Holonic Multi-Agent Control of Intelligent Power Distribution Systems

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Project Team

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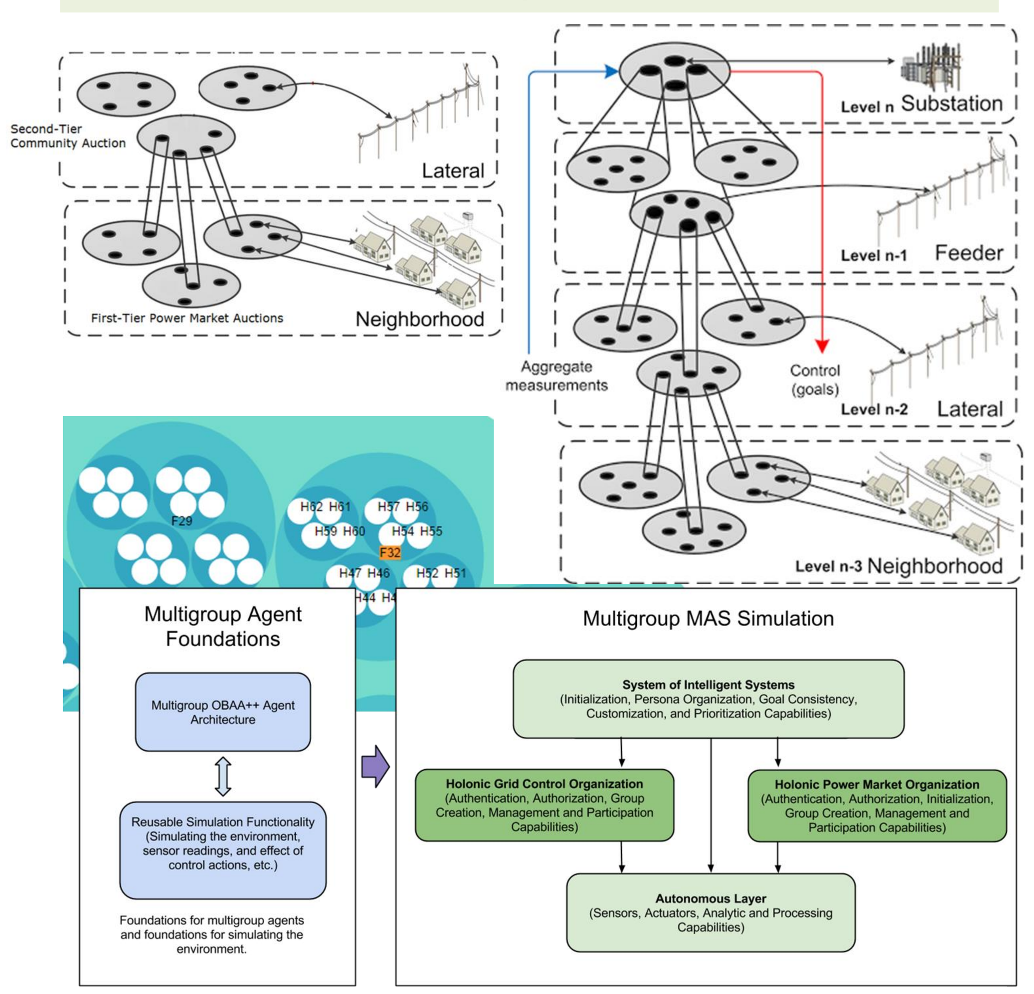
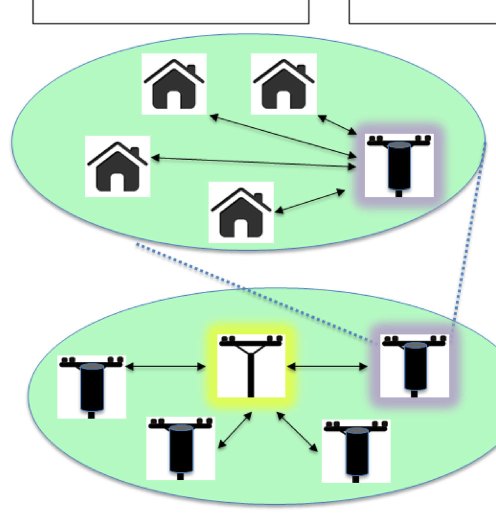
Abstract: The project demonstrates a holonic multi-agent system (HMAS) architecture capable of adaptively controlling future electrical power distribution systems, which are expected to include a large number of renewable power generators, energy storage devices, and advanced metering and control devices. The project provides a general, extensible, and secure cyber architecture based on holonic multi-agent principles to support adaptive PDS. It will produce new analytical insights to quantify the impact of information delay, quality and flow on the design and analysis of the PDS architecture. The architecture will be capable of optimizing performance and maintaining the system within operating limits during normal and minor events, such as cloud cover that reduces solar panels output. The architecture will also allow the operation of a distribution system as an island in emergencies, such as hurricanes/earthquakes, grid failures, or terrorist acts.

HMAS to Physical System

Goal: An agent architecture that can support HMAS for cyber-physical systems; simulation of multigroup organizations of distributed CPS agents in Intelligent Power Distribution Systems.





Tier 1 N48. 4 homes bid for future power:

1. H49: BUY 4.6 @$0.1707
2. H50: BUY 6.3 @ $0.2320
3. H51: BUY 2.7 @ $0.1000
4. H52: SELL 7.4 @ $0.1676

T1 Result: clearing price = $0.1684
10.9 desired at a good price; only 7.4 to sell.
→ Looking to BUY 3.5 MORE @ $0.1684

Tier 2 N48 bids with 4 other neighborhoods

1. N43: BUY 2.1 @$0.1139
2. N48: BUY 3.5 @ $0.1684 (Wins)
3. N53: SELL 10.3 @ $0.1462 (Wins)
4. N58: SELL 1.5 @ $0.1768

T2 Result: clearing price = $0.1573
→ N48 gets to BUY 3.5 MORE @ $0.1573

Intelligent power distribution agents were enhanced to achieve the goals of multiple independent organizations; agents collaborated in two concurrent holarchies: one for power quality control and one for autonomous online power auctions.

Voltage Control

Motivation: Distribution losses average about 7% in the U.S. (262.72 Billion kWh); 4% in distribution system

Challenge: Scalability

Goal: Inverter PV Var scheduling;
Three-level hierarchical optimization;
Centralized methods: Precise solution;
Decentralized methods: Fast solution;
Reducing computational complexity.

Substation level:

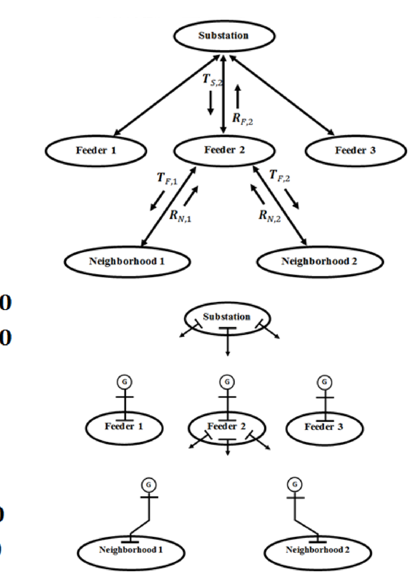
$$\min_{\mathbf{X}_S} P_S^y(\tilde{\mathbf{X}}_S^y) + \varepsilon_{SF} \qquad g_S(\tilde{\mathbf{X}}_S^y) = 0$$
$$\sum_{m\in\mathbb{H}_S} \|\mathbf{T}_{S,m}^y - \mathbf{R}_{F,m}^y\|_2^2 \le \varepsilon_{SF} \qquad h_S(\tilde{\mathbf{X}}_S^y) \le 0$$

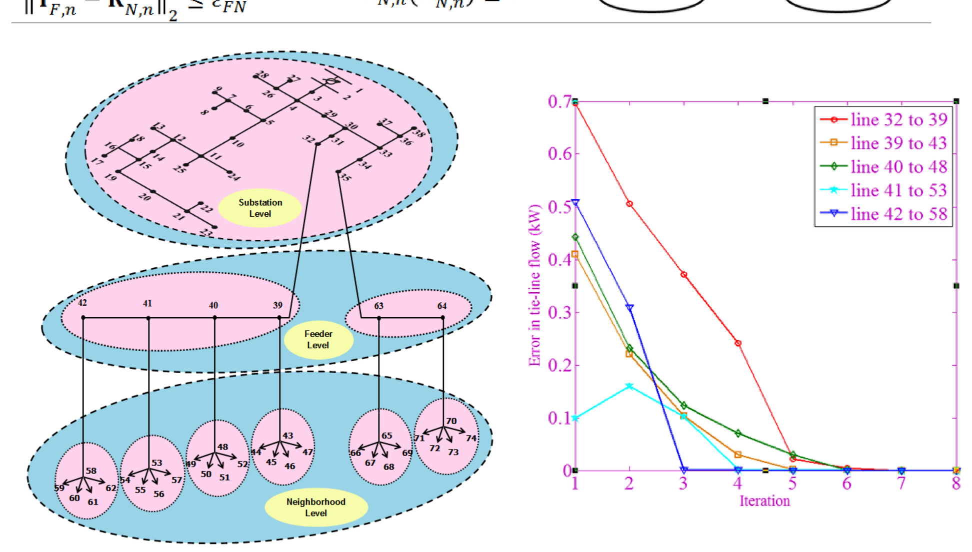
Feeder level:

$$\min_{\mathbf{X}_{F,m}} P_{F,m}^y(\tilde{\mathbf{X}}_{F,m}^y) + \varepsilon_{SF} + \varepsilon_{FN}$$
$$\|\mathbf{T}_{S,m}^y - \mathbf{R}_{F,m}^y\|_2^2 \le \varepsilon_{SF} \qquad g_{F,m}(\tilde{\mathbf{X}}_{F,m}^y) = 0$$
$$\sum_{n\in\mathbb{H}_{Fm}} \|\mathbf{T}_{F,n}^y - \mathbf{R}_{N,n}^y\|_2^2 \le \varepsilon_{FN} \qquad h_{F,m}(\tilde{\mathbf{X}}_{F,m}^y) \le 0$$

Neighborhood level:

$$\min_{\mathbf{X}_{N,n}} P_{N,n}^y(\tilde{\mathbf{X}}_{N,n}^y) + \varepsilon_{FN} \qquad g_{N,n}(\tilde{\mathbf{X}}_{N,n}^y) = 0$$
$$\|\mathbf{T}_{F,n}^y - \mathbf{R}_{N,n}^y\|_2^2 \le \varepsilon_{FN} \qquad h_{N,n}(\tilde{\mathbf{X}}_{N,n}^y) \le 0$$





	Local control			Holonic		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
P_{loss} (kW)	8.6213	4.156	6.597	6.597	3.469	4.709
Q_{loss} (kVar)	3.446	1.299	2.570	2.570	1.174	1.564
$\sum Q_g$ (kVar)	65.852	238.400	156.600	156.600	204.710	214.780
P_s (kW)	387.150	361.700	384.600	384.600	360.360	382.210
Q_s (kVar)	368.070	197.800	278.200	278.200	232.960	263.070

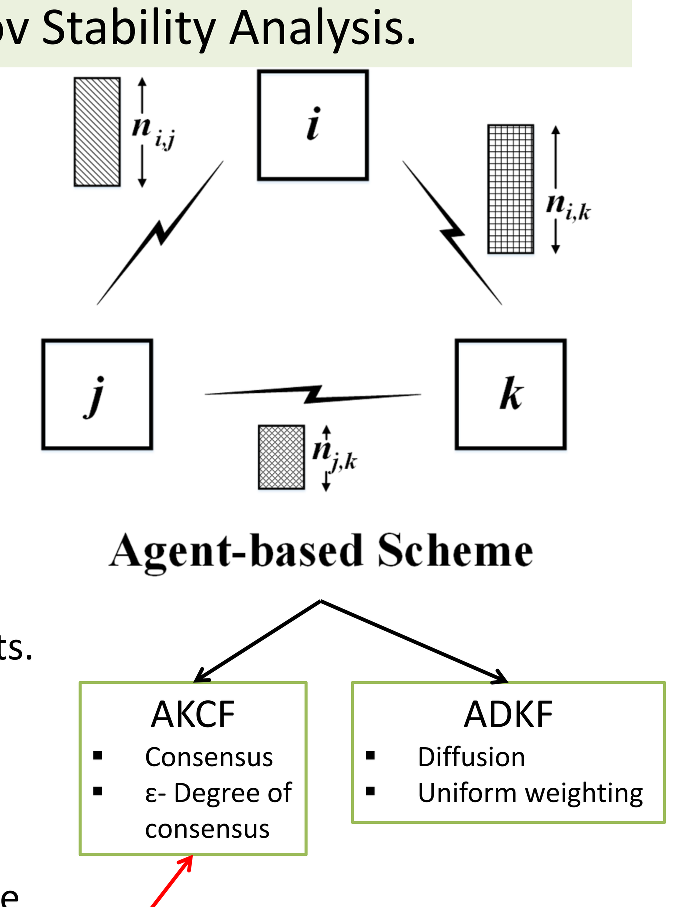
Results match for small-scale system; execution time: 93 seconds for distributed approach and 225 seconds for centralized approach; centralized approach is not applicable for large-scale system.

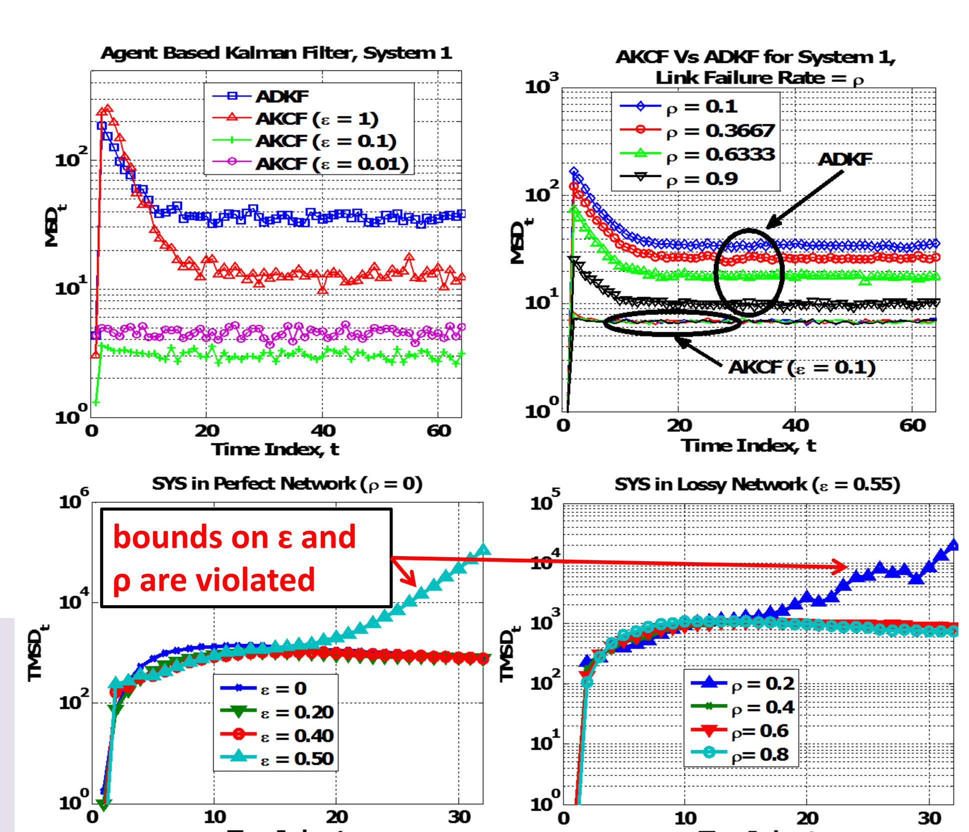
State Estimation

Goal: Formulate Agent-based Kalman Filter for a Dynamical System; Investigate Estimator performance under Lossy Communication Network; Explore the Bounds of Filter Parameters from Lyapunov Stability Analysis.

Approach: Network of Cooperative Agents.

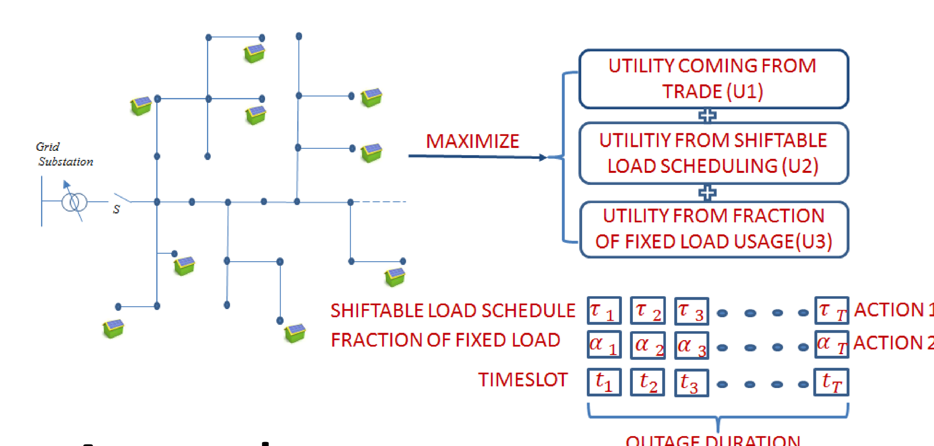
Agent observes "part" of the dynamics. "Physical" Neighbors: Share the State Elements. Neighborhood Information Exchange: Local Estimates of only the "Shared" State Elements.





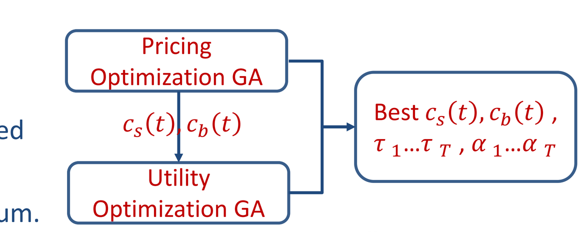
Online Energy Trading

Goal: Develop a general model for energy trading; maximize agent and overall utility; design a setting where selfish agents can autonomously act.



Approach:

- Fixed and Variable over time slots pricing.
- Double Layer Constrained Genetic Algorithm(GA).
- Establish Nash Equilibrium.



Power Balance Constraint $P_i(t) = PV_i(t) - \alpha_i(t)LF_i(t) - \sum_{k=1}^{K} LS_{i,k}\delta(t,\tau_{i,k})$

Maximize $V_i(\alpha_i,\tau_{i,k}) = \underbrace{\sum_{t=1}^{T} TR(P_i(t))}_{U1} + \underbrace{\sum_{t=1}^{T} UF_i(\alpha_i(t)LF_i(t))}_{U2} + \underbrace{\sum_{k=1}^{K} US_i(LS_{i,k},\tau_{i,k})}_{U3}$

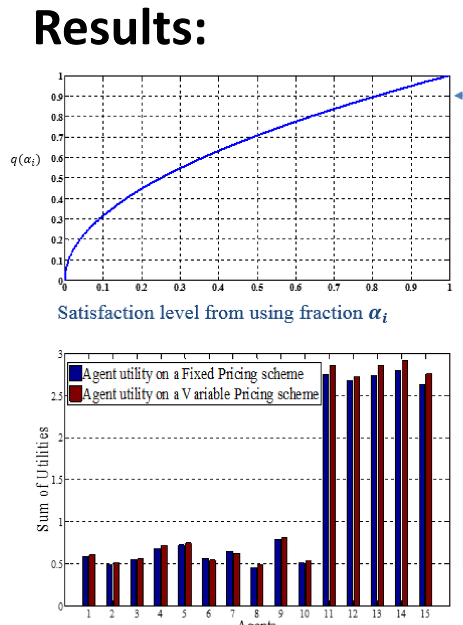
$TR(P_i(t)) = \begin{cases} c_s(t)|P_i(t)|, & P_i(t) \ge 0 \\ -c_b(t)|P_i(t)|, & P_i(t) < 0 \end{cases}$ $UF_i(\alpha_i(t)LF_i(t)) = LF_i(t)*q(\alpha_i)$ $US_i(LS_{i,k},\tau_{i,k}) = d_{i,k}(\tau_{i,k})$

Maximize $\Lambda = \sum_{i=1}^{N}\left(\sum_{t=1}^{T} TR(P_i(t)) + \sum_{t=1}^{T} LF_i(t)*q(\alpha_i) + \sum_{k=1}^{K} d_{i,k}(\tau_{i,k})\right)$

Subject to $\sum_{i=1}^{N}\sum_{t=1}^{T} P_i(t) = 0$ *for Fixed* and $\sum_{i=1}^{N} P_i(t) = 0$ *for Variable Pricing.*

Results:

$UF_i(\alpha_i(t)LF_i(t)) = LF_i(t)*q(\alpha_i)$



Ag.	Scenario I					Scenario II				
	α			τ		α			τ	
	$\alpha(1)$	$\alpha(2)$	$\alpha(3)$	τ_1	τ_2	$\alpha(1)$	$\alpha(2)$	$\alpha(3)$	τ_1	τ_2
1	0.256	0.252	0.241	1	0	0.250	0.250	0.250	1	0
2	0.251	0.248	0.245	0	0	0.250	0.250	0.250	0	0
3	0.248	0.248	0.246	0	1	0.250	0.250	0.250	0	1
4	0.258	0.242	0.263	3	3	0.250	0.250	0.250	3	3
5	0.249	0.244	0.250	1	3	0.250	0.250	0.250	1	3
6	0.255	0.237	0.249	0	2	0.250	0.250	0.250	0	2
7	0.251	0.247	0.248	3	2	0.250	0.250	0.250	3	2
8	0.263	0.235	0.245	0	0	0.250	0.250	0.250	0	0
9	0.265	0.228	0.235	1	3	0.250	0.250	0.250	1	3
10	0.253	0.237	0.245	0	0	0.250	0.250	0.250	0	0
11	0.249	0.248	0.250	1	2	0.250	0.250	0.250	3	2
12	0.249	0.252	0.253	2	2	0.250	0.250	0.250	2	2
13	0.246	0.252	0.244	2	2	0.250	0.250	0.250	0	3
14	0.258	0.240	0.239	3	2	0.250	0.250	0.250	3	2
15	0.251	0.250	0.250	2	3	0.250	0.250	0.250	3	3

Action results at NE for α_i and $\tau_{i,k}$

The sum of customer utilities under Variable Pricing (20.269) is higher than that of under Fixed Pricing (19.578).

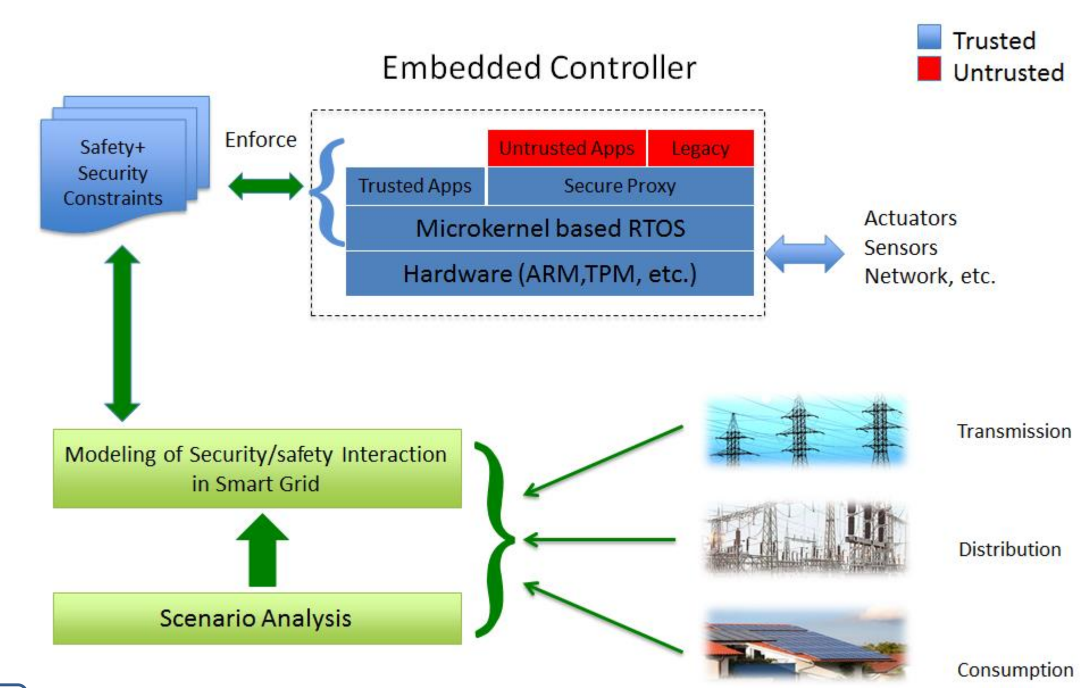
Secure Microkernel

Goal: Enforce security, safety in smart grid

- Understand the diversity of power grid control
- Extracts crucial security and safety constraints
- Using layered approach guarantees secure policies

Design a new secure embedded platform

- Implements secure policies from bottom-up
- Real-time and functional correctness



Model of Distribution Grid: