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

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***Abstract*—Smart grid is an emerging cyber-physical system which aims at making power systems more intelligent and efficient. One of the major attributes of smart grid is integration of distributed renewable power resources into the traditional power grid. As a result, traditional centralized control is not always effective in smart grid, and distributed control is essential for flexible energy management. To facilitate distributed control, Intelligent Electronic Devices (IEDs), which are embedded computers equipped on power devices, are interconnected based on the peer-to-peer communication model. An open question is whether such a distributed control mechanism over peer to peer communication is delay-efficient to support time-critical smart grid applications. To answer this question, we establish a micro smart grid, called Green Hub, to measure the delay performance for both distributed and centralized control systems. Our results show that, for computationally intensive applications, the delay performance of the distributed system is worse than that of the centralized control system, mostly due to IEDs' limited capability. In addition, we find that in distributed control systems, the peer to peer communication may cause different behaviors of physical devices in power systems, and consequently deviates their decisions from optimal. Our experimental study reveals the distributed control system in smart grid does not necessarily performs better than the centralized control system for certain applications, and the peer to peer communication in the distributed control system may bring new concerns which did not exist in the centralized control system. A special attention need to be paid on the effectiveness and efficiency aspects when design algorithms/schemes for smart grid.**

I. I

Smart grid is an emerging cyber-physical system which aims at increasing energy efficiency, integrating renewable sources of energy, and building a sustainable and prosperous economy [1]. One of the major attributes of smart grid is the integration of distributed resources and generation, including renewable resources, into the traditional power grid [2]. In particular, the traditional customers are no longer pure power consumers, instead, they are able to participate the power generation by using distributed renewable energy generators, such as Wind Turbine (WT) or Photovoltaic (PV).

Because of the integration of distributed resources, the traditional centralized control system operation is no longer effective, and a distributed control system is needed for smart grid management [3], [4]. Effective distributed control of the distributed resources requires the power devices to be intelligent, i.e., know their own state and communicate to other concerned entities. To enable such a distributed intelligence, power devices are quipped with Intelligent Electronic Devices (IEDs), which are usually embedded systems running on relatively lower-end CPUs. Those IEDs are interconnected with each other to form a peer to peer communication network, which is demanded by the distributed control system.

The research on intelligent distributed control for smart grid as been a hot topic in recent years [5], [6], [3]. However, most of those work only focus on their schemes' usability, they do not consider the extra delay which may be caused by IEDs' limited computational capability. Power system is a delay-sensitive system, and it has stringent delay requirement for message delivery. An out-of-date message could result in potential system failures. For example, when a fault happens, the "trip" message needs to be sent from control node to circuit breaker within 3 ms, so that the circuit breaker can open circuit in time and isolate the fault within a small area [7]. Therefore, an open yet fundamental question is *whether the delay performance of distributed peer to peer network can support time-critical smart grid applications*.

To address this question, we establish a real environment of a micro smart grid, known as *Green Hub*, in the Future Renewable Electric Energy Delivery and Management (FREEDM) systems center, and choose a typical scenario in power system to serve as our case study. Our scenario involves distributed calculation of state estimation [5], [8], the algorithm which was ran solely on the control center to estimate power system states; and distributed load shedding [6], [9], [10], which intelligently disconnect a certain amount of local load to maintain load-generation balance in power system. Both applications rely on the Distributed Network Protocol 3.0 (DNP3) over TCP/UDP protocols [11] for message delivery. Our objective is to evaluate the practical delay performance of smart grid under both distributed and centralized control systems, and compare the results.

Intuitively, the peer to peer communication in distributed control systems should achieve a better delay performance because in such a system, peer nodes communicate with each other directly, and thus there is no need for the control center to forward any messages. However, our experiments show the contrary, and indicates the delay performance of centralized control systems is not necessarily worse than that of distributed control systems. To the best of our knowledge, we are the

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first to setup a practical testbed of a distributed smart grid, and measure the delay performance under such a distributed control system. Our findings can be summarized as three-fold.

First, we find that the distributed IEDs are significantly inferior in terms of computational capability, which makes the delay performance of distributed control system much worse for computationally intensive applications. Although the peer to peer communication in distributed control system reduces transmission delay, the overall delay performance suffers because the computational processing delay increases significantly. To run a simple 3-bus state estimation algorithm, the IED costs 10 ms to complete, while the control center costs less than 1 ms. This shows that when design algorithms/schemes for smart grid, their computational effectiveness should always be a critical factor.

Second, we find that the *DNP3 over UDP* architecture, although performs better than *DNP3 over TCP*, still cannot meet the stringent time requirement. For "trip" message, the IED to IED end to end delay is 14-16 ms, and IED to control center end to end delay is 8-11 ms, which are still much longer than the 3 ms requirement specified in IEC 61850 standard [7]. This indicates that a further optimization is needed for DNP3 transmission mechanism.

Third, our experiment shows that, in distributed control systems, the peer to peer communication may cause different behavior of physical devices under the same situation, and consequently makes their decisions deviate from optimal. This phenomenon is caused by the asynchronous message delivery, which is the consequence of the random delay introduced by peer nodes in distributed systems. We simulate the asynchronous message delivery scenario and design a metric to measure its impact. We believe this is a practical problem in smart grid, and thus an effective message handling scheme is in demand.

The reminder of this paper is organized as follows. In Section II, we introduce the background of the concepts we used in our case study. In Section III, we present our experimental setups. In Section IV, we illustrate our experimental result and discuss our findings. And in Section V, we conclude our work.

II. B

In this section, we first introduce the architecture of Green Hub in FREEDM center, then we describe the Distributed Grid Intelligence (DGI) and DNP3 protocol, finally we give the concept of Distributed Load Shedding, which is used in our case study.

A. Green Hub

The Green Hub System is a novel distribution level microgrid which has been developed at FREEDM center for the study of power management strategies [12]. The Green Hub is based on actual 12 kV residential distribution system, in which the distribution transformers are upgraded with Solid State Transformers (SSTs), and various renewable resources such as photovoltaic (PV) and Wind Turbine (WT) are integrated.

As an testbed to simulate and study the performance and issues on such a system, an actual 230 kV/ 22.86 kV substation along with two 22.86 kV distribution feeders from this substation in the Raleigh area have been selected and implemented in both PSCAD [13] and OMNet++, for studying of its physical and cyber aspect, respectively.

The physical architecture of the studied system is shown in Fig. 1. The studied system is a 17-bus distribution system. Each bus is connected with a SST, which is able to implement the bi-directional energy flow as well as DC/AC transformation. As illustrated in this figure, each SST is connected with a load (we use "load" to represent AC load, and Plug-in Hybrid Electric Vehicle (PHEV) as an typical representation of DC load) and a renewable energy source (PV, WT, or DESD). Under normal operation, the renewable sources generate power to accommodate the load, and may feed extra power back to the grid. To ensure the reliability of the system, two Fault Insulation Devices (FIDs) are deployed on feeder 1 and feeder 2, which could open the circuit breaker and isolate the Green Hub from upper level power grid in case a fault happens. Furthermore, for the two branches of feeder 1 and feeder 2, because they geographically locate in woody areas which may increase the fault probability, two extra FIDs (FID3, FID4) were deployed to make the system more reliable.

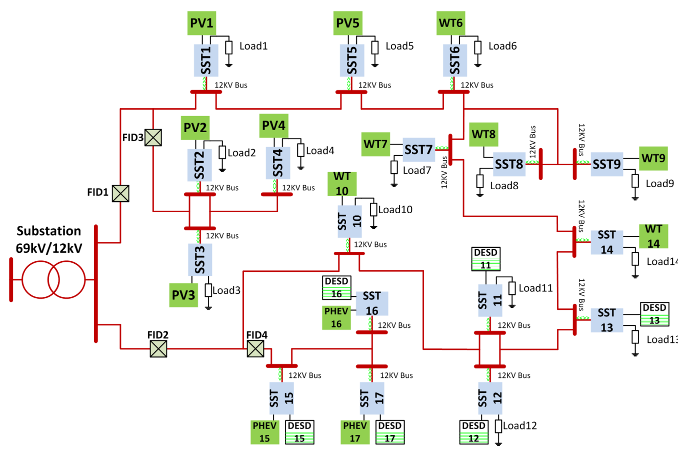


Fig. 1. Physical architecture of Green Hub.

Directly mapping from the Green Hub physical architecture, we have the communication infrastructure shown in Fig. 2. In this figure, we map each bus as a small Local Area Network, within which all the IEDs communicate with each other and exchange messages. An access point was equipment at each bus as the interface for the IEDs to access the backbone network, also shown in this figure is the communication methods (Zigbee, Ethernet, Wireless) we have implemented in FREEDM center.

B. Distributed Grid Intelligence (DGI)

The Distributed Grid Intelligence (DGI) is a major cyber component in FREEDM system [14]. The DGI is a distributed control scheme, in which each residential node runs as a part of the DGI, and the whole nodes coordinate to manage the

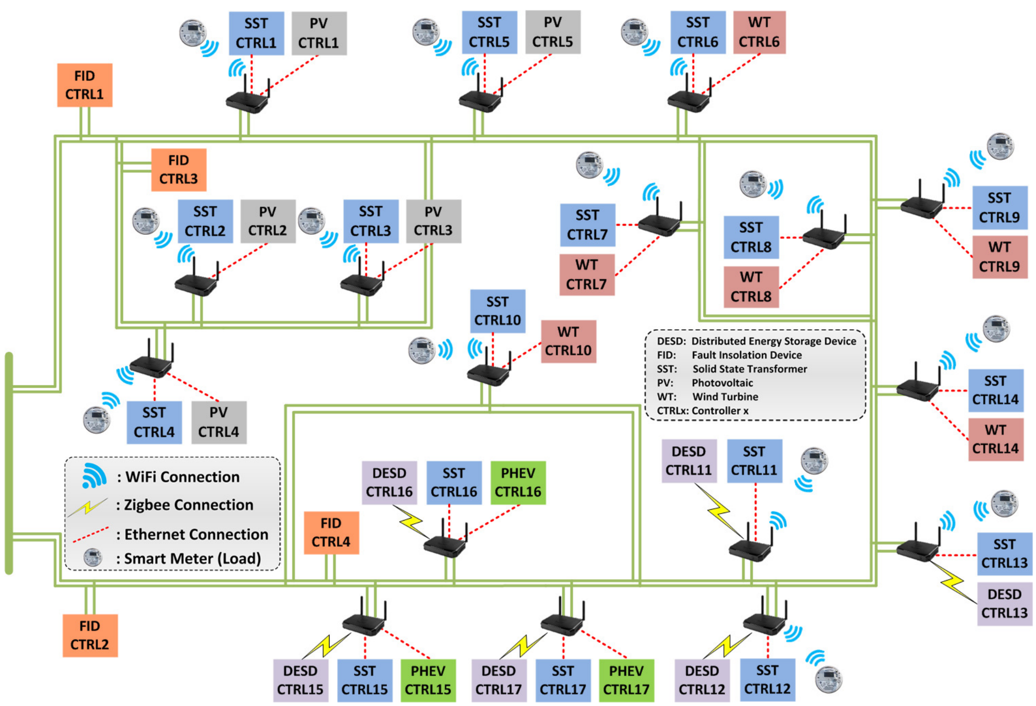


Fig. 2. Communication Infrastructure of Green Hub.

utilization, storage and distribution over the distributed power grid.

The DGI features a intelligent and distributed control system, against the centralized control system used in the traditional system. As stated before, a distributed control is the trends of the future smart gird, thus a thorough study of its communication performance is a fundamental and critical milestone on the way to deploy such a system.

C. Distributed Network Protocol 3.0 (DNP3)

DNP3 protocol is a widely used communication protocol in power system in North America [15]. The DNP3 protocol was originally designed to operate in traditional power grid and over serial links. Toward the migration from traditional power grid to smart grid, reuse of current communication protocols is widely considered as a cost-efficient and backward-compatible solution [16], [11]. Because DNP3 does not specify its own network and lower layers, DNP3 over TCP/IP has been proposed as a communication protocol for smart grid. In [11], the author studied the delay performance for DNP3 over TCP, and drew the conclusion that DNP3 over TCP is not suitable to be directly used for time-critical message transmission, and pointed out that DNP3 over UDP might be a better solution. Therefore, in our case study, we take DNP3 over UDP as the communication protocol so as to reduce the transmission delay.

D. Distributed Load Shedding Control

When a power system operates at a stable state, the total input power from generators is equal to the sum of all the loads and the real power loss in the system. If the load demand exceeds the overall power generators' capability, the stability will be break; if proper solutions are not launched in time, the instability may cause a cascading blackout, and may damage the generators. A load shedding is an action takes by the system, which intentionally and automatically disconnect a portion of load in order to make the remaining load equals to the generation and thus make the system regain a stable state [9]. Load shedding is the final solution used in power system to prevent it from totally collapse. Traditionally, the load shedding is implemented in a centralized way [6]. Recently, with the emerging concept of "smart home", a decentralized load shedding scheme was proposed, e.g., customer-level load shedding [17], or soft load shedding [10]. In those schemes, "smart homes" will be able to negotiate with each other and make load shedding decision by themselves, by taking advantage of modern communication technologies.

III. E S

In this section we introduce the test scenario used in this paper and the setup of our testbed.

A. Communication scenarios

1) Base scenario: In this paper we consider a *fault detection and clearance* scenario from [18].The procedures of such a scenario are:

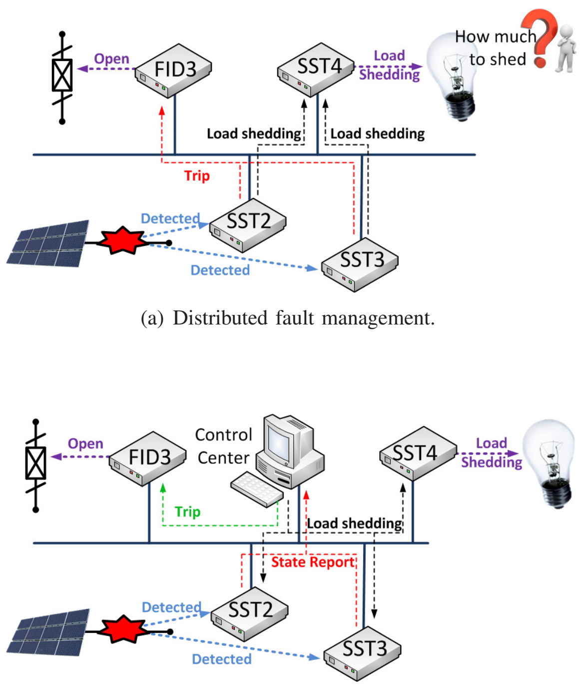
i. Assume a fault happens on one device within the system, say the PV2 in Fig. 1. SST2 first senses the fault current/voltage, and then locate the fault location.
ii. On locating the fault, the DGI node resides in SST2 (SST2 controller) sends "trip" message to FID3, asks it to open the circuit breaker in order to isolate the fault. Because the

outage of PV2, the load in the isolated island exceeds the generation, SST2 makes decision to shed load to maintain the system balance. And according to the distributed load shedding control scheme, SST2 also sends message to SST3/SST4 to inform them the load shedding decision.

iii. Because SST3 and SST2 are geographically adjacent, SST3 also senses the current/voltage fluctuation right after the fault happens, and takes same actions as SST2 does.

iv. As a result, FID3 opens the circuit breaker after receives the requests sent from SST2/SST3, and SST4 may also need to shed certain amount of load based on the load shedding information of SST2/SST3.

This procedure can be shown in Fig. 3(a).



(a) Distributed fault management.

(b) Centralized fault management.

Fig. 3. Communication scenarios.

2) Centralized fault handling scenario: As our objective is to measure the delay performance of the distributed control system and compare it with the centralized control system, we also design the corresponding centralized fault handling scenario according to the base scenario. Without loss of generality, we only consider one event of the whole process in the base scenario, specifically, the "trip" message sent from SST2 to FID3.

It is easy to tell from the first scenario that, it takes 2 steps to handle such an event in the distributed control system: i) SST2 controller takes sample value and executes state estimation algorithm; ii) SST2 controller sends "trip" message to FID3 controller.

However, in the centralized control system, because the existence of the control center, the event handling is more complex. As shown in Fig. 3(b), instead of local calculation of state estimation, SST2 sends the sampled value directly to the control center, the control center executes the state estimation algorithm, and issues commands to corresponding devices when a fault happens. The handling of such an event involves 3 steps: i) SST2 sends sampled value to control center; ii) control center executes state estimation algorithm; iii) control center sends "trip" message to FID3.

3) Asynchronous message delivery scenario: Comparing the centralized control and distributed control scenarios, it is easy to notice that, in the centralized control, SST4's load shedding decision is made based on single message, which was sent from control center. However, in the distributed control, SST4 controller makes decision based on two messages, which were sent by both SST2 controller and SST3 controller. Because the current/voltage surge propagates fast along power feeders, the load shedding decision needs to be made as soon as possible, and therefore it is not suitable for SST4 to wait until all messages arrive, and as a matter of fact, SST4 does not know how many messages will arrive beforehand. Consequently, in the distributed control system, SST4 may make load shedding decision based on the first arrived message. In such a situation, which message arrives first becomes a critical factor, and different message arrival order may cause a different behavior of physical devices. Such a difference in message arrival, or asynchronous message delivery, is inevitable in peer to peer distributed networks, because each node may introduce its own random delay. We simulate this scenario and analyze its impact.

B. Testbed Setup

We setup a practical testbed to evaluate the delay performance in the scenario described above. Such scenario involves 2 types of devices, the various IEDs, which we use ARM based embedded systems in affiliate with FREEDM, and the control center, which we use a core-i7 based laptop. Detailed parameters are listed in Tab. I.

TABLE I

L .

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

IV. E R

In this section, we present our experimental result in the fault detection and handling scenario we described in Section III. First, we measure the delay performance and compare it with corresponding fault management secnario in centralized control system. Then we study the asynchronous message delivery in the distributed control system and design a metric to measure its impact.

A. Case Study I: Delay performance in distributed system verses centralized system

In this case study we measure the delay performance for both distributed control system (base scenario) and centralized control system (centralized fault management scenario)

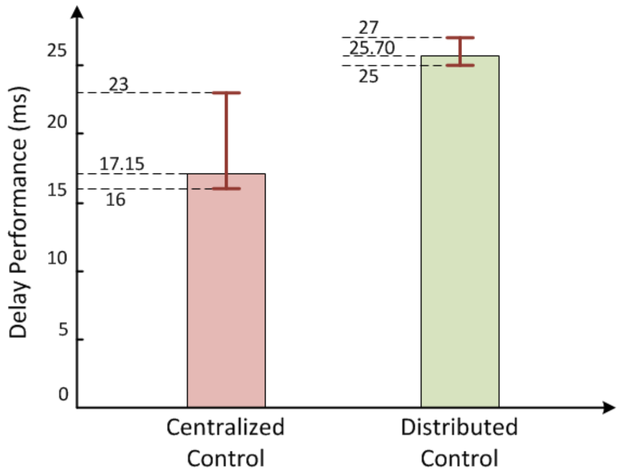


Fig. 4. Delay performance comparison: Distributed vs Centralized.

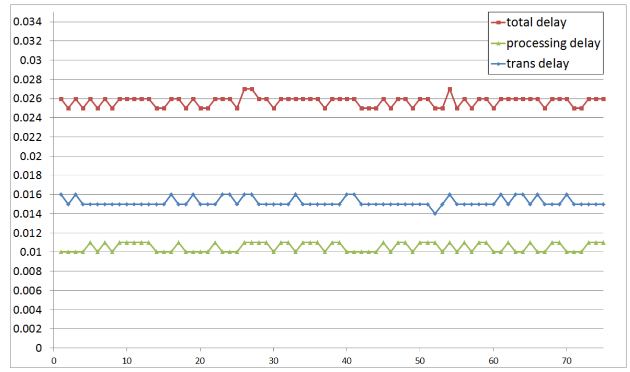
described in Section III, and compare their results. Intuitively, distributed control scenario seems more efficient because its simplified event handling process. However, our experiment result shows the contrary.

1) Experimental Results: Fig. 4 shows the delay performance for both the distributed control scenario and the centralized control scenario described above. The average delay of the centralized control is 17.15 ms, with maximum delay of 23 ms and minimum delay of 16 ms; while for the distributed control scenario, the average delay is 25.70 ms, with maximum delay of 27 ms, and minimum delay of 25 ms. We can tell from the figure that although the centralized control scenario suffers one more step when handling an event, its delay performance is actually better than that of distributed control systems. Specifically, in this case study, the centralized control systems outperforms the distributed control systems by 50%.

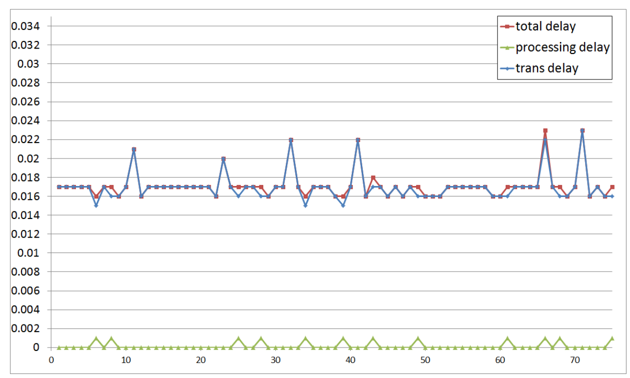
In this experiment, we measure the delay performance for both distributed control scenario and centralized control scenario, and get a counter intuitive result: although the centralized control suffers more complicated process to handle an event, its delay performance is actually better than that of a distributed control.

To further explore the cause of such a result, we take a close look at the entire process and breakdown the total delay according to its event handling steps. Drawn in Fig. 5 are the delay components which compose the total delay. For the distributed control scenario, we divide the total delay into 2 parts according to the 2 steps of event handling: the algorithm processing delay, and transmission delay; for the centralized control scenario, we also divide the total delay into 2 parts: as step 1 (SST2 to control center) and step 3 (control center to FID3) are both regular DNP3 message transmission and only different at the direction, we combine them together.

For easier comparison, we put the result of two scenarios together and draw the result in Fig. 6. For the distributed scenario, the state estimation calculation by the IED consumes a significant part of total delay. Specifically, the calculation occupies 40.82% of total delay. However, in the centralized scenario, the time consumed on state estimation calculation by the control center is negligible. For some cases where the processing delay is 1 ms, we believe it is because we did not do a sub-millisecond measurement, e.g., calculation starts at 10.9 ms and completes at 11.3 ms is measured as a 1 ms delay.



(a) Delay performance in Distributed Control



(b) Delay performance in Centralized Control

Fig. 5. Delay performance: Distributed vs. Centralized.

2) Result Analysis: The transmission delay of the centralized scenario is slightly longer than that of the distributed scenario, this is because the centralized control system takes 2 steps for message delivery. However, we can infer from the comparison that the time consumed by control center to process a DNP3 message is much shorter than the IED. The transmission delay in the distributed scenario, t_{trans_dist}, represents the time consumed by an IED to package and unpackage an DNP3 message (propagation delay is negligible), whose average is around 15 ms; while the transmission delay in the centralized scenario, t_{trans_ctr}, represents the total time consumed by an IED and the control center to package and un-package a DNP3 message, whose average is around 17 ms. Therefore, the difference of the two represents the time the control center consumes to process a DNP3 message, whose average value is around 2 ms, which is much shorter than the time consumes by the IED.

3) Observation: Recall our objective is to compare the delay performance of the distributed control system and the centralized control system. Based on our analysis in Section

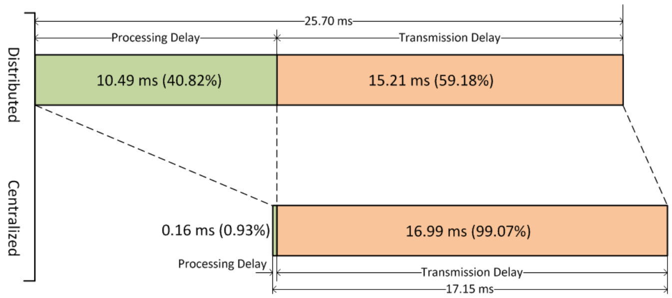


Fig. 6. Ratio of average delay component: Distributed vs. Centralized.

I, intuitively the distributed control system should achieve a better delay performance, because IEDs in such a system have direct route to each other and do not need the control center to forward messages. However, through our experiment we observe a counter intuitive result. Our observation is two-folded:

i. 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. In this case study we run a 3-bus state estimation algorithm, which is relatively simple, and it caused a non-negligible processing delay on IEDs. We believe when execute much complicated algorithms, the processing delay will be much longer, and the difference compared to the time consumed by the control center will be much more significant. Our experimental result indicates that, for computational intensive smart grid applications, the distributed control system is unable to achieve a better delay performance than centralized control system, mainly because the IEDs' limited computational capability. The result also suggests us, when designing distributed algorithms or schemes for smart grid, besides their usability, their effectiveness and computational intensity should also be carefully evaluated.

ii. Although the transmission delay of the *DNP3 over UDP* is much better than the *DNP3 over TCP*, its delay performance is still unable to meet the stringent delay requirement of power systems. The IEC 61850 standard requires 3 ms for the delay of relay protection (trip message), and 16 ms for data monitoring [7], [19]. However, We can see in our test case that, for IED to IED, the end to end delay is 15 – 16 ms, which is just on the threshold for monitoring message; for control center to IED, the end to end delay is 8 – 9 ms, which is capable to handle the monitoring message delivery. And we can also see that both of them are still far from 3 ms delay requirement for "trip" message. Our result indicates that a much more efficient and effective optimization for DNP3 message transmission is needed.

B. Case Study II: Impact of asynchronous message delivery

As described in Section III, SST4 makes load shedding decision based on information received from SST2/SST3. In the centralized control system, the control center has an overall view of the system and is able to make the optimal decision based on the whole system situation when a fault happens; however, in the distributed control system, as described in Section III, SST4 controller may make different load shedding decision based on different message delivery order.

Assume in order to make the power system return to a stable status, the total load needs to be shed is l_t, the load shed by SST2 and SST3 are l_2 and l_3, respectively, and the load SST4 will shed is l_4. It is obvious the optimal load shedding solution for SST4 is $l_t - l_2 - l_3$, which is easy to be achieved in a centralized control system. However, in the distributed control system, the SST4 makes decision based on the information it received, which might be incomplete, and therefore may derive a non-optimal solution. The possible load shedding solutions for SST4 could be $l_t - l_2 - l_3$, $l_t - l_2$ or $l_t - l_3$, which correspond to 3 message deliver scenarios: i) message from SST2 and SST3 arrive at the same time; ii) message from SST2 arrives first; and iii) message from SST3 arrives first. In this experiment, we simulate this scenario and design a metric to measure the impact due to such asynchronous message delivery.

1) Experimental Result: Fig. 7 illustrates the result of asynchronous message delivery. We can tell from this figure that, there are some cases where the load shedding messages from SST2 and SST3 arrive at the same time, which represents that SST4 can achieve the optimal solution for its load shedding decision. However, for most cases, due to the random delay caused both by the state estimation calculation and network transmission, messages do not arrive synchronously, the longest difference between their arrival is 3 ms.

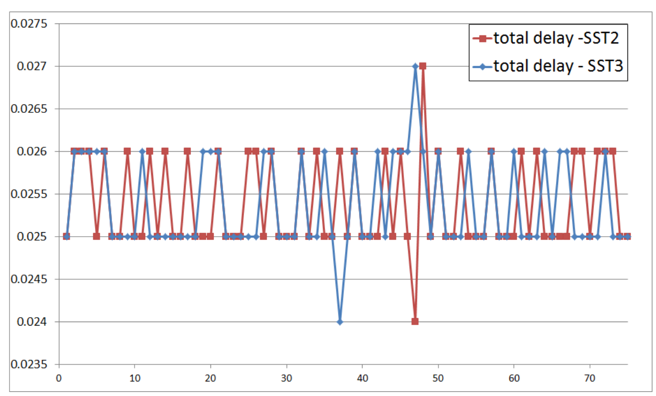


Fig. 7. Asynchronous message delivery.

2) Result Analysis: In this experiment, we simulate the asynchronous message delivery caused by the random delay of peer nodes in distributed control systems. We found that the asynchronous delivery may cause different behavior of physical devices, as a result, the optimal solution cannot always be guaranteed to achieve. To better analyze the impact caused by such asynchronous message delivery, we design a metric, the *Expected Load Shedding (ELS, l_{Ex})*, to measure this effect. We define the ELS as the expectation of shed load under the non-deterministic scenario. In our case study, for SST4, its load shedding has 3 possible solutions: $l_t - l_2 - l_3$, $l_t - l_2$ and $l_t - l_3$. We do statistical analysis on our experiment result based on such 3 scenarios, and Fig. 8 shows the percentage of each scenario occupies in our experiment.

Based on Fig. 8, we can calculate SST4's ELS as:

$$\begin{aligned} l_{Ex} &= 14.67\%(l_t - l_2 - l_3) + 34.67\%(l_t - l_2) \\ &\quad +50.67\%(l_t - l_3) \\ &= l_t - 49.34\% l_2 - 65.34\% l_3 \end{aligned}$$

which is obviously larger than the optimal solution $l_t - l_2 - l_3$. Therefore, because of the asynchronous message delivery caused by distributed control systems, SST4's load shedding is unable to achieve its optimal value, but only a portion of it, which can be represented by l_{Ex}.

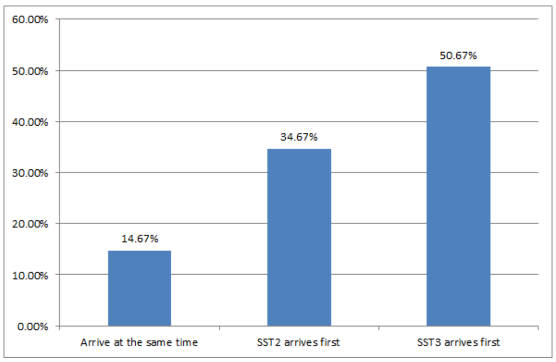


Fig. 8. Asynchronous message delivery.

3) Observation: Our experiment results indicate 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. In a practical power system where hundreds or even thousands of IEDs are interconnected, the situation will become much more complicated, and the optimal solution will be more difficult to achieve. We believe it is a practical problem in smart grid of how to handle the asynchronous message delivery in a distributed control system.

V. C

In this paper, based on Green Hub, the micro smart grid, we conducted experimental case study on the distributed control system in smart grid, and compared the result to the traditional centralized control system.

Our experimental results show that for computationally intensive applications, distributed control system causes a worse delay performance compared to centralized control system. In particular, the centralized control system outperforms the distributed control system by 50% in our case study. We observe that although the DNP3 over UDP protocol performs better than the DNP3 over TCP, it is still unable to meet the stringent delay requirement in smart grid, and thus a more efficient and effective communication scheme is highly demanded in smart grid. We also identify the impact caused by the asynchronous message delivery in the distributed control system, and define a metric, the *Expected Load Shedding*, to measure this impact. Our future work includes design schemes which is computationally suitable for distributed IEDs, and design schemes to handle the asynchronous message delivery.

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[1] G. Locke and P. D. Gallagher, "NIST framework and roadmap for smart grid interoperability standards, release 1.0," *National Institute of Standards and Technology*, p. 33, 2010.
[2] www.GovTrack.us, "H.R. 6–110th Congress: Energy Independence and Security Act of 2007," 2007.
[3] M. U. Tariq, S. Grijalva, and M. Wolf, "Towards a distributed, service-oriented control infrastructure for smart grid," in *Cyber-Physical Systems (ICCPS), 2011 IEEE/ACM International Conference on*. IEEE, 2011, pp. 35–44.
[4] A. Monti, F. Ponci, A. Benigni, and J. Liu, "Distributed intelligence for smart grid control," in *Nonsinusoidal Currents and Compensation (ISNCC), 2010 International School on*. IEEE, 2010, pp. 46–58.
[5] L. Xie, D.-H. Choi, S. Kar, and H. Poor, "Fully distributed state estimation for wide-area monitoring systems," *Smart Grid, IEEE Transactions on*, vol. 3, no. 3, pp. 1154–1169, 2012.
[6] A. Apostolov, D. Tholomier, and A. Edwards, "Advanced load-shedding functions in distribution protection relays," in *The 19th International Conference and Exhibition on Electricity Distribution (CIRED)*, 2007.
[7] IEC Standard, "IEC 61850: Communication networks and systems in substations," 2003.
[8] G. N. Korres, "A distributed multiarea state estimation," *Power Systems, IEEE Transactions on*, vol. 26, no. 1, pp. 73–84, 2011.
[9] S. Shokooh, T. Khandelwal, F. Shokooh, J. Tastet, and J. Dai, "Intelligent load shedding need for a fast and optimal solution," *IEEE PCIC Europe*, 2005.
[10] D. Craciun, S. Ichim, and Y. Besanger, "A new soft load shedding: Power system stability with contribution from consumers," in *PowerTech, 2009 IEEE Bucharest*. IEEE, 2009, pp. 1–6.
[11] X. Lu, Z. Lu, W. Wang, and J. Ma, "On network performance evaluation toward the smart grid: A case study of dnp3 over tcp/ip," in *Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE*. IEEE, 2011, pp. 1–6.
[12] Z. Shen, Z. Liu, and M. Baran, "Power management strategies for the green hub," in *Power and Energy Society General Meeting, 2012 IEEE*. IEEE, 2012, pp. 1–4.
[13] H. Hooshyar, "System protection for high pv-penetrated residential distribution systems (green hubs)." 2011.
[14] F. Meng, R. Akella, M. Crow, and B. McMillin, "Distributed grid intelligence for future microgrid with renewable sources and storage," in *North American Power Symposium (NAPS), 2010*. IEEE, 2010, pp. 1–6.
[15] K. Curtis, "A DNP3 protocol primer," *DNP User Group*, 2005.
[16] S. Mohagheghi, J. Stoupis, and Z. Wang, "Communication protocols and networks for power systems-current status and future trends," in *Power Systems Conference and Exposition, 2009. PSCE'09. IEEE/PES*. IEEE, 2009, pp. 1–9.
[17] S. Koch, S. Chatzivasileiadis, M. Vrakopoulou, and G. Andersson, "Mitigation of cascading failures by real-time controlled islanding and graceful load shedding," in *Bulk Power System Dynamics and Control (iREP)-VIII (iREP), 2010 iREP Symposium*. IEEE, 2010, pp. 1–19.
[18] "2012 FREEDM annual report: Volume ii - research reoporting and results," 2012.
[19] "IEEE standard communication delivery time performance requirements for electric power substation automation," *IEEE Std 1646-2004*, pp. 1–24, 2005.