Toward Distributed Intelligent: A Case Study of Peer to Peer Communication in Smart Grid

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Outline

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Smart grid's distributed nature

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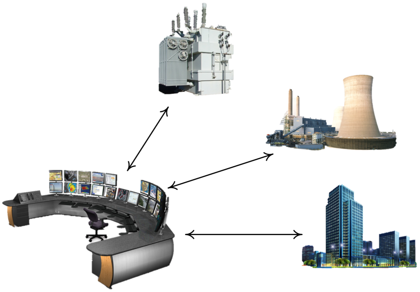

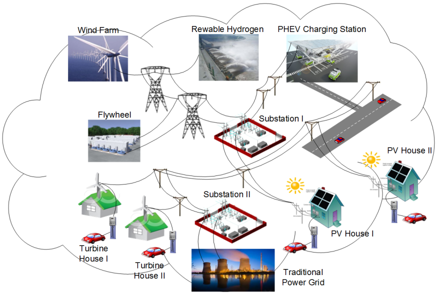

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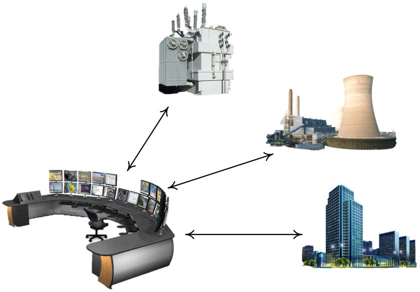
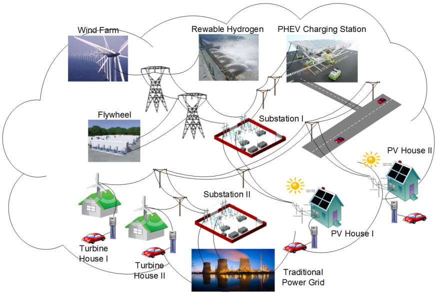
- Smart grid's distributed nature necessitates a *distributed control system*.





The dilemma

Distributed controllers' limited computational capability

- x00 MHz CPU frequency.
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Smart grid's strict message delay requirement [1]

- Protection message need to be delivered in 3ms.
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[1] IEC 61850 standard

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[1] IEC 61850 standard

Question

Whether the delay performance of distributed peer to peer network can support time-critical smart grid applications?

Approach

Related work

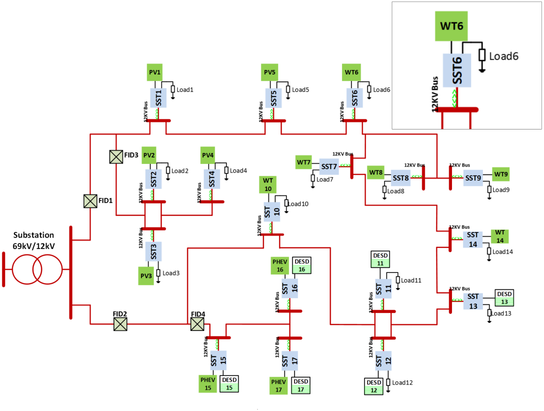
- A. Monti, *et al*, 2010. Identified problems and challenges in distributed smart grid control.
- L. Xie, *et al*, 2012. Proposed distributed state estimation for smart grid.
- X. Lu, *et al*, 2011. Measured message delivery performance in a centralized control power grid.

Our approach

In order to get practical data, we implement a *physical testbed*, the Green Hub, to measure device to device realtime delay performance of distributed control in smart grid.

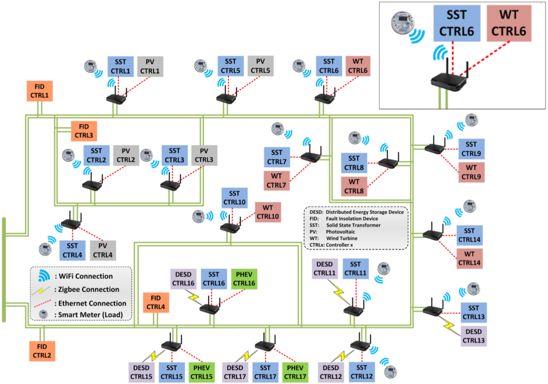
Outline

Green Hub physical architecture



- Distribution level microgrid abstracted from practical.
- 17-bus, each bus connects to a Solid State Transformer (SST), and renewable energy sources.

Green Hub distributed control architecture



- Each device is equipped with Intelligent Electronic Devices (ARM based micro-controllers).
- IEDs communicate with each other in distributed manner without a central controller.

Outline

Background

Communication protocol

- Distributed Network Protocol 3.0 (DNP3) is the most widely used communication protocol in power system in North America.
- It was used over serial links, not designed for layered network.
- DNP3 over TCP/UDP was proposed for cost-efficiency and backward-compatible.

Fault protection event

1. An IED senses an fault happened at an nearby location.
2. The fault message is sent to circuit breaker controller.
3. The circuit breaker will be opened to isolate the fault.

Communication scenario

Centralized control vs. Distributed control

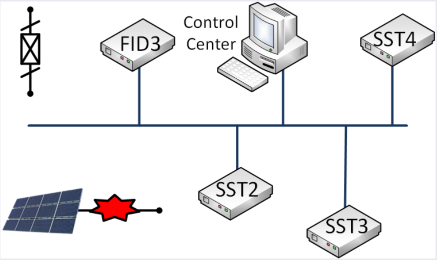


Figure : Centralized control

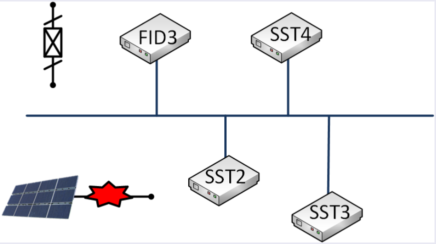
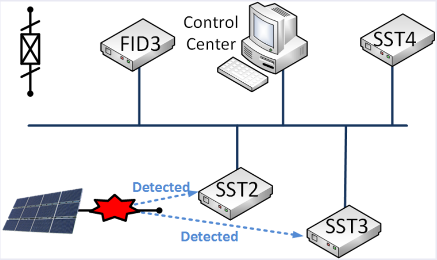


Figure : Distributed control

Step 1: Fault happens.

Communication scenario

Centralized control vs. Distributed control



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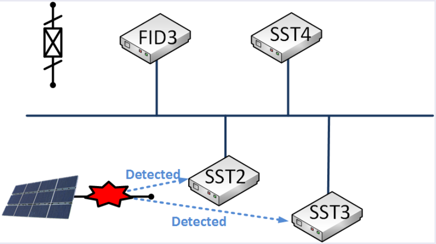
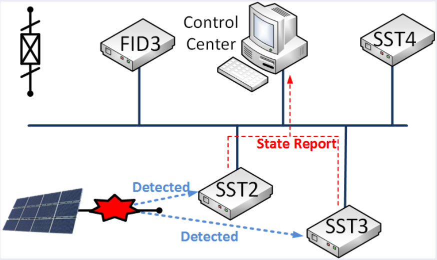


Figure : Distributed control

Step 2: Fault detected.

Communication scenario

Centralized control vs. Distributed control



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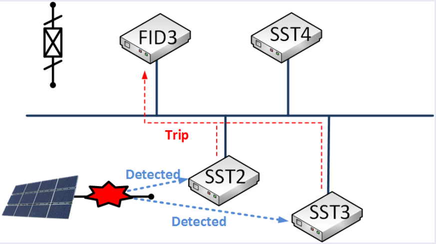


Figure : Distributed control

Step 3: Fault message sent to CC —— Fault message delivered.

Communication scenario

Centralized control vs. Distributed control

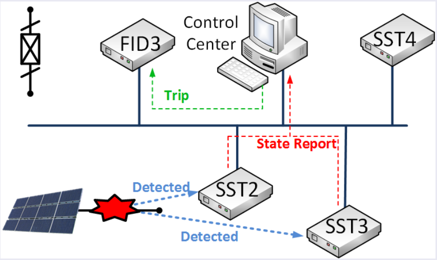


Figure : Centralized control

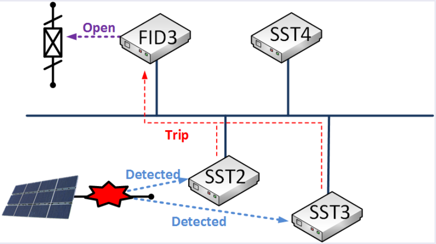


Figure : Distributed control

Step 4: Fault message delivered —— Circuit breaker opened .

Communication scenario

Centralized control vs. Distributed control

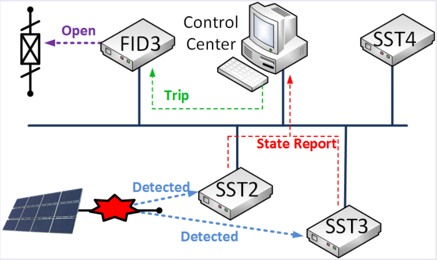


Figure : Centralized control

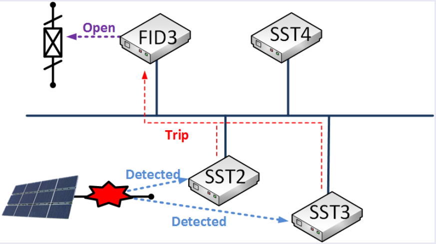
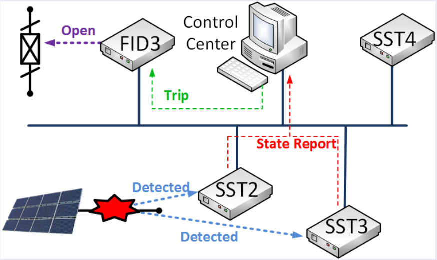


Figure : Distributed control

Step 5: Circuit breaker opened.

Communication scenario

Question



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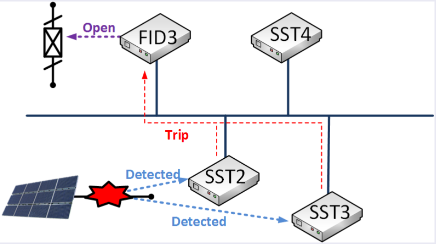
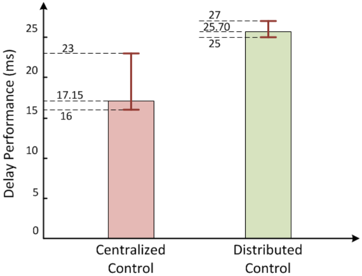


Figure : Distributed control

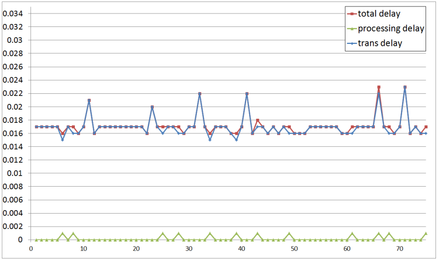
Question: In which scenario the message is delivered faster?

Result: delay performance comparison

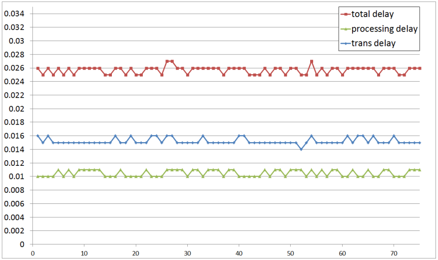


- Average delay for centralized control is 17.15 ms, with maximum delay of 23 ms and minimum delay of 16 ms.
- Average delay for distributed control is 25.70 ms, with maximum delay of 27 ms, and minimum delay of 25 ms.
- The centralized control systems outperforms the distributed control systems by 50%.

Result: delay time breakdown



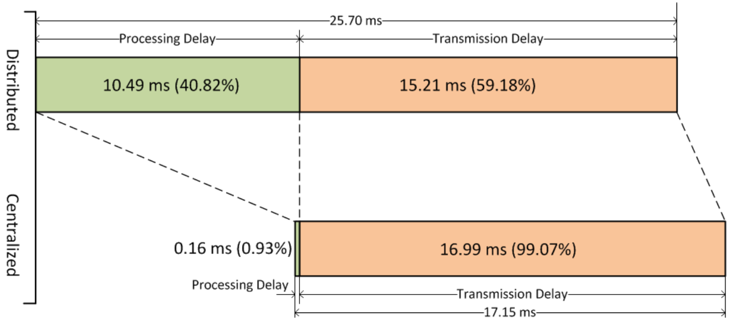
(a) Centralized Control



(b) Distributed Control

- Processing time at control center is negligible.
- Processing time is considerable on IEDs.

Result: ratio of average delay component



- For distributed control, state estimation calculation occupies 40.82% of total delay.
- For centralized control, the calculation time is negligible.

Case I: Observation

Observation 1

- Although the distributed control system architecturally fits better to smart grid than the centralized control system, the system performance in the distributed control system is sacrificed.

Observation 2

- *DNP3 over TCP/UDP* can not meet smart grid message delay requirement, a better communication protocol design/optimization is needed.

Outline

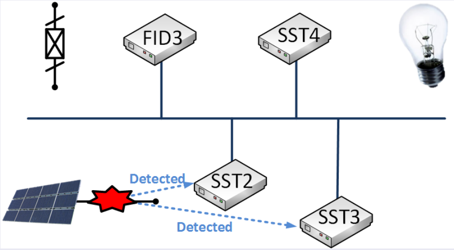
Background

Distributed Load Shedding Control

- Power consumption needs to be equal to power generation in power system.
- If a power shortage happens, some load need to be shedded to maintain system stability.
- Centralized load shedding: command issued by control center.
- Distributed load shedding: IEDs negotiate with each other to make load shedding decision, without interference from control center.

Communication Scenarios

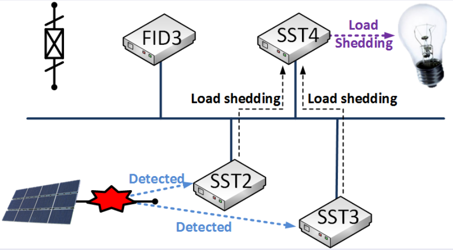
Asynchronous message delivery



- Fault happened and detected.
- Assume total load need to be shedded is L_t, and load shedded by SST2 and SST3 are L_2 and L_3, respectively.
- SST4 need to make decision based on first coming message.

Communication Scenarios

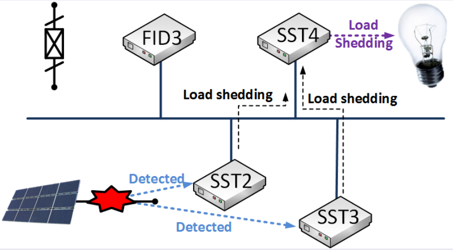
Asynchronous message delivery



- Message arrived at the same time.
- $L_4 = L_t - L_2 - L_3$.

Communication Scenarios

Asynchronous message delivery



- Message from SST3 arrived first.
- $L_4 = L_t - L_3$.

Communication Scenarios

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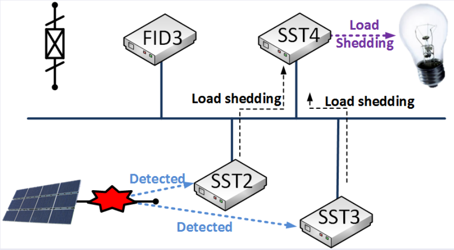
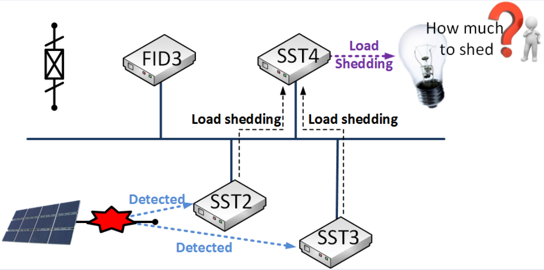


- Message from SST2 arrived first.
- $L_4 = L_t - L_2$.

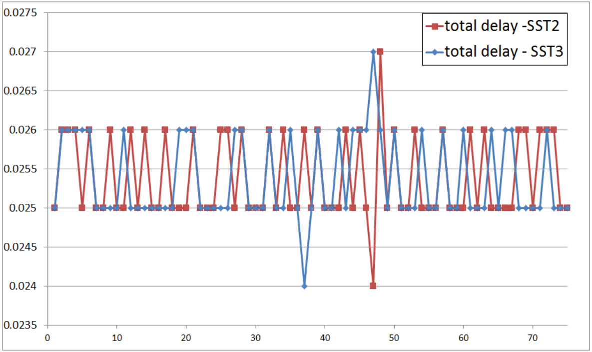
Communication Scenarios

Asynchronous message delivery



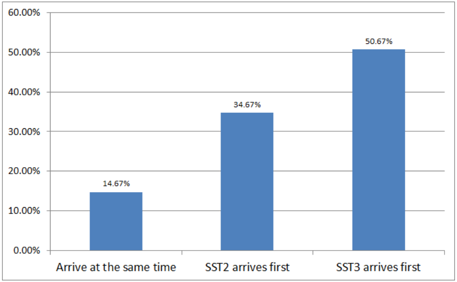
- Question: how much load to shed?

Result: asynchronous message delivery



- Messages arrive asynchronously due to random processing and transmission delay.
- Largest difference is 3ms.

Result: message arrival distribution



- *Expected Load Shedding*: the expectation of shedded load under the non-deterministic scenario.

$$\begin{aligned} L_{Ex} &= 14.67\%(L_t - L_2 - L_3) + 34.67\%(L_t - L_2) \\ &\quad + 50.67\%(L_t - L_3) \\ &= L_t - 49.34\% L_2 - 65.34\% L_3 \end{aligned}$$

Case II: Observation

Observation

- The peer to peer communication may cause different behavior of a physical device, and consequently deviates their decisions from the optimal. This consequence is caused by the asynchronous message delivery, which is an inevitable result of the peer to peer communication in distributed control systems. Special attention is needed or a distributed control system design.

Outline

Conclusion

1. Based on the Green Hub, we conducted experiments to measure message delay performance in both centralized and distributed control of smart grid, and show that distributed control is not necessarily better than centralized control in terms of delay performance.
2. We show that the *DNP3 over TCP/UDP protocol* can not meet smart grid message delivery delay requirements. A better design and optimization is needed for DNP3 to fit smart grid communication.
3. We identified asynchronous message delivery, which stems from distributed peer to peer communication. We show that asynchronous message delivery may cause indeterministic device behavior and defined *expected load shedding* to measure its result.

Questions?

Backup: Testbed Setup

Device specs in experiments

Table : List of device hardware and software in experiments.

Device	CPU	Memory	System Version
IED	ARM9 500MHz	128MB	ts-linux 2.6.21
Control Center	CORE i7 2.9GHz	4GB	ubuntu 12.04 LTS