 00s	0m 11.4s	0m 16.2s	0m 17.8s	0m 21.1s
CREATE VQSM	DEFINITIONS	READ CONSTRAINTS	SOLVING OPTIMIZATION	
	0m 00s	0m 4.8s	0m 6.4s	0m 10.7s

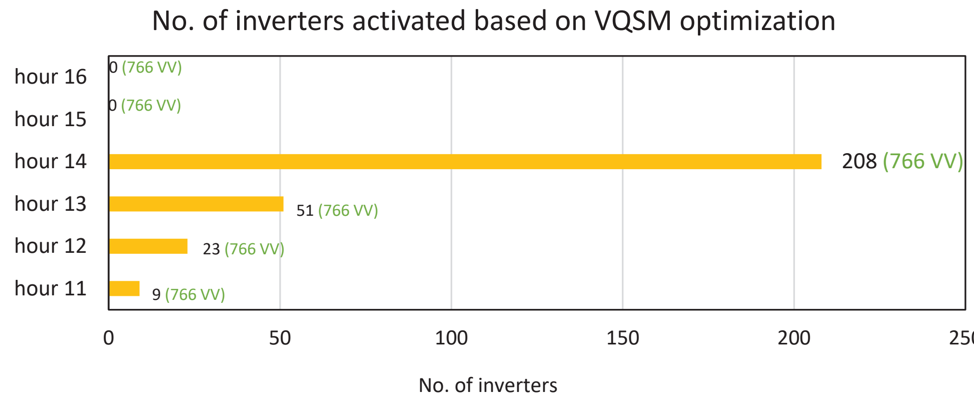
Comparison of voltage control methods

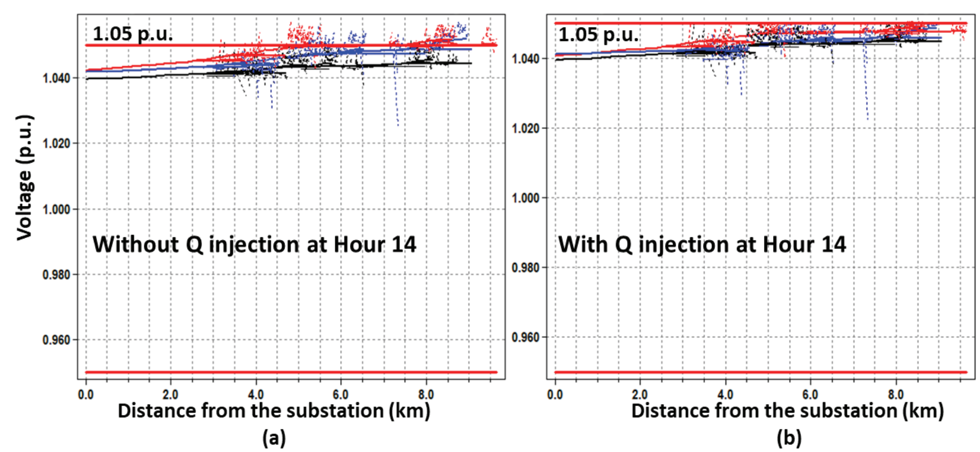
- 29.7% of nodes exceed the 1.05 p.u. overvoltage limit at Hour 14 in March 15 data set due to 3.6 MW PV and 2.03 MW reverse power flow
- Voltage profiles for 8098 nodes in the network from Hour 11 to 16 for March 15 are plotted for various inverter mode operations
  - Unity power factor
  - Power factor at 0.95 (injecting Q)
  - Power factor at 0.9 (injecting Q)
  - Volt-var mode operation
  - Optimized Q based on VQSM



Comparison of voltage control methods

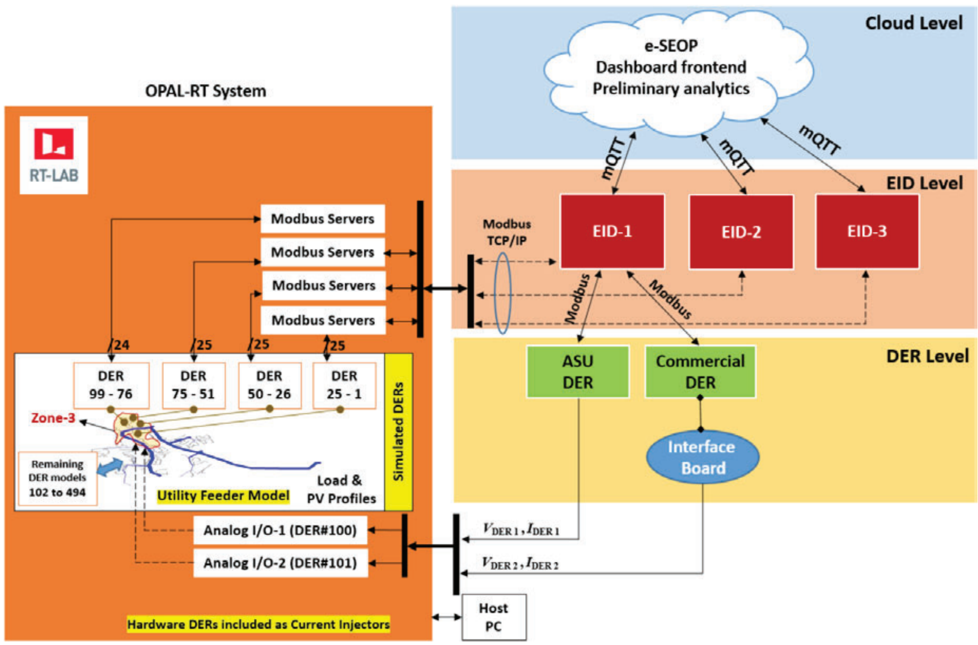




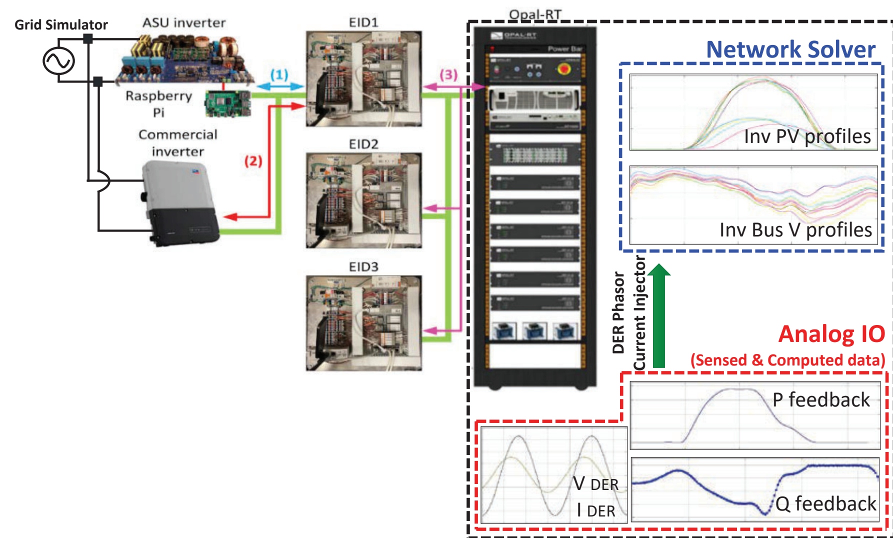


- VQSM based Q injection using system-wide measurements results in minimum number of inverter control and minimum Q support to mitigate all violations

HIL testbed with end-end communication



Modbus communication and HIL testing



- Bidirectional Modbus communication among DER hardwares and simulated model
- MQTT for EID-cloud communication
- Hardware DERs emulate PV injection based on P profile and Q commands from EID
- Dynamic response of hardware DERs included as phasor current inputs in network model
- Demonstrated elimination of overvoltages by control from a subset of DER inverters

Thank You

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