ICT Impact on Primary Frequency Control Support and Coordination from ReGen Plants

Agreement no.:	PSO ForskEl 12347
Project Name:	Ancillary Services from Renewable Power Plants
Acronym:	RePlan
Duration:	2015 - 2018
Coordinator:	DTU Wind Energy

Document information

Document name:	ICT Impact on Primary Frequency control support and coordination form ReGen plants
Document number:	TR 3
Lead Author	Kamal Shahid
Contributors:	Rasmus L. Olsen, Florin Iov, Mufit Altin
Document type:	Technical Report T3
Date:	20.02.2018
WP:	3

Content

Preface 5
1 Scope of document 1
2 Communication for On-line Frequency Support and Coordination 2
2.1 ICT Challenges in Primary Frequency Stability Support 3
2.2 Supervisory Control and Data Acquisition (SCADA) 3
2.3 SCADA with Cellular Network Communication 5
2.3.1 Cellular Network Performance in Denmark 5
3 Use Case and Test Scenarios 8
4 Evaluation Criteria – Key Performance Parameter (KPI) 9
5 Evaluation Setup and Test Cases 10
5.1 Power System Simulation Model 10
5.2 Communication model 10
5.3 Reference Case 11
5.3.1 Partial Loads 11
5.3.2 Full Loads 12
5.4 Test cases 12
5.4.1 Test Case 1 – Standard Communication 12
5.4.2 Test Case 2 – Higher delays 13
6 Test Results – Impact of Communication Properties on On-Line Frequency Control Coordination 13
6.1 Test Scenario 1 14
6.1.1 Partial Load 14
6.1.2 Full Load 14
6.1.3 Comparison 15
6.2 Test Scenario 2 15
6.2.1 Partial Load 15
6.2.2 Full Load 16
6.2.3 Comparison 16
6.3 Test Scenario 3 17
6.3.1 Partial Load 17
6.3.2 Full Load 17

6.3.3 Comparison ... 18
7 Conclusion and Recommendations ... 18
8 References ... 20
9 Appendix A – Detailed Results of Each Test Scenario ... 21
9.1 Test Scenario 1: Ideal Case ... 21
9.1.1 Impact of Standard Communication ... 21
9.2 Test Scenario 2: ... 22
9.2.1 Impact of Standard Communication ... 23
9.2.2 Impact of Delays in Communication ... 24
9.3 Test Scenario 3: ... 26
9.3.1 Impact of Standard Communication ... 27
9.3.2 Impact of Delays in Communication ... 28

Preface

This is a technical report in connection to the deliverable D3 in WP3 in the project "Ancillary services from Renewable power Plants" (RePlan). RePlan is funded as POS project 2015 no. 12347 by the Danish PSO-programme ForskEL, which is administered by Energinet.DK. RePlan is carried out in collaboration between DTU Wind Energy, DTU Elektro, Aalborg University Energy Technology, Aalborg University Wireless Communication Networks and Vestas Wind System A/S. DTU Wind Energy is manager of the project.

1 Scope of document

This technical report presents ICT impact on the frequency stability control support from ReGen plants as a part of WP3, including the related models, methodologies and case study considered for the fast frequency response FFR proposed in D3. The overall objective of this report is to assess the impact of ICT on the frequency control support from ReGen plants (with special focus on wind power plants)

2 Communication for On-line Frequency Support and Coordination

Frequency stability refers to the ability of a power system to maintain steady frequency following a severe disturbance between generation and load [1]. It depends on the ability to restore equilibrium between system generation and load, with minimum loss of load. Frequency instability may lead to sustained frequency swings leading to tripping of generating units or loads. During frequency excursions, the characteristic times of the processes and devices that are activated will range from fraction of seconds like under frequency control to several minutes, corresponding to the response of devices and hence frequency stability may be a short-term phenomenon or a long-term phenomenon.

Document [2] summarizes the results of work package 3 (Frequency support from ReGen plants), including the related models, methodologies, development of controls and study cases considered for both primary and secondary frequency control. The focus in [2] was to improve the frequency control support from ReGen plants (with special focus on wind power plants) by optimizing and coordinating the total support from ReGen plants.

According to [2], the provision of frequency support in power systems is usually based on the measurements of frequency deviation and rate of change of frequency. The measurements of frequency deviation are quick and reliable, however measuring the rate of change of frequency is done over sliding windows of several hundred milliseconds and is thus always afflicted with a delay. For the online coordination, ReGen plants should send status updates at regular intervals to the aggregator or TSO directly, based on which set-points are calculated and sent back to the ReGen plants (see Figure 1). Since, the ReGen plants as well as the control centers will be located quite far apart from each other, a time delay is expected in receiving the set-points. As a result, the contribution of a ReGen plant to the system frequency support will be also be delayed. The delay and other such properties of communication depend on the underlying network communication infrastructure. Thus, the optimized FFR support discussed in [2] will likely be non-optimum, if not deteriorating to the system response.

Therefore, the overall objective of this report is to investigate: 1) the different communication network options that can be used in the future to support communication between ReGen plants and the control centers, and 2) the extent to which the delays associated to these networks can impact frequency support coordination from ReGen plants. The optimization process employed in [2] is used as such including the various delays in measurement and communication.

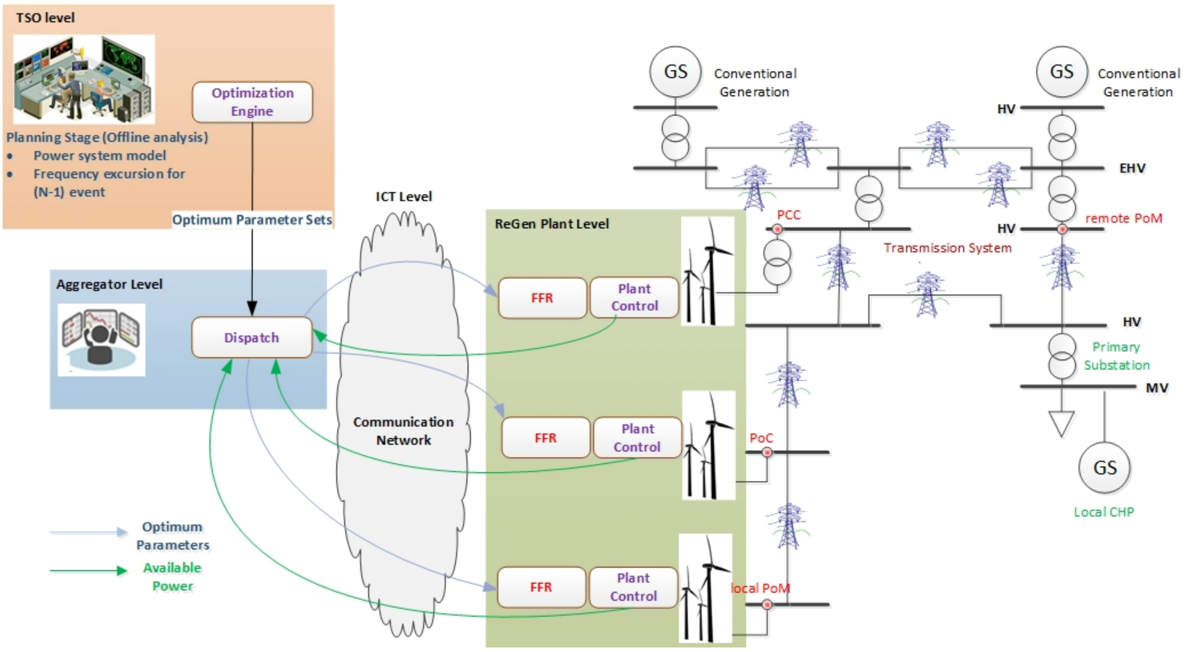


Figure 1. Implementation of Offline Optimization Approach with Control Levels

2.1 ICT Challenges in Primary Frequency Stability Support

When it comes to provide frequency support and coordination from power generation plants, there is a need to add supervisory control and data acquisition (SCADA) communication to the intelligent electronic devices (IEDs). Fiber-optic cables are an extremely reliable means of transporting information between the control center (aggregator/TSO) and remotely located ReGen plants. Fiber-optic cable has the following advantages over copper cables: isolation from ground potential rise, prevention of induced electrical noise, and elimination of signal ground loops. However, for wide-area SCADA network, fiber-optic cabling installation can be expensive and slow. Wireless networking offers a cost-effective alternative to running fiber-optic cable in this regards. Wireless networks, specifically cellular networks, can provide up to 90 percent savings [3] versus installing fiber-optic cabling, with greatly expedited implementation. The cellular networks have become the dominant mode of communication for machine-to-machine (M2M) communication as in smart grids. According to [4], Victoria's South East Water replaced its digital radio system with a high-speed IP-based communications hub with 3G and 4G cellular modems, as well as DSL direct links. Therefore, in this report we focus mainly on using the cellular networks for communication between the ReGen plants and the control center.

Before outlining various aspects and impact of using cellular network communication in the said scenario, the requirements for SCADA communication are first addressed.

2.2 Supervisory Control and Data Acquisition (SCADA)

A SCADA system provides the monitoring and control of remote devices through a communications network. SCADA systems in the early stages were designed as telemetry systems with 'little' to 'no control' because of communications bandwidth constraints. Today, SCADA networks consist of many remote terminal units

(RTUs) that communicate back to a central computer using standard Modbus® or DNP3 communications protocols. These SCADA system protocols use polling schemes to gather information from each end device and report the data back to a central SCADA master. The system can then automate control decisions based on the data received. Since SCADA networks are developed around low-speed communications, the throughput and latency requirements within the communications network are not demanding and allow for large implementations of networked devices.

SCADA was initially designed to monitor and control industrial processes using proprietary serial protocols. It was typically kept isolated from other computer systems. However, SCADA ICS are now being connected with cooperate networks on the internet. This allows the convergence of many different network types (e.g. voice, data, video, physical security and control signals) onto a single network and can represent significant cost savings to a business. Many businesses have increased connectivity between the SCADA and corporate network in order to gain improved business and allow more informed decisions to be made, with no consideration for security of the SCADA and corporate systems. With an increased level of risk in the Internet Protocol (IP) world and the increasing interest in the security of control systems, it is important that asset owners understand the various IP-based solutions available in order to make an effective security based risk management decision.

Communication in SCADA can be inter-domain or intra domain. Inter-domain communications usually occur via wide-area network backhaul communications. Devices that are in the operations domain use the backhaul communications links to gather information for SCADA applications. However, for intra-domain communications, there are several options available, including fiber for greenfield installations and short-range wireless for existing installations. There are instances where information collected via these short-range links is transported to the SCADA master in the operations domain via backhaul communications links. Since SCADA data collection applications (DNP3 and Modbus) were originally designed for use with low-bandwidth serial data communications links, these were tolerant of long communications latencies with most likely deterministic delays due to direct link between Application layer and MAC layer. While in IP based SCADA, the higher data rates associated with wireless IP data links, or wired Ethernet networks, allow for lower communications latency, with naturally stochastic delay types. Latency requirements for a specific SCADA scheme depend on how many devices are being polled and the rate at which they need to be polled relative to control system response time requirements. The user can trade off wireless network size to achieve a desired response time for a given wireless network data rate. Wireless systems with higher throughput rates allow more flexibility with respect to network size and polling rates.

SCADA polling and response messages typically range from less than 100 bytes to around 350 bytes in length [3]. SCADA sampling rates can vary widely but are not usually faster than once a second or once every other second [3]. This results in an approximate upper bound on network loading of 100 to 350 bytes per second (800 to 2,800 bits per second [bps] per device being polled [3]. This does not account for wireless link protocol overhead and inefficiency in channel access, which may be equivalent to doubling the amount of data sent across the link, resulting in a total wireless network burden of about 1.6 to 5.6 kbps per SCADA device polling once per second. For less frequent polling intervals, the network load can be as much as ten times less than this upper bound [3].

Based on the above discussion, it can be concluded that:

- Wireless systems with very low data rate (throughput on the order of 10 kbps) will be able to support relatively small number of devices with a fast polling cycle, while support more devices with less frequent polling intervals.
- Wireless systems with throughput around 100 kbps should be able to handle a moderate number of devices with a fast polling rate and a large number of devices with a slower polling rate.
- Higher speed wireless networks with throughput around 1 Mbps or higher will be able to handle a large number of devices regardless of polling rate.

2.3 SCADA with Cellular Network Communication

In a cellular network, a given area is separated into individual cells, with each cell establishing its connection to a wireless transceiver. These cells are interconnected to cover long distances. Cellular networks have many distinct advantages over other forms of wireless data communication. For instance, cellular communications network and base station infrastructure being ubiquitous, allows greater system access while providing easy scalability. With high data speeds and low initial costs, it seems as if cellular communications would be the best-fit option for any application.

Advantages of cellular communications include the following:

- High data speeds.
- Longer link range when using existing networks.
- Easily scalable.
- Reduced efforts and costs associated with mounting antennas.

Disadvantages of cellular communications include the following:

- Ongoing operating expenses.
- Data overages.
- Network controlled by providers (customers have no control over the provider coverage area policies or prices).
- Delays can be non-deterministic and not guaranteed (depending on a network being public or private).

2.3.1 Cellular Network Performance in Denmark

Since the delay and other communication properties (such as packet loss etc.) in cellular networks are non-deterministic, it is worth exploring the exact range of these properties for analyzing the impact of using these networks to support frequency control and coordination from ReGen. In the following, the range of delays and packet loss probabilities is discussed, specifically for Denmark.

2.3.1.1 Information Collection and Description:

NetMap [5], [6] is used to obtain information about cellular technologies and their performance in terms of Round Trip-Times (RTTs) and measured signal strength [7]. NetMap is a crowd sourcing based system for performing and collecting measurements of cellular network connection performance. NetMap is exploiting the ubiquity of smartphones by having them perform and collect measurements of network performance using the cellular connection. This is done by having users install an app on their smartphones, acting as front-end client software, which handles the measurements and scheduling. The collected measurements are then submitted to the back end system, where measurements are collected and processed. NetMap is currently only deployed and measuring cellular networks in Denmark [5].

2.3.1.2 Measurement scenario

To understand the measurement results it is important to understand what is being measured. The NetMap setup consists of a front-end component and a back end component where the connection between is measured. The front-end component is an app on a smartphone with a cellular connection, and the back end component is a fixed measurement server, connected to the research network in Denmark. This means that the connection covers two types of connections: 1) the wireless cellular connection to the radio access network, and 2) the connection between radio access network and measurement server. The assumption is that the main influence to the network performance origins from the cellular connection in terms of delay and variance.

In Denmark there are three cellular networks (in reality four but two of them share cellular network resources) [8]. The three networks (referred to as **A**, **B** and **C** in Table 1 to Table 4) are connected to the same internet exchange point, Danish Internet Exchange (DIX) [8]. The measurement server is connected to the Danish research network, which also is connected DIX. This means that the performance of the different ISP networks can be compared because the measurements only differ in which ISP wireless and internal network they are performed on.

The devices that perform the measurements are regular consumer smartphones, which means that there are many factors that influence measurements. For instance, different applications on the devices consuming resources and utilizing the connection, as well as the mobility of measuring devices.

The measurements that are used in this context are round trip time (RTT) and signal strength measurements. RTT is measured using both UDP and TCP. A request packet is sent to the server that replies as fast as possible. The time between the request and the reply packets is logged as the RTT. Request/reply sequences are not overlapping and for TCP the connection handshake is done before the measurement is initiated. NetMap performs a set of measurements periodically, and for each period 20 RTT request/reply sequences are performed. The signal strength is logged for the currently active connection after the RTT measurement is done.

In the following, measurements from the three different ISP networks are presented, based on 2G, 3G and 4G technologies. These measurements are based on packet loss and RTT measured using 10 different devices. The measurements are based on around 3500 TCP-RTT measurement sequences at different distances/locations of the end devices from the communication masts of different ISPs, capturing almost entire Denmark (for details, see [5]). These measurements have been obtained over a period of one and a half year with varying number of end devices. In Table 1 to Table 4 the results of the measurements are summarized in terms of packet loss and minimum, middle and maximum RTTs based on the CDF. The minimum is found as when the CDF exceeds 10%, the middle as when the CDF exceeds 50%, and the maximum as when the CDF exceeds 90%.

Table 1 TCP RTTs measured using three cellular networks in Denmark

Cellular Network		**A**			**B**			**C**		
		RTT [ms]			**RTT [ms]**			**RTT [ms]**		
		Min.	Mid.	Max.	Min.	Mid.	Max.	Min.	Mid.	Max.
Technology	**2G**	100	135	260	160	220	375	150	165	265
	3G	40	215	320	40	60	90	40	265	415
	4G	25	30	40	25	35	70	30	60	95

Table 2 UDP RTTs measured using three cellular networks in Denmark

Cellular Networks		**A**			**B**			**C**		
		RTT [ms]			RTT [ms]			RTT [ms]		
		Min.	Mid.	Max.	Min.	Mid.	Max.	Min.	Mid.	Max.
Technology	2G	95	135	340	155	215	460	150	175	320
	3G	40	195	315	40	60	95	40	220	385
	4G	25	30	40	25	35	70	30	60	90

Table 3 Packet loss for TCP RTTs measured using three cellular networks in Denmark

Cellular Networks		**A**		**B**		**C**	
		No. of Pkts	P_{LOSS} [%]	No. of Pkts	P_{LOSS} [%]	No. of Pkts	P_{LOSS} [%]
Technology	**2G**	110100	8.9864	130760	11.8415	11200	8.8571
	3G	957440	3.0012	1282780	2.6680	411500	5.8233
	4G	1113400	0.3536	841100	0.9845	553280	1.5627

Table 4 Packet loss for UDP RTTs measured using three cellular networks in Denmark

Cellular Networks		**A**		**B**		**C**	
		No. of Pkts	P_{LOSS} [%]	No. of Pkts	P_{LOSS} [%]	No. of Pkts	P_{LOSS} [%]
Technology	**2G**	134260	17.2255	150260	18.2138	15160	17.7309
	3G	988120	7.5207	1335660	14.3146	436280	11.1092
	4G	1147620	1.6073	886540	1.8816	568160	1.5710

3 Use Case and Test Scenarios

With regards to the use case as well as test scenarios, following considerations/assumptions are made in this report:

- As a part of power production from ReGen plants, only WPP generation is considered. The contribution from other renewable sources (such as PVP) is also important; however, it is left for future research.
- Out of the total generation capacity, wind energy is around 45% [9]. For this report, the wind power penetration is set to contribute 50% of the total generation. The rest of power generation is contributed from steam, hydro and nuclear power plants, respectively.
- There are three WPPs connected to the power system. These WPPs are divided into following 3 groups with equal share of power generation, see Table 5:

Table 5. Size and Share of Three WPPs Connected to the Power System

WPP type	Size	Size in MW	Contribution
Offshore	Large	Above 100	33%
Onshore	Medium	50 – 100	33%
	Small	<25 – < 50	33%

- When kinetic energy of a wind turbine is used, there can be a reduced active power output at the recovery period depending on the wind speed [10]. Therefore, two different wind speeds (7 and 14 m/s) are selected to test the impact of communication on frequency control support from WPPs. Here 7m/s is the wind speed corresponding to partial loads in the WT, while 14 m/s is the wind speed corresponding to full loading (full power production). (for details of these wind speeds, see [2])
- Tests cases are only based on uniform wind speeds on all WPPs.

Table 6. Wind Speeds for Test Cases

	Wind Power Plants		
	Offshore	Onshore	
		Medium	Small
Wind Speeds (m/s)	7	7	7
	14	14	14

- As in [11], two kinds of network connections can be employed i.e. private or public (for details of both connections, see [11]). For the offshore WPPs, the network connection is set to be private, so that a fixed deterministic delay as well as other communication properties can be guaranteed.
- While for the onshore WPPs, both private as well as public network connections are considered in the test cases (see Table 7).
- As an ideal case, a test scenario with all private connections is considered to guarantee fixed deterministic latency in communication.

Table 7. Test Scenarios based on Network Connections

	Wind Power Plants		
	Offshore	Onshore	
		Medium	Small
Network Connections	Private	Private	Private
	Private	Private	Public
	Private	Public	Public

4 Evaluation Criteria – Key Performance Parameter (KPI)

The results of each test scenario will be discussed and evaluated with regards to the following three important frequency metrics for the operation of a power system (see Figure 2) [2]:

- **Frequency Nadir (f_{Nadir}):** It describes the minimum point reached by the frequency after a disturbance (see Figure 2). This metric is important as too low values might trigger protection devices. An improved frequency response should therefore increase the frequency nadir, i.e. reduce the maximum frequency deviation. Due to the under-frequency load shedding limits, the value of f_{Nadir} is fixed around 800 mHz in systems with 50 Hz operational frequency [12], while it is 900 mHz in systems with 60 Hz operational frequency [12].
- **Time to reach frequency nadir (T_{Nadir}):** It is related to the system inertia. The earlier the nadir is reached, the more energy is released directly after the disturbance. It is, therefore, preferable to reduce T_{Nadir} (see Figure 2), as it can also have an impact on primary and secondary control.
- **Time to reach steady state frequency ($T_{SteadyState}$):** Since the goal of primary frequency control is to contain the frequency to a new steady state after the disturbance and thereby reduce the dynamic part of the response, a quicker return to steady state is favourable. Therefore, an improvement in the frequency support is indicated by a smaller value of $T_{SteadyState}$ (see Figure 2).

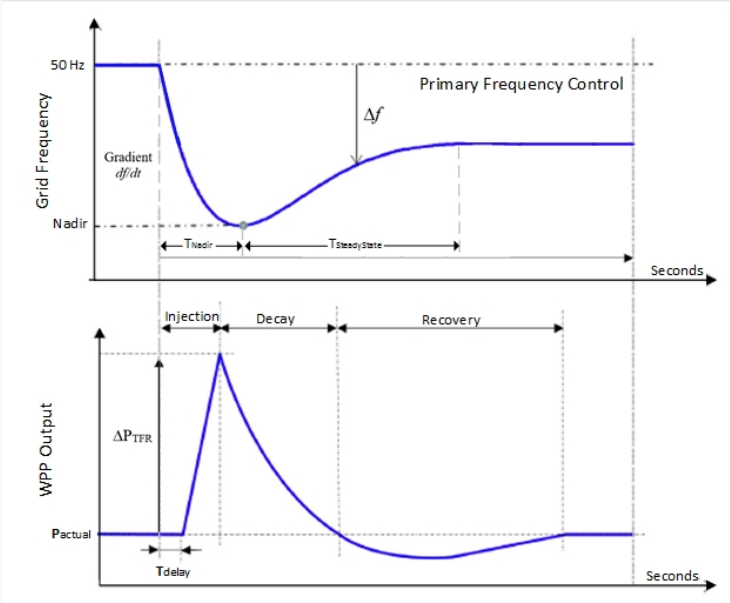


Figure 2. Reference frequency and output power shapes of WPP [2]

5 Evaluation Setup and Test Cases

5.1 Power System Simulation Model

The power system model developed for online frequency control coordination in [2] is used as such. The only modifications are the addition of a simulation model for communication network. This is shown in Figure 3.

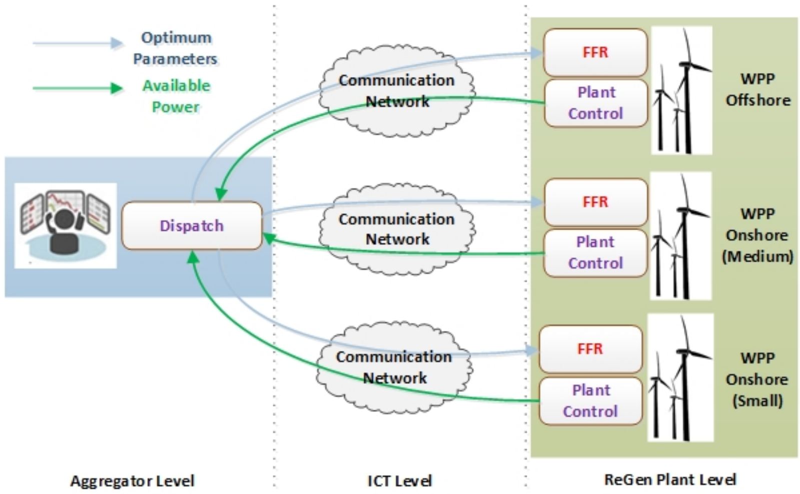


Figure 3. Simulation Model with three distinct levels.

5.2 Communication model

Typically, to understand network behavior or the impact of delay on information, a simple transport layer delay is used. However, in reality there's much more on top of a simple delay by which a signal might be effected. For instance, as discussed in Section 2, while considering public networks as a means of coordination between ReGen plants and the system operators (TSO/DSO), a constant delay or packet loss cannot be guaranteed. It is, therefore, necessary to see how different network conditions (in terms of higher delays or packet drops) affect the performance of a signal. For this, a network simulator is developed (see Figure 4) that uses the traces (based on delay etc.) from a real network and shapes the information accordingly (for details, see [13]). For this report, the delay traces are obtained using NetMap, as discussed in Section 2.

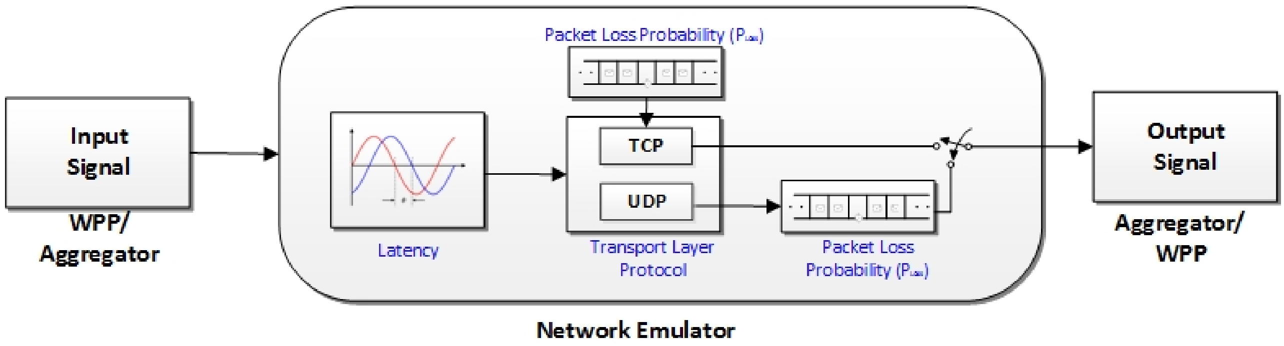


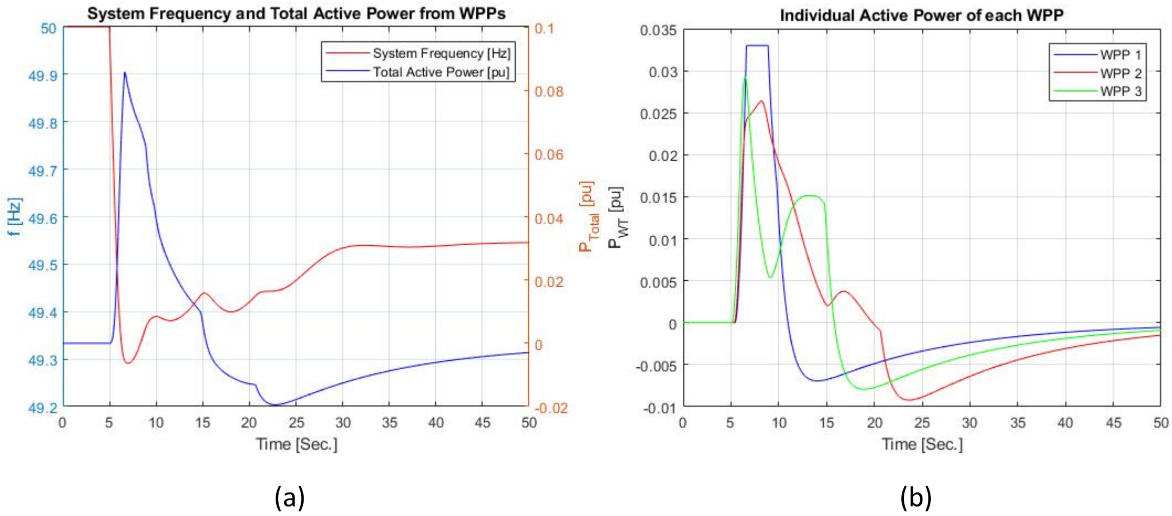
Figure 4. Communication Model Used for Evaluation of Online Frequency Support from ReGen [13]

5.3 Reference Case

In [2], results related to frequency response and power output of WPPs were obtained through optimized parameters without any communication model. Those results were based on uniform as well as non-uniform wind speeds. However, for this report, the tests cases are only based on uniform wind speeds (i.e. 7 and 14 m/s, see Section 3). Therefore, the results based on uniform wind speeds in [2] are considered as reference and used to evaluate the deviation from optimum frequency control coordination due to added latencies.

5.3.1 Partial Loads

Figure 5(a) shows the system frequency and total active power from WPPs, while Figure 5(b) shows the active power from individual WPP at partial loads which corresponds to an average wind speed of 7 m/s.

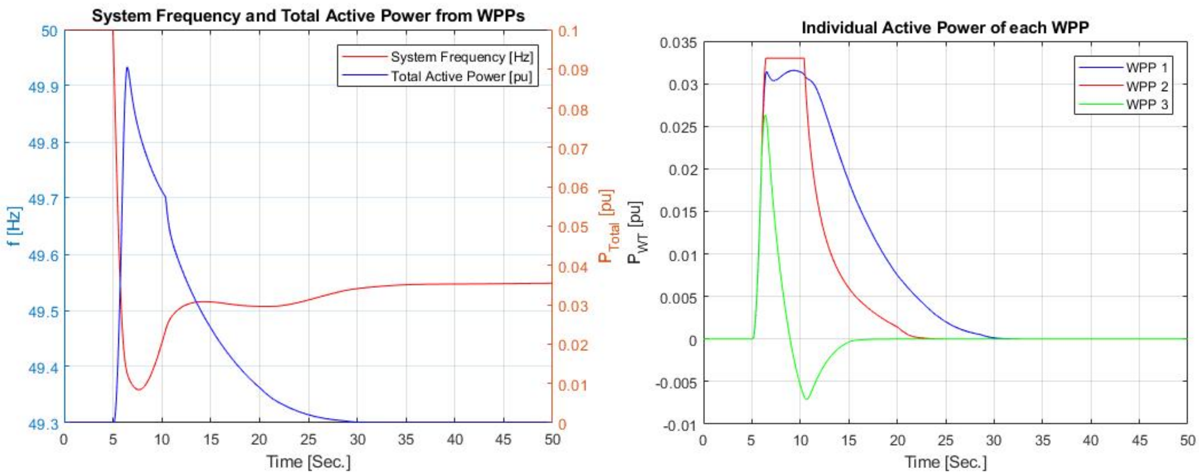


(a) (b)

Figure 5. Reference (a) System Frequency and Total Active Power from WPPs (b) Individual Active Power from WPPs at partial loads

5.3.2 Full Loads

Figure 6(a) shows the system frequency and total active power from WPPs, while Figure 6(b) shows the active power from individual WPP at high wind speed (14 m/s).



(a) (b)

Figure 6. Reference (a) System Frequency and Total Active Power from WPPs (b) Individual Active Power from WPPs at full loads

5.4 Test cases

For each test scenario described in Table 7, two tests are considered based on the inclusion of a communication network i.e. a) with standard communication parameters (specifically delay), and b) with higher delays in case of public networks due to cross traffic and/or network congestion etc.

5.4.1 Test Case 1 – Standard Communication

As in a private network, there is a full control over the network traffic and a constant delay can be guaranteed, therefore, a fixed standard delay of 10ms is considered. However, in case of public networks, a constant delay cannot be guaranteed (as seen in section 2), thus the delay traces from a real network are used instead. Combining the results of delay traces obtained from NetMap (see Figure 7), it can be concluded that the information packet is delayed around 15ms (30 ms TCP RTT) for the maximum times.

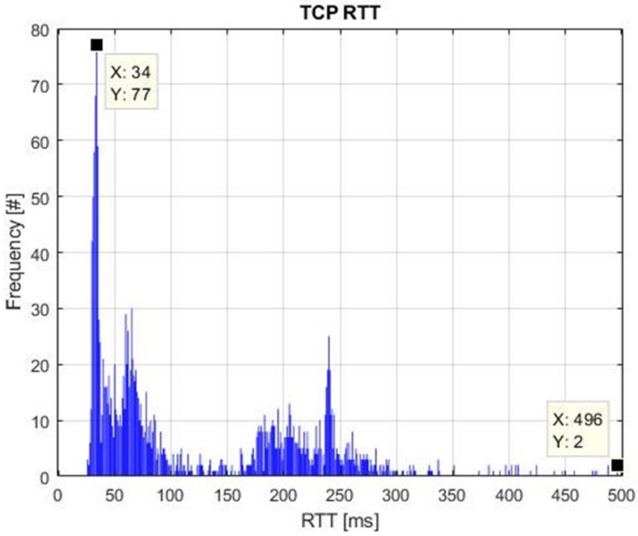


Figure 7 Distribution of TCP-RTT traces measured using NetMap.

5.4.2 Test Case 2 – Higher delays

For higher delays in communication, three different delays are considered on top of standard communication delays, i.e. **100ms**, **500ms** and **1s** to observe the deviation of frequency response from the one obtained from optimum parameters. The 1 second delay in communication is considered to be the minimum delay that incurs in case of a failure at a communication mast level etc.

6 Test Results – Impact of Communication Properties on On-Line Frequency Control Coordination

In the following, system frequency reference cases considered in Section 5.3 are compared with those obtained under different delay conditions to get an understanding of how much a network delay may affect the system frequency response. The individual system frequency, total active power as well as individual active power of each WPP under the three test scenarios (defined in Table 7) in combination with the two wind speeds (defined in Table 6) are provided in **Appendix A**.

6.1 Test Scenario 1

6.1.1 Partial Load

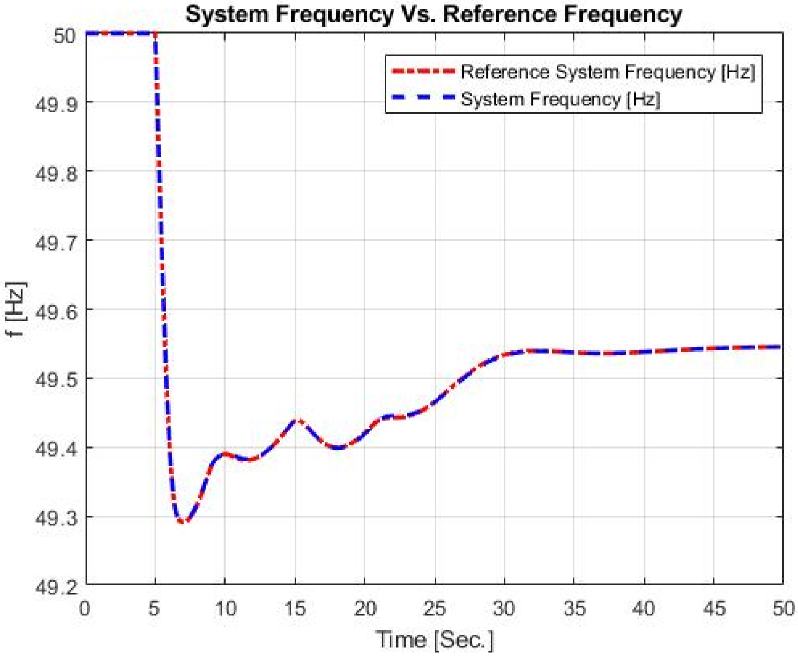


Figure 8. System Frequency Compared to the Reference Frequency at Partial Load

6.1.2 Full Load

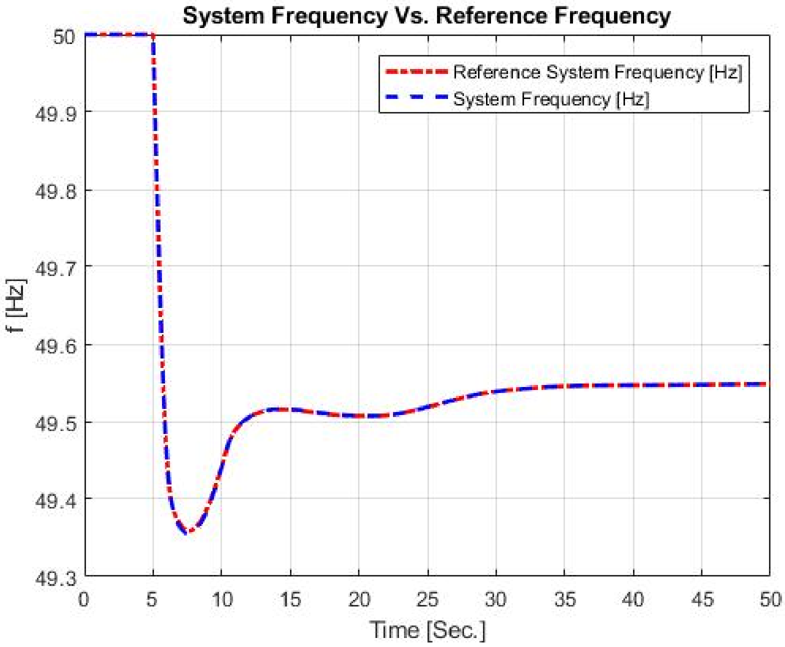


Figure 9. System Frequency Compared to the Reference Frequency at Full Load

6.1.3 Comparison

Table 11 summarizes, for partial load and full load, the difference of f_{Nadir}, T_{Nadir} and $T_{SteadyState}$ from the one obtained as reference in Section 5.3

Table 8. Comparison of System Frequency KPIs with that of Reference Frequency

		Test Scenario 1	
		Partial Load	Full Load
Frequency Nadir [Hz.]	Reference	49.31	49.35
	Normal Comm.	49.31	49.35
T_{Nadir} [Sec.]	Reference	6.95	7.618
	Normal Comm.	6.95	7.618
$T_{SteadyState}$ [Sec.]	Reference	40	40
	Normal Comm.	40	40

It can be noted that with private network connections between WPPs and control center (aggregator/TSO), all performance metrics match with that of the reference metrics.

6.2 Test Scenario 2

6.2.1 Partial Load

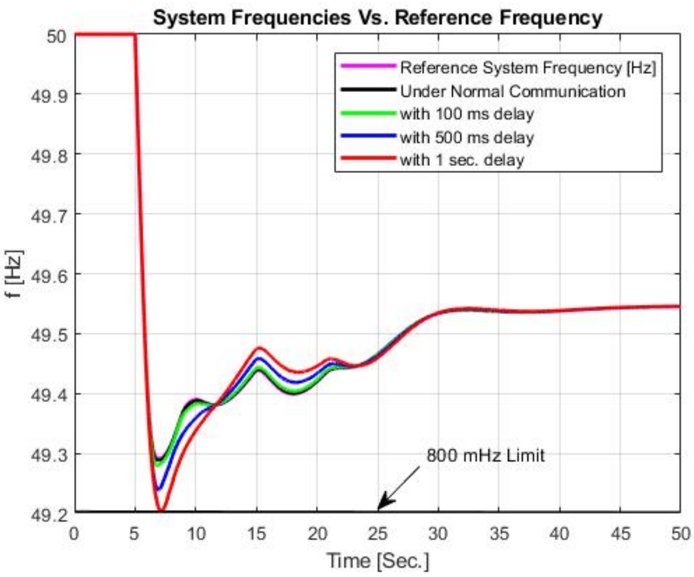


Figure 10. System Frequency under different delay conditions compared to the Reference Frequency at Partial Load

Based on the results shown in Figure 28 it can be concluded that the frequency nadir is decresing with an increase in communication delays in public networks. The frequency limit of 800 mHz is reached for delays of around 1 sec.

6.2.2 Full Load

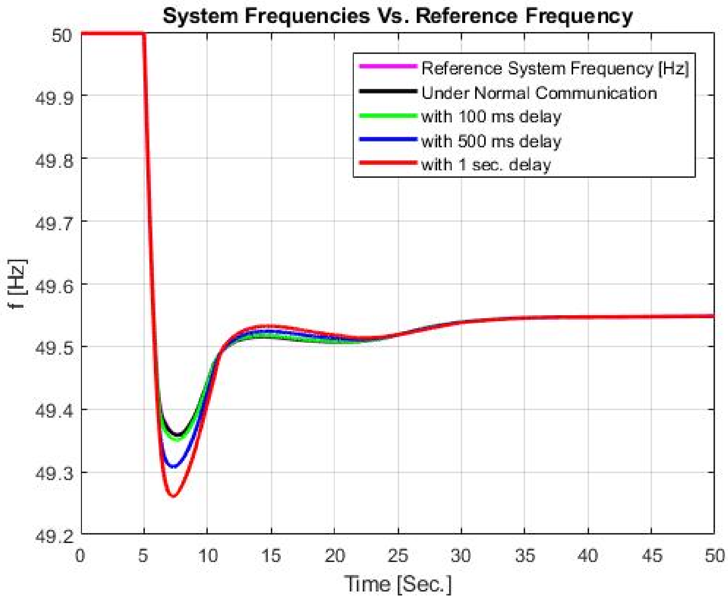


Figure 11. System Frequency under different delay conditions compared to the Reference Frequency at Full Load

In this case again by increasing communication delays the frequency nadir is lowered as well as the time to reach it.

6.2.3 Comparison

Table 12 summarizes for partial load and full load the difference of each f_{Nadir} as well as T_{Nadir} from the one obtained as reference in Section 5.3 in terms of Δf_{Nadir} and ΔT_{Nadir}, respectively. Where, Δf_{Nadir} and ΔT_{Nadir} are given as:

$$\Delta f_{Nadir}[mHz] = f_{Nadir,Reference} - f_{Nadir,WithDelay}$$

And,

$$\Delta T_{Nadir}[mSec.] = T_{Nadir,Reference} - T_{Nadir,WithDelay}$$

Table 9. Comparison of System Frequency KPIs with that of Reference Frequency

		Test Scenario 2	
		Partial Load	Full Load
Reference $f_{Nadir}[Hz]$		**49.29**	**49.36**
Δf_{Nadir} $[mHz]$	Normal Comm.	0	0
	With 100ms delay	10	10
	With 500ms delay	50	50
	With 1 sec. delay	90	100
Reference $T_{Nadir}[Sec.]$		**6.95**	**7.5**
ΔT_{Nadir} $[mSec.]$	Normal Comm.	0	0
	With 100ms delay	150	0

	With 500ms delay	20	250
	With 1 sec. delay	-210	280

It is also pertinent to mention here that, the values of $T_{SteadyState}$ remains the same for all cases, as clear from Figure 28 and Figure 29.

6.3 Test Scenario 3

6.3.1 Partial Load

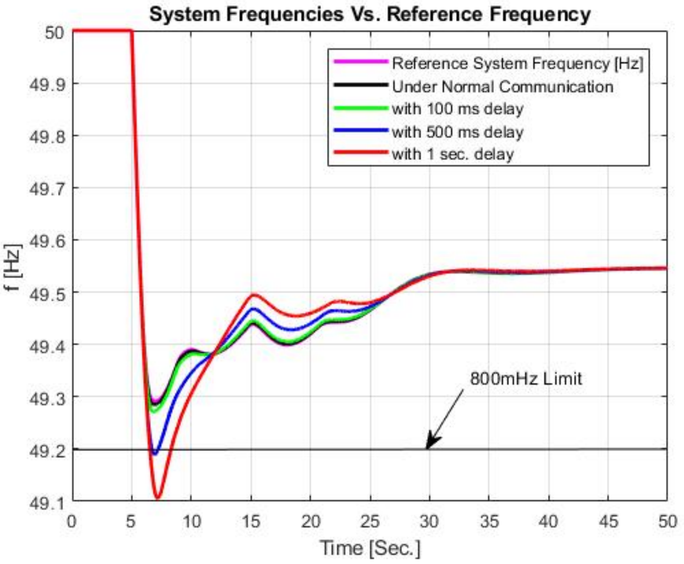


Figure 12. System Frequency under different delay conditions compared to the Reference Frequency at Partial Load

6.3.2 Full Load

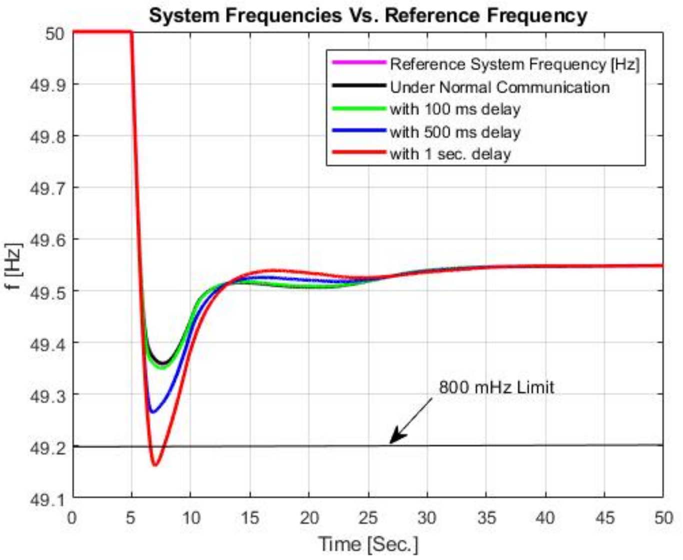


Figure 13. System Frequency under different delay conditions compared to the Reference Frequency at Full Load

6.3.3 Comparison

As in Section 7.2.3, Table 13 summarizes for partial load and full load the difference of each f_{Nadir} as well as T_{Nadir} from the one obtained as reference in Section 5.3 in terms of Δf_{Nadir} and ΔT_{Nadir}, respectively (already defined in Section 7.2.3).

Table 10. Comparison of System Frequency KPIs with that of Reference Frequency

		Test Scenario 3	
		Partial Load	Full Load
Reference $f_{Nadir}[Hz]$		**49.29**	**49.36**
Δf_{Nadir} $[mHz]$	Normal Comm.	0	0
	With 100ms delay	20	10
	With 500ms delay	100	90
	With 1 sec. delay	180	200
Reference $T_{Nadir}[Sec.]$		**6.95**	**7.5**
ΔT_{Nadir} $[mSec.]$	Normal Comm.	0	0
	With 100ms delay	170	-10
	With 500ms delay	30	700
	With 1 sec. delay	-240	500

As in Test Scenario 2, the values of $T_{SteadyState}$ remain the same for all cases, (see Figure 30 and Figure 31), therefore not included in the table.

This test case reveals that having a large share of ReGen plants on public communication networks is degrading the overall optimum response of grid frequency. Both frequency nadir and time to reach it are decreasing when increasing delays. The load shedding limit of 49.2 Hz is exceeded for delays of 1 sec.

7 Conclusion and Recommendations

This technical report is assessing the impact of Information and Communication Technologies on the frequency control support (FFR) from ReGen plants, with special focus on wind power plants. Considerations on main characteristics of delays in public and private networks are shown using real measurements. A coordination scheme for FFR including parameters as proposed in [2] is considered for analysis. Two operating conditions of wind power plants are taken into consideration namely partial and full load respectively. Various delays according to statistical measurements on traffic are also considered.

The study reveals the following:

- Communication delays are having a large impact on the overall response of ReGen plants on system frequency. Frequency nadir and time to reach it are decreasing when increasing the delays.
- Public networks are more prone to affect the overall frequency response due to stochastic nature of the delays compared to private ones where the delays are fixed and have low values.
- Communication delays and their mechanisms must be considered in the design process of the proposed coordinated frequency control in [2]

Based on the findings of this study the following recommendations are made:

- Design and tuning methodology for frequency control must account for the delays in ICT especially when using public networks
- Coordination and activation of ReGen plants for provision of frequency control must account for the ICT delays

In order to get more insight on the impact of ICT on fast frequency response additional work is required as:

- Account for a realistic power system model that takes into account transmission lines and ReGen plants location and thus a realistic mapping of ICT layer
- Consider other control schemes and coordination methods in-line with the new ENTSO-E recommendations given in [14]

8 References

[1] Dr. B. Kalyan Kumar, *Power System Stability and Control*. Department of Electrical Engineering, Indian Institute of Technology Madras, Chennai, India.

[2] Müfit Altin, Junjie Hu, and Anca D. Hansen, "Frequency stability control support from ReGen plants," Aug. 2017.

[3] Steve T. Watt, Henry Loehner, Shankar V. Achanta, Andy Kivi, and Ben Rowland, "Extending SCADA Networks Using Wireless Communications," presented at the 2nd Annual PAC World Americas Conference Raleigh, North Carolina, 2015.

[4] "Trends in SCADA: New technologies and adaptive processes." [Online]. Available: http://processonline.com.au/content/process-control-systems/article/trends-in-scada-new-technologies-and-adaptive-processes-867485507.

[5] "NetMap - Website." [Online]. Available: http://info.iet.unipi.it/~luigi/netmap/.

[6] L. M. Mikkelsen, S. R. Thomsen, M. S. Pedersen, and T. K. Madsen, "NetMap - Creating a Map of Application Layer QoS Metrics of Mobile Networks Using Crowd Sourcing," in *Internet of Things, Smart Spaces, and Next Generation Networks and Systems*, vol. 8638, S. Balandin, S. Andreev, and Y. Koucheryavy, Eds. Cham: Springer International Publishing, 2014, pp. 544–555.

[7] M. Lauridsen, I. Rodriguez, L. M. Mikkelsen, L. C. Gimenez, and P. Mogensen, "Verification of 3G and 4G received power measurements in a crowdsourcing Android app," 2016, pp. 1–6.

[8] "DIX - Danish Internet eXchange point." [Online]. Available: http://www.dix.dk/.

[9] "Energinet.dk." [Online]. Available: https://energinet.dk:443/.

[10] G. C. Tarnowski, *Coordinated frequency control of wind turbines in power systems with high wind power penetration: PhD thesis*. Kgs. Lyngby: Department of Electrical Engineering, Technical University of Denmark, 2011.

[11] "D1.2 - Technical Feasibility of Ancillary Services provided by ReGen plants," DTU Wind Energy E-0099.

[12] M. Altin, *Dynamic frequency response of wind power plants*. Aalborg: Aalborg University, Department of Energy Technology, 2012.

[13] Florin Iov, Kamal Shahid, Lennart Petersen, and Rasmus Løvenstein Olsen, "Verification of ancillary services in large scale power system."

[14] "Rate of Change of Frequency (RoCoF) withstand capability. ENTSO-E guidance document for national implementation for network codes on grid connection." ENTSO-E, Jan-2018.

9 Appendix A – Detailed Results of Each Test Scenario

In this appendix, system frequency, total active power as well as individual active power of each WPP under the three test scenarios (defined in Table 7) in combination with the two wind speeds (defined in Table 6) are shown based on the test cases defined in Section 5.

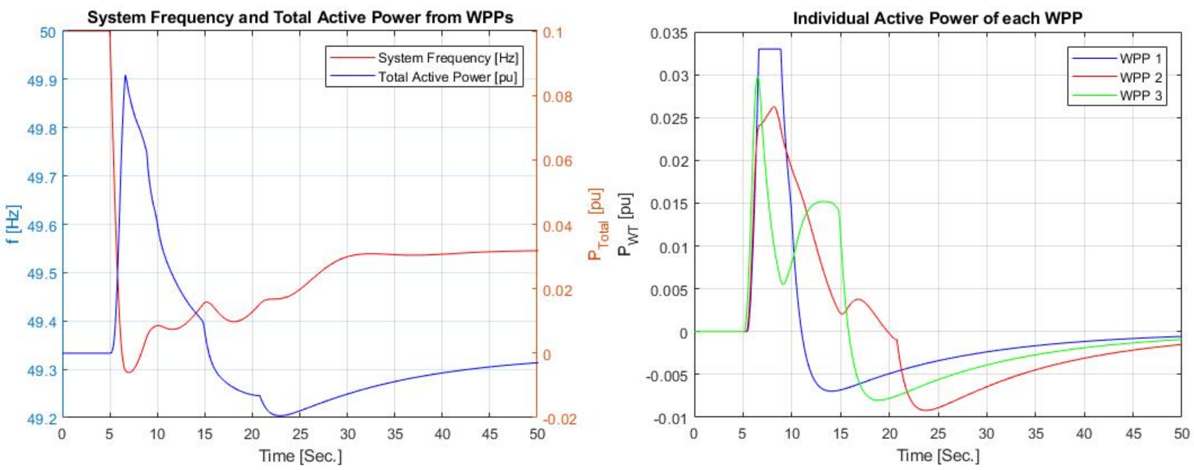
9.1 Test Scenario 1: Ideal Case

Table 11. Test Scenario with all Private Network Connections – Ideal Case

	Wind Power Plants		
	Offshore	**Onshore (Medium)**	**Onshore (Small)**
Network Connection	Private	Private	Private
Wind Speeds (m/s)	7	7	7
	14	14	14

9.1.1 Impact of Standard Communication

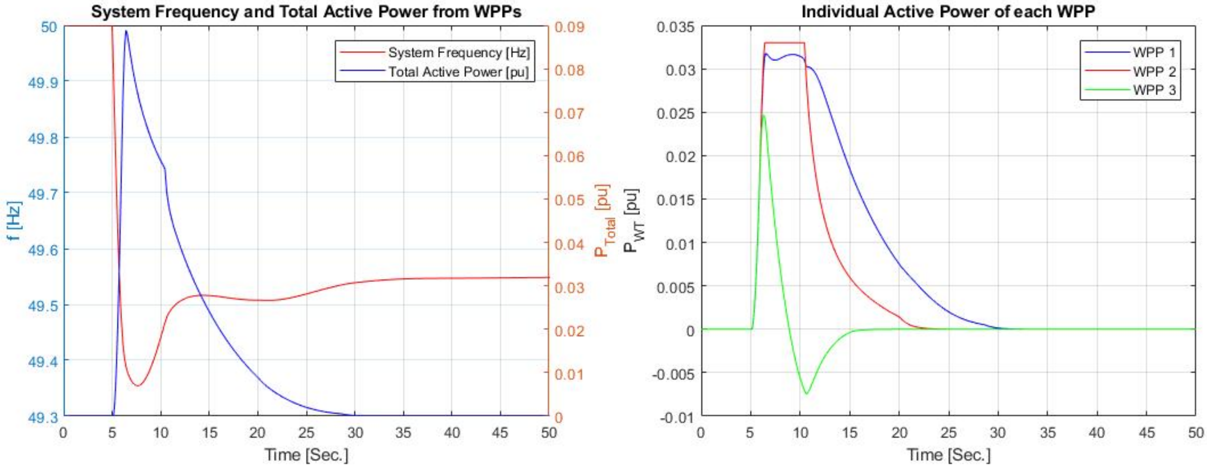
9.1.1.1 Partial Load



(a) (b)

Figure 14. (a) System Frequency and Total Active Power from WPPs, (b) Individual Active Power from WPPs at Partial Load with Standard Communication

9.1.1.2 Full Load



(a) (b)

Figure 15. (a) System Frequency and Total Active Power from WPPs, (b) Individual Active Power from WPPs at Full Load with Standard Communication

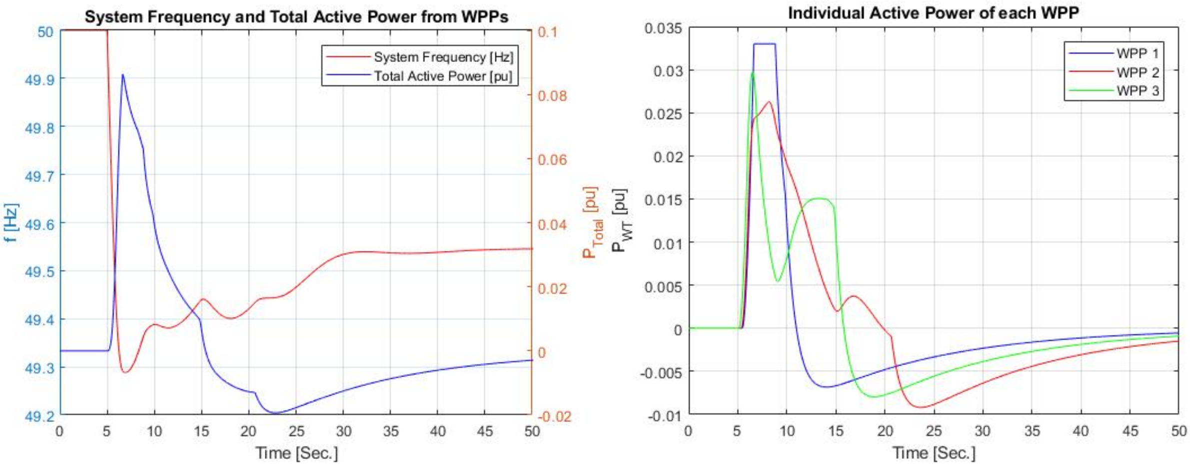
9.2 Test Scenario 2:

Table 12. Test Scenario with Public Network Connection for Small Onshore WPPs

	Wind Power Plants		
	Offshore	**Onshore (Medium)**	**Onshore (Small)**
Network Connection	Private	Private	Public
Wind Speeds (m/s)	7	7	7
	14	14	14

9.2.1 Impact of Standard Communication

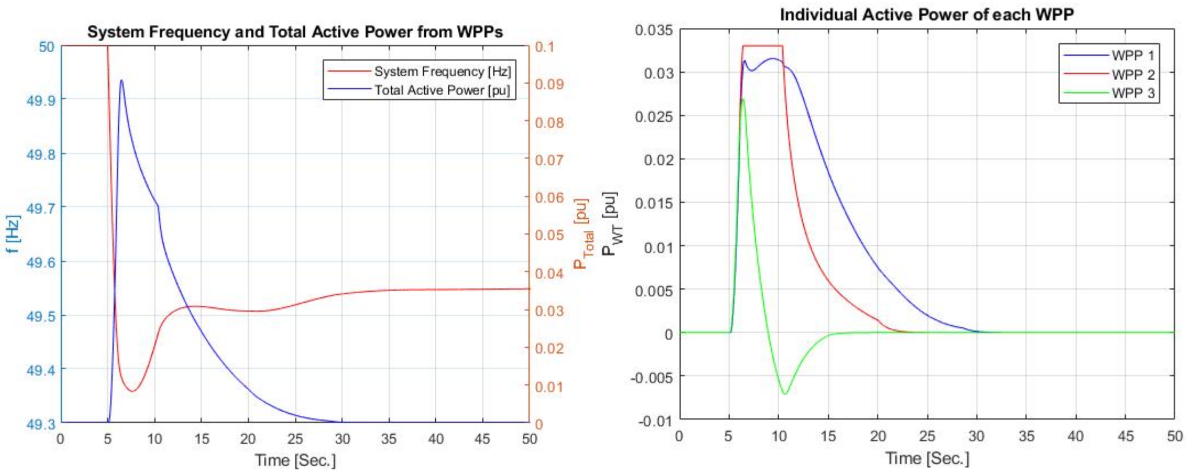
9.2.1.1 Partial Load



(a) (b)

Figure 16. System Frequency and Total Active Power from WPPs, (b) Individual Active Power from WPPs at Partial Load with Standard Communication

9.2.1.2 Full Load



(a) (b)

Figure 17. System Frequency and Total Active Power from WPPs, (b) Individual Active Power from WPPs at Full Load with Standard Communication

9.2.2 Impact of Delays in Communication

9.2.2.1 Partial Load

9.2.2.1.1 Delay of 100 ms in Standard Communication

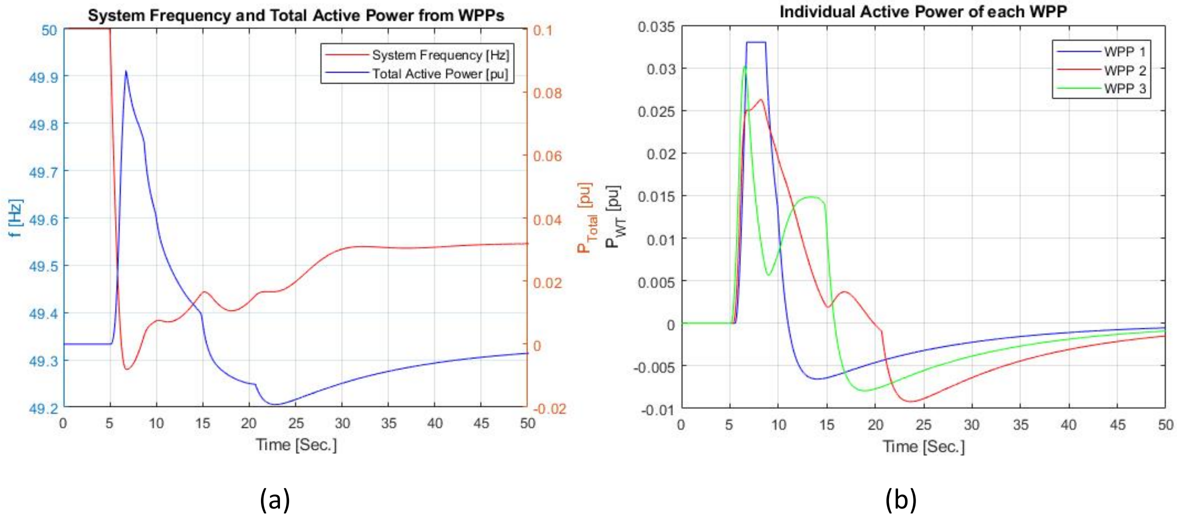


Figure 18. System Frequency and Total Active Power from WPPs, (b) Individual Active Power from WPPs at Partial Load with 100ms delay in Standard Communication

9.2.2.1.2 Delay of 500 ms in Standard Communication

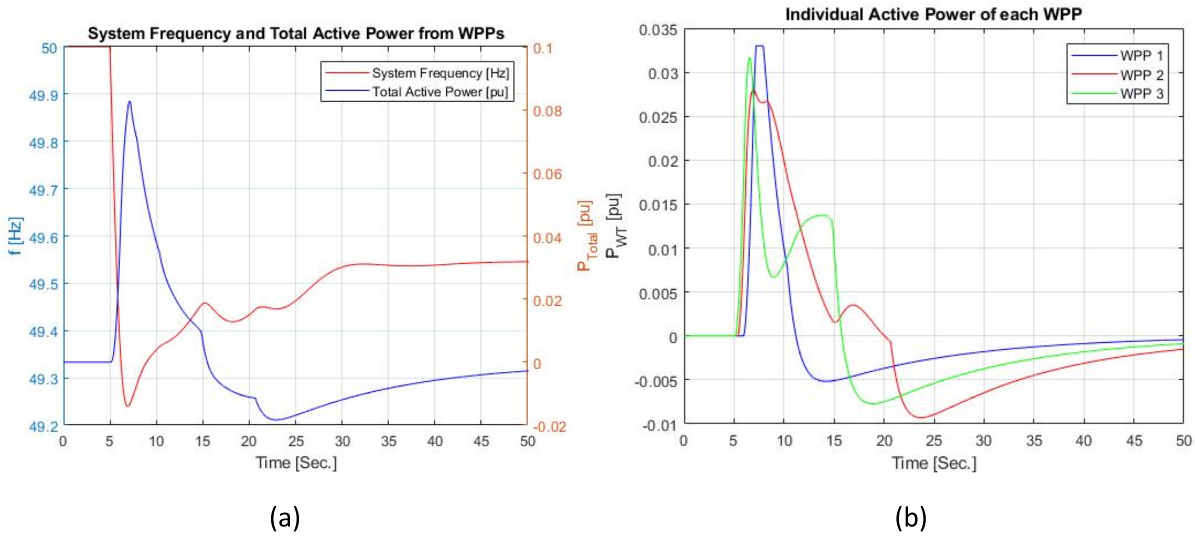
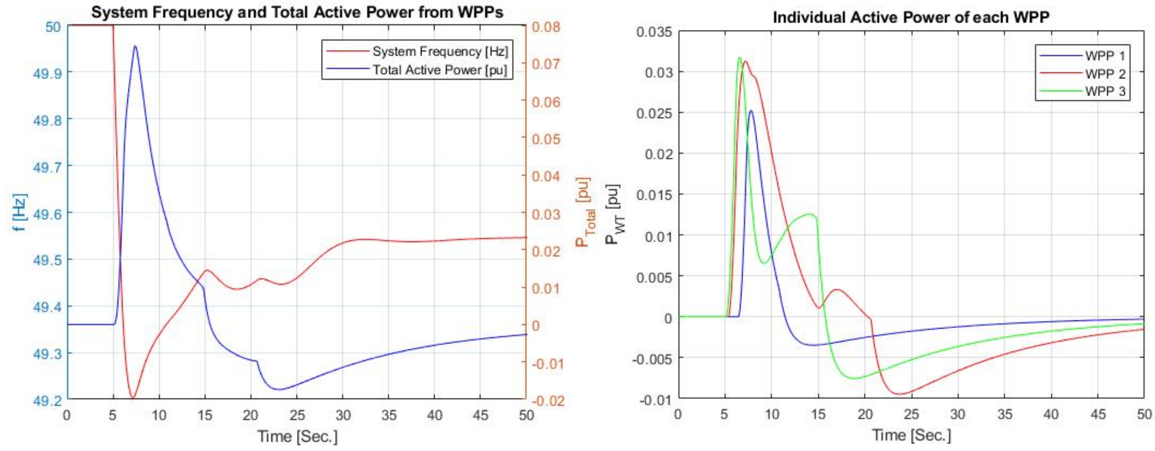


Figure 19. System Frequency and Total Active Power from WPPs, (b) Individual Active Power from WPPs at Partial Load with 500ms delay in Standard Communication

9.2.2.1.3 Delay of 1 Second in Standard Communication

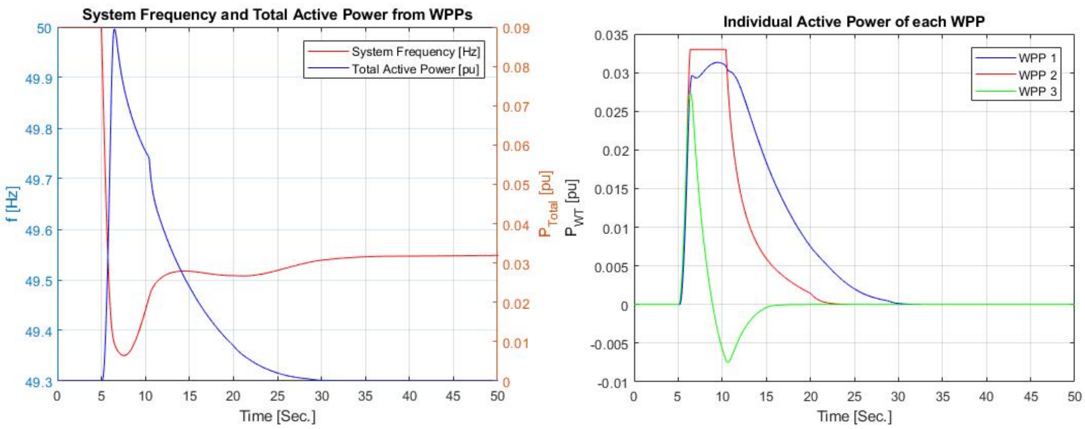


(a) (b)

Figure 20. System Frequency and Total Active Power from WPPs, (b) Individual Active Power from WPPs at Partial Load with 1s delay in Standard Communication

9.2.2.2 Full Load

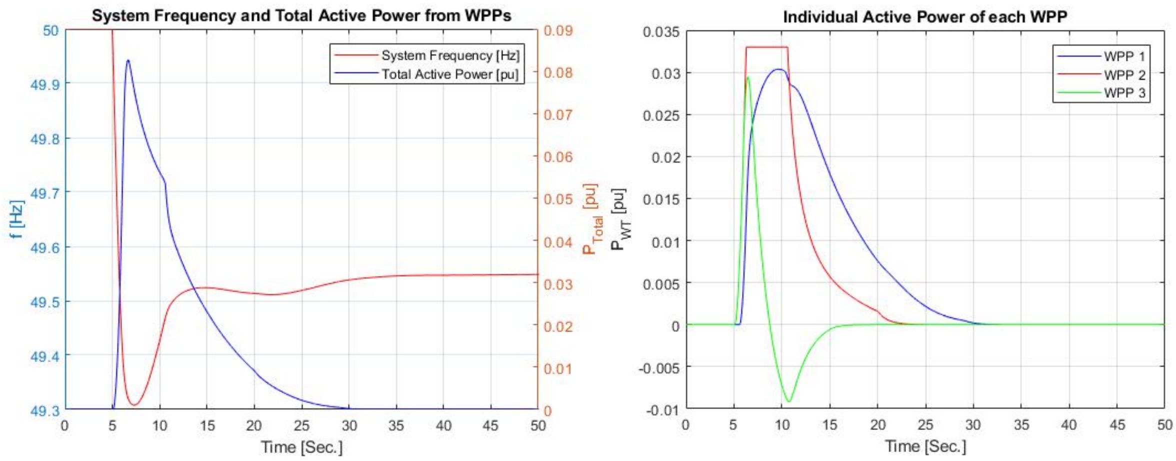
9.2.2.2.1 Delay of 100 ms in Standard Communication



(a) (b)

Figure 21. System Frequency and Total Active Power from WPPs, (b) Individual Active Power from WPPs at Full Load with 100ms delay in Standard Communication

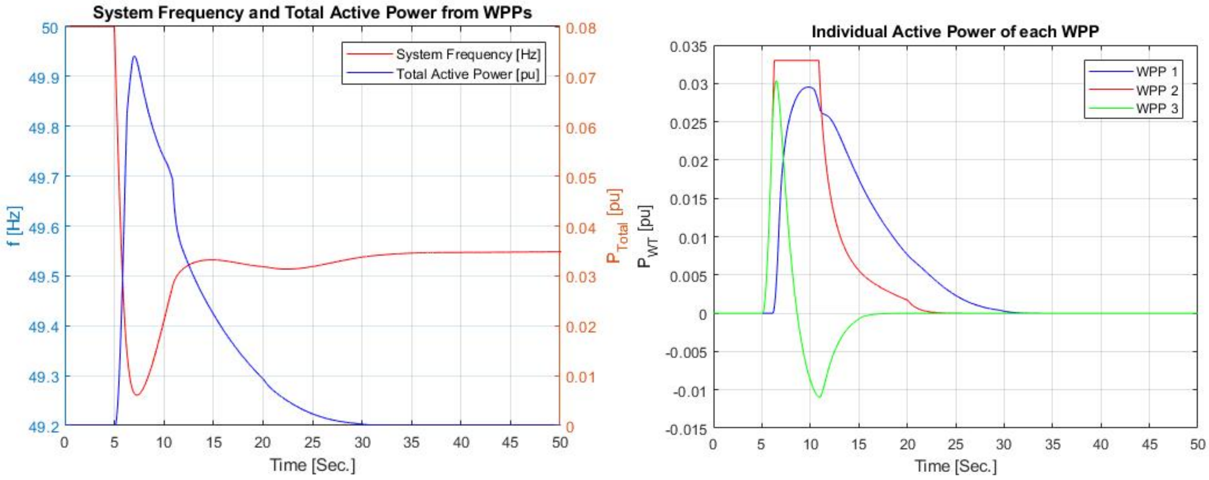
9.2.2.2.2 Delay of 500 ms in Standard Communication



(a) (b)

Figure 22. System Frequency and Total Active Power from WPPs, (b) Individual Active Power from WPPs at Full Load with 500ms delay in Standard Communication

9.2.2.2.3 Delay of 1 Second in Standard Communication



(a) (b)

Figure 23. System Frequency and Total Active Power from WPPs, (b) Individual Active Power from WPPs at Full Load with 1s delay in Standard Communication

9.3 Test Scenario 3:

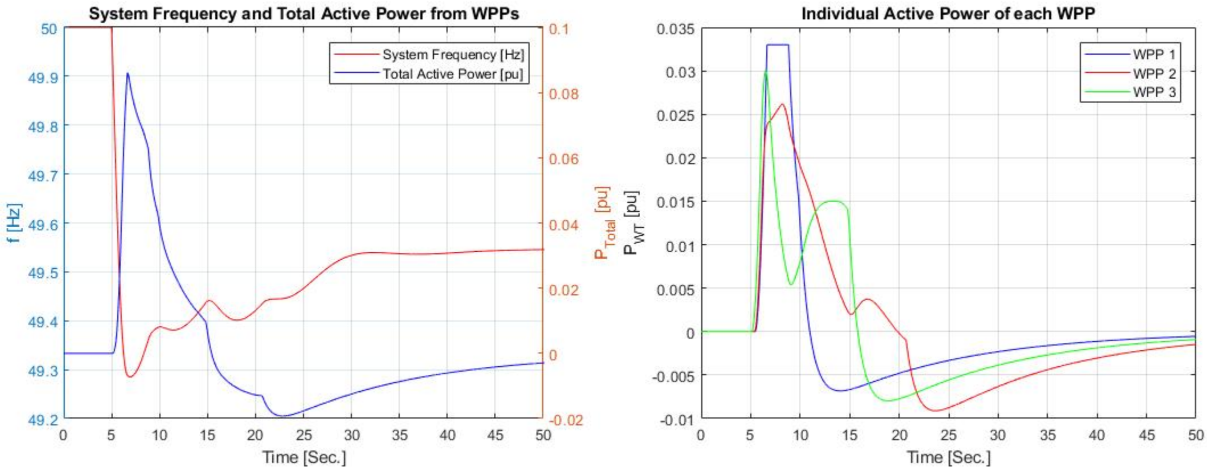
Table 13. Test Scenario with Public Network Connections for both Onshore WPPs

	Wind Power Plants		
	Offshore	**Onshore (Medium)**	**Onshore (Small)**

Network Connection	Private	Public	Public
Wind Speeds (m/s)	7	7	7
	14	14	14

9.3.1 Impact of Standard Communication

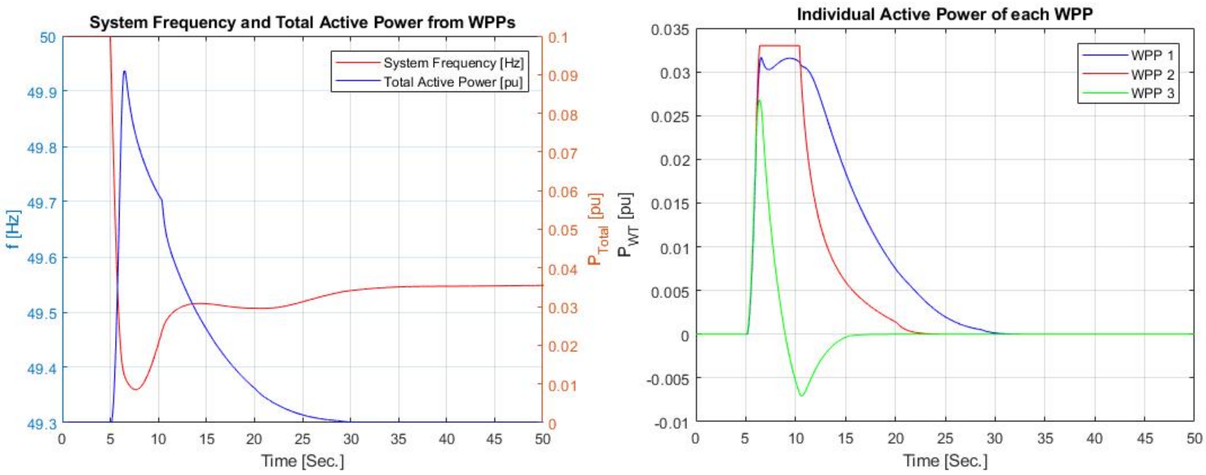
9.3.1.1 Partial Load



(a) (b)

Figure 24. System Frequency and Total Active Power from WPPs, (b) Individual Active Power from WPPs at Partial Load with Standard Communication

9.3.1.2 Full Load



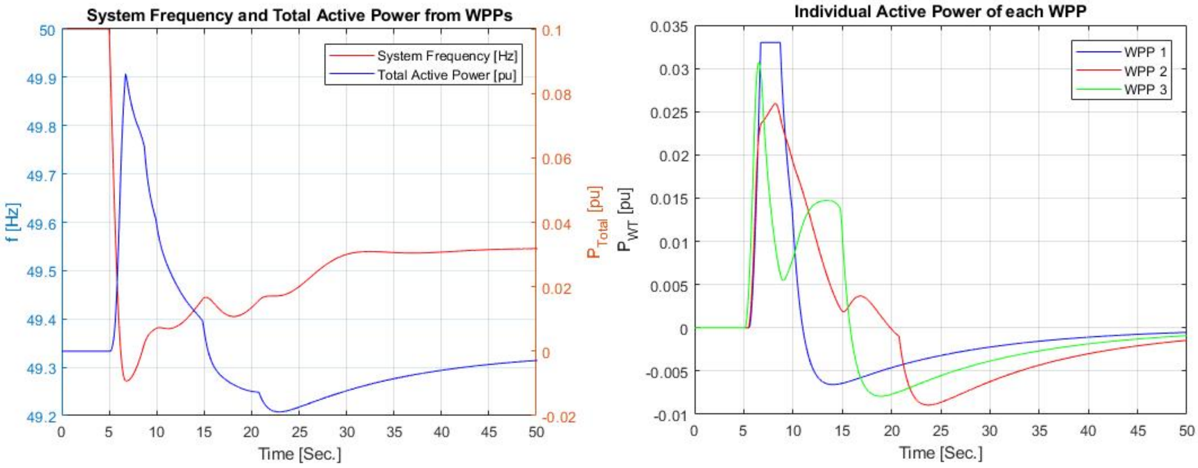
(a) (b)

Figure 25. System Frequency and Total Active Power from WPPs, (b) Individual Active Power from WPPs at Full Load with Standard Communication

9.3.2 Impact of Delays in Communication

9.3.2.1 Partial Load

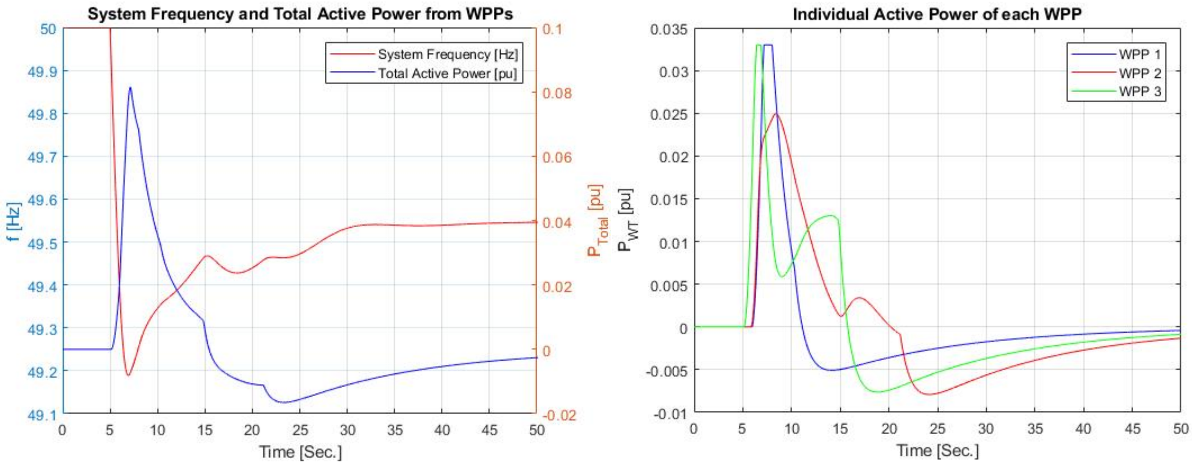
9.3.2.1.1 Delay of 100 ms in Standard Communication



(a) (b)

Figure 26. System Frequency and Total Active Power from WPPs, (b) Individual Active Power from WPPs at Partial Load with 100ms delay in Standard Communication

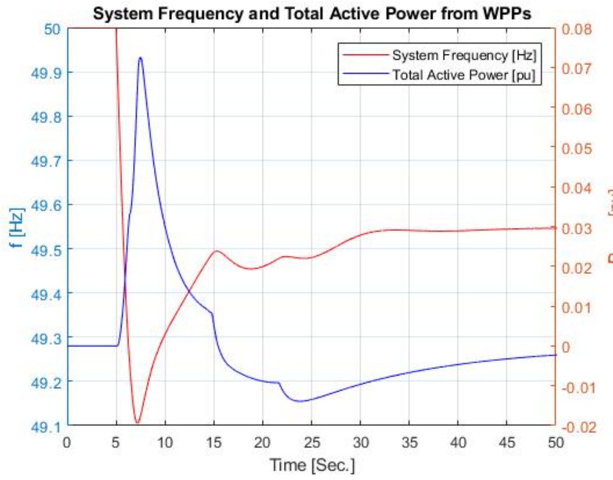
9.3.2.1.2 Delay of 500 ms in Standard Communication



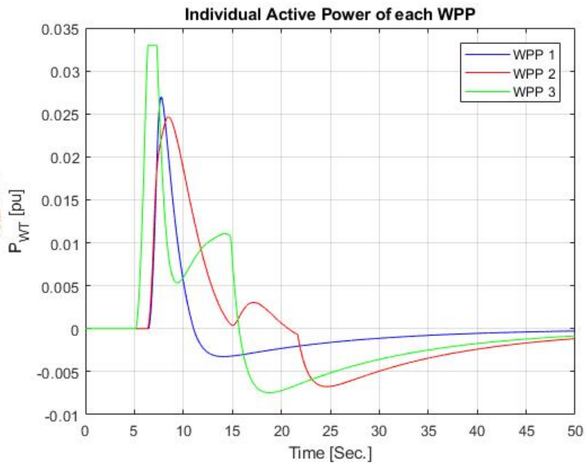
(a) (b)

Figure 27. System Frequency and Total Active Power from WPPs, (b) Individual Active Power from WPPs at Partial Load with 500ms delay in Standard Communication

9.3.2.1.3 Delay of 1 Second in Standard Communication



(a)

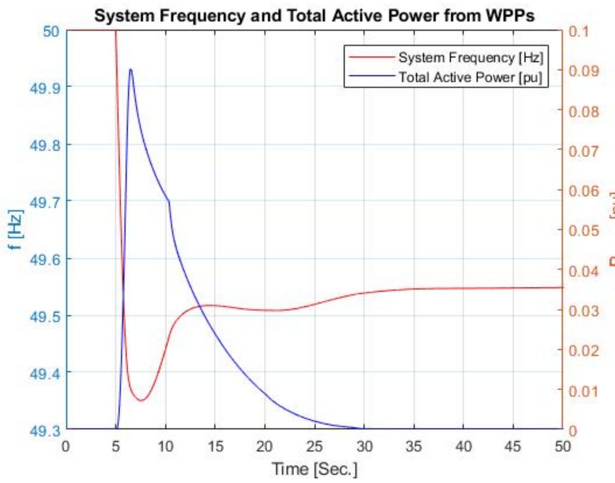


(b)

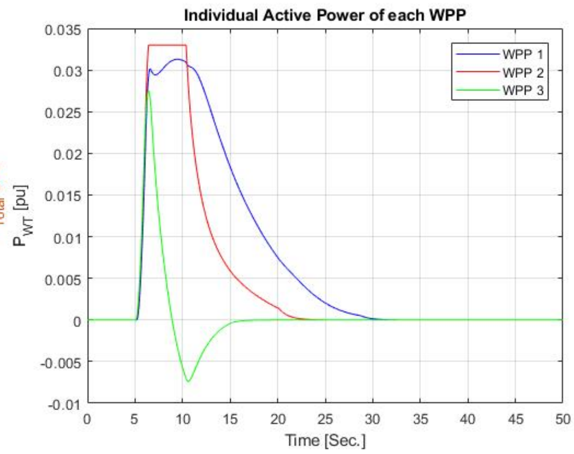
Figure 28. System Frequency and Total Active Power from WPPs, (b) Individual Active Power from WPPs at Partial Load with 1s delay in Standard Communication

9.3.2.2 Full Load

9.3.2.2.1 Delay of 100 ms in Standard Communication



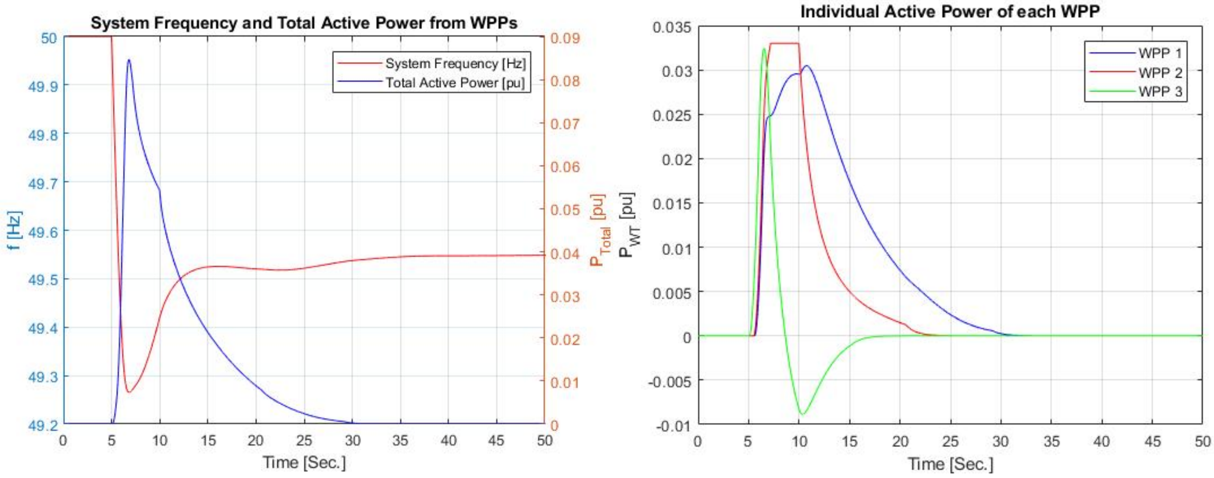
(a)



(b)

Figure 29. System Frequency and Total Active Power from WPPs, (b) Individual Active Power from WPPs at Full Load with 100ms delay in Standard Communication

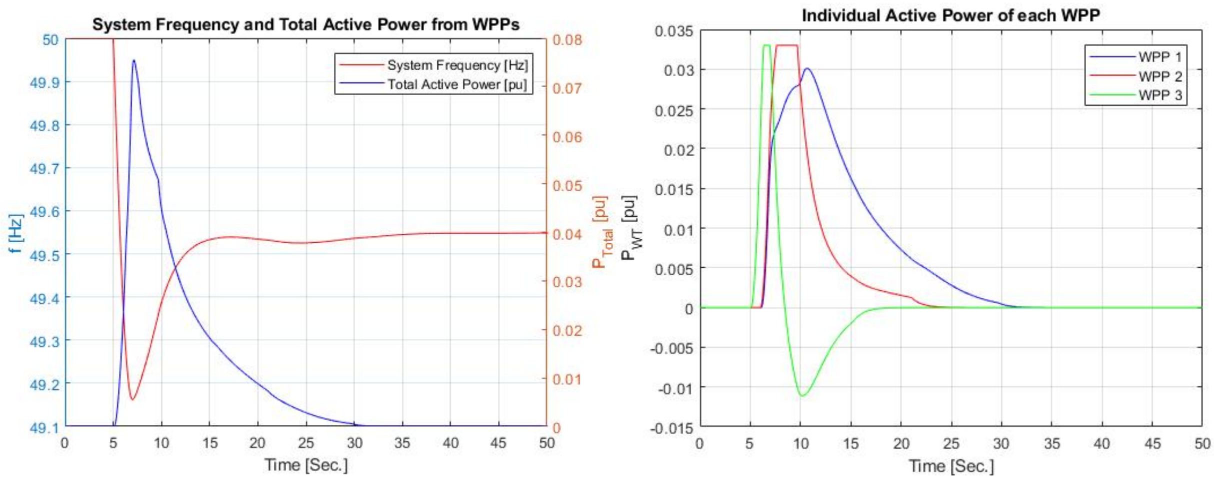
9.3.2.2.2 Delay of 500 ms in Standard Communication



(a) (b)

Figure 30. System Frequency and Total Active Power from WPPs, (b) Individual Active Power from WPPs at Full Load with 500ms delay in Standard Communication

9.3.2.2.3 Delay of 1 Second in Standard Communication



(a) (b)

Figure 31. System Frequency and Total Active Power from WPPs, (b) Individual Active Power from WPPs at Full Load with 1s delay in Standard Communication