Remote Monitoring with Hierarchical Network Architectures for Large-Scale Wind Power Farms

Mohamed A. Ahmed*, Minho Song**, Jae-Kyung Pan*** and Young-Chon Kim†

Abstract – As wind power farm (WPF) installations continue to grow, monitoring and controlling large-scale WPFs presents new challenges. In this paper, a hierarchical network architecture is proposed in order to provide remote monitoring and control of large-scale WPFs. The network architecture consists of three levels, including the WPF comprised of wind turbines and meteorological towers, local control center (LCC) responsible for remote monitoring and control of wind turbines, and a central control center (CCC) that offers data collection and aggregation of many WPFs. Different scenarios are considered in order to evaluate the performance of the WPF communications network with its hierarchical architecture. The communications network within the WPF is regarded as the local area network (LAN) while the communication among the LCCs and the CCC happens through a wide area network (WAN). We develop a communications network model based on an OPNET modeler, and the network performance is evaluated with respect to the link bandwidth and the end-to-end delay measured for various applications. As a result, this work contributes to the design of communications networks for large-scale WPFs.

Keywords: Wind power farm, Communications network, Control center, Logical node, IEC 61400-25, OPNET.

1. Introduction

Wind energy is growing very quickly relative to other sources of renewable energy. As the wind power industry and its related technologies become more mature, large-scale wind power farms (WPFs) can move toward offshore sites in deeper water. These new WPFs have a higher capacity since the size and number of the wind turbines continues to rise. WPFs are located onshore and offshore in harsh environment where there are abundant wind resources, and a reliable communication infrastructure between the control center and the wind turbines is needed in order to efficiently manage and control these scattered WPFs. This communications infrastructure allows for the control center to receive real-time monitoring information and to send commands back when necessary. Therefore, the communications network between the wind turbines and the control center should be reliable and should operate in a stable manner.

Recently, WPFs in South Korea have been moving offshore due to both the limited space and the other challenges faced by onshore sites. The absence of a unified communications network for WPFs has resulted in each turbine manufacturer developing their own monitoring and control systems according to their specific needs [1].

Recent studies have shown that large wind turbines have a high failure rate and thus need more maintenance. Therefore, different condition monitoring systems (CMS) need to be used to monitor the conditions faced by wind turbines, including vibration analysis, acoustic emission, ultrasonic testing, oil analysis, strain measurement, and thermography. Regardless of the technique that is used to monitor the wind turbines, the capacity of the CMS is limited by the types and numbers of sensor nodes in the system [2].

In South Korea, many large-scale WPF projects are currently underway. Some are already operating, some are under construction, and others are in the design phase. Fig. 1 shows conventional WPF network architectures. The

Fig. 1. Conventional WPF network architecture
Mohamed A. Ahmed, Minho Song, Jae-Kyung Pan and Young-Chon Kim

local control center (LCC) is connected to the WPF using a wired or wireless communications network. The main functions of the LCC are to monitor and control the individual wind turbines and to receive monitoring data from the wind turbines, measuring devices, and meteorological masts. After the LCC processes the monitoring data that is received, the appropriate actions are then taken [3]. The limitations of conventional WPF architectures is that they have an isolated structure because each of the LCC is dedicated for a WPF and there is no global view of all WPFs.

The design of the LCC is based on the data type, the amount of information, the level of the data criticality and the future need to use the data that is received [4]. Fig. 2 shows the future of WPF network architectures. The main difference when compared to conventional WPF architectures is that the central control center provides central management and shares data from the local control centers. The function of the central control center is to enable managements of the WPFs that are scattered in order to maximize power generation and availability.

Little research has been completed on wind power farm communications networks. To the best of our knowledge, no simulation model has been designed for communications networks of large-scale WPFs. Previous studies only provided a description of the communications network of the existing WPF projects [5, 6], and other works have implemented the monitoring systems based on a small number of sensor nodes [7]. Our work is related to the design of a communications network architecture that can be used to monitor and control large-scale WPFs [8]. The main objective is to: 1) design the communications network inside the wind turbine based on the IEC 61400-25 standard; 2) design the wind farm communications network between the wind turbines and a local control center based on a switch-based architecture; 3) explore the network architecture of large-scale WPFs with different levels of data aggregation (local control center and central control center); 4) evaluate the network performance of the control centers in view of the link bandwidth and the end-to-end delay for various applications.

This paper is structured as follows. Section 2 provides the related work. In Section 3, the proposed hierarchical network architecture for large-scale WPFs is described. Section 4 provides a performance evaluation, results, and discussion. Finally, Section 5 presents the conclusion and the direction for future work.

2. Related Work

2.1 Wind power farm electric topology

The electric network configuration of a WPF consists of wind turbines, offshore substations, onshore point of common coupling (PCC), and electric power cables, as shown in Fig. 3. The electrical topology can be divided into two parts: the collection system and the transmission system [9]. The collection system represents the connections among all wind turbines, and the transmission system is used to transmit at a higher voltage from the offshore platform to the grid.

The wind turbines in a wind farm are divided into groups. Each group is linked to one or more offshore platforms using submarine electrical cables, where the low voltage output of each group is connected to a step-up transformer at the offshore platform. The communications network of a WPF usually follows the electrical topology because the optical fiber cables are integrated with the submarine cables used by the wind farm.

2.2 Wind turbine internal communications network

A typical wind turbine consists of the blades, the hub,
the gear box, the generator, the tower, the foundation, and the protection and control system as shown in Fig. 4. The condition monitoring system (CMS) is located within the turbine nacelle. It receives the sensing data from the sensor nodes and is connected to the main wind turbine controller (WTC) located at the base of the tower. The sensor nodes are installed at different points on the wind turbine to measure the critical parameters such as temperature, vibration, wind speed, wind direction, etc. Based on the IEC 61400-25 standard, a wind turbine can be represented by logical nodes (LNs) including WROT, WTRM, WGEN, WCNV, WTRF, WNAC, WYAW, and WTOW [10]. The LNs are modeled as a virtual model related to the real wind turbine. For example, the WNAC is related to the logical node of wind turbine nacelle and the WMET is related to the logical node to generate meteorological information. Each LN can transmit and receive various types of data: analogue, status and control information. Fig. 4 shows the network architecture to communicate data between logical nodes and the WTC inside wind turbine. It can be implemented with either wired or wireless communication technologies.

In order to enable communications among the wind turbines, Ethernet switches are used to connect the wind turbines together by using different communications network topologies [11].

2.3 Wind farm external communications network

The wind farm consists of three main parts: wind turbines, meteorological towers, and the control center. In a WPF communication network, the Ethernet standard based on optical fiber is widely used, where the network is considered as a local area network (LAN). The supervisory control and data acquisition (SCADA) system is used at the control center in order to enable the system operators to remotely monitor and control individual wind turbines. Following from the work presented in Ref. [7], the CMS of the wind turbines consists of a front-end device, a host and a server. Both the host and the server are located at the control center, and the front-end device is located on the side of the wind turbine. The main function of each part is given as follows:

- The front-end is installed inside of the turbine nacelle. It consists of a main controller, a power supply, and a data acquisition system (DAS). The DAS is connected to sensor nodes that capture a variety of data, including temperature, vibration, etc.
- The host is installed at the control center in order to receive real-time data from the front-end devices of the wind turbines. The data that are received are stored in a database and are sent to the server.
- The server is located at the control center and can receive all of the sensing data from the sensor nodes and measuring devices. Different devices and server types are located at the control center, including a meteorological server, human machine interface (HMI), wind turbine controller (WTC), condition monitoring system (CMS), metering server, etc.

3. Hierarchical Communications Network Architecture for Large-Scale WPFs

In order to design a communications network for large-
scale WPFs, a hierarchical architecture is considered as shown in Fig. 5. It consists of three levels: a wind power farm (WPF), a local control center (LCC) and a central control center (CCC).

**Wind power farm (WPF):** The WPF consists of wind turbines and meteorological towers. The communications network within the WPF is regarded as a local area network (LAN). We considered three different applications on the side of the wind turbine: analogue measurements, status information, and protection and control information.

**Local control center (LCC):** The LCC is responsible for monitoring and controlling the meteorological towers and wind turbines that may belong to different wind manufacturers. Also, the LCC is dedicated to a single WPF and can manage many wind farms in the same area. Independent servers are used to store the information received from different wind farms. All of the monitoring data collected from the wind turbines are aggregated at the LCC. Several WPFs that are located in the same geographical area can share LCCs and can be connected together. In this case, one of the LCCs is considered to be the area control center, and it connects to other LCCs. The communication among the LCCs occurs through a wide area network (WAN).

**Central control center (CCC):** The CCC is responsible for global data collection from the LCCs. The main function of the CCC is to manage energy by optimizing decision. The hierarchical architecture offers data aggregation at different levels.

### 4. Network Modeling and Simulation

In this part, we describe the network models that were built to study the performance of communications network for large-scale WPF. The communications network was built based on the electric topology configuration of Ref. [12] which consists of 48 wind turbines. The OPNET modeler [13] is used to evaluate the network performance in view of the end-to-end delay associated with various applications with different bandwidth links.

#### 4.1 Wind power farm network model

Fig. 6 shows the communication network model of a large-scale WPF through the OPNET. The modeled WPF consists of 48 wind turbines that are divided into 4 clusters. There are six octagon nodes which represent different subnets: cluster 1, cluster 2, cluster 3, cluster 4, offshore platform, and local control center. Each cluster subnet consists of a meteorological tower and 12 wind turbines with a star topology. The wind turbines and the meteorological mast are modelled using OPNET workstations. The offshore platform subnet consists of an Ethernet switch which is connected to the control center through the main communication link. The distance from the offshore platform to the local control center is 5 Km. The local control center subnet consists of three servers and an Ethernet switch. The three servers are a SCADA server, a protection and control server, and a meteorological server.

The communications network of the WPF is configured as a switch-based architecture where each wind turbine has a dedicated link to the cluster main switch. All of the clusters are connected to an Ethernet switch that is located on the offshore platform, and the Ethernet switch is connected to the local control center through a main communications link. In the control center side, there are three servers that can store and process the data received from the wind turbines and the meteorological masts.

We assumed that the wind turbines operate under a normal mode, and each wind turbine transmits three different applications: analogue measurements, status information, and protection and control information to the LCC. The network traffic of the wind turbines is given in Table 1. Each application constantly sends a constant bit rate on the network. The details of the data traffic calculation for each application inside of the wind turbine

![OPNET configuration of large-scale WPF](image-url)
were given in our previous study [14]. The link capacities were set to 100Mbps and 1Gbps.

4.2 Communication timing requirements

In the context of the wind power communications network, the IEC 61400-25 standard does not offer any specific timing requirements for the wind power domain. We defined the latency requirements of the WPF communications network for different applications based on an electrical power system [15]. In our network model, the internal and external timing requirements for the power substation automation are considered to evaluate the network model, as shown in Table 2.

Table 2. IEEE 1646: communication timing requirements for electric substation automation

<table>
<thead>
<tr>
<th>Application</th>
<th>Internal</th>
<th>External</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protection</td>
<td>4 ms</td>
<td>8-12 ms</td>
</tr>
<tr>
<td>Monitoring and Control</td>
<td>16 ms</td>
<td>1 s</td>
</tr>
<tr>
<td>Operation and Maintenance</td>
<td>1 s</td>
<td>10 s</td>
</tr>
<tr>
<td>Audio and Video</td>
<td>1 s</td>
<td>1 s</td>
</tr>
</tbody>
</table>

We mapped the analogue measurements (AM) and the status information (SI) for monitoring and control information. The protection and control information (PCI) from the IEDs is mapped for monitoring and control information, and the data from Met. towers are mapped for operation and maintenance.

4.3 Network model validation

First, we validated the communications network model of large-scale WPF by measuring the amount of traffic received at the LCC servers. The total amount of upstream traffic at the LCCs is given in Table 3, where the sensing data are calculated according to the number of wind turbines.

Table 3. Amount of total upstream data from WTs to LCCs

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Number of WTs</th>
<th>LCC Traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>12 WTs</td>
<td>29.04 Mbps</td>
</tr>
<tr>
<td>B</td>
<td>24 WTs</td>
<td>58.09 Mbps</td>
</tr>
<tr>
<td>C</td>
<td>48 WTs</td>
<td>116.18 Mbps</td>
</tr>
</tbody>
</table>

The simulation results show that the traffic received at the LCC is consistent with our calculations for different scenarios. Considering Scenario 3 as an example, Fig. 7 shows that the received traffic at the protection server is of

![Fig. 7. Traffic received at the LCC (SCADA & Protection)](image)

about 3,687,168 bytes/s (48*76,816) and the received traffic of the analogue measurements at the SCADA server are of about 10,826,112 bytes/s (48*225,544). Also, Fig. 8 shows that the traffic received at the Met. Mast server is of about 6,680 bytes/s (4*1,670), and the traffic received for status information at the SCADA server is of about 2,784 bytes/s (48*58).

![Fig. 8. Traffic received at the LCC (Status & Met. Mast)](image)

4.4 End-to-End delay from WTs to LCC

The network performance in the view of the end-to-end (ETE) delay is evaluated for different scenarios: a different number of WTs (one cluster), 12 WTs (one cluster), 24 WTs (two clusters) and 48 WTs (four clusters). The ETE delay (in seconds) is the amount of time it takes for the data to be delivered from the source to the destination along the communications path. Various applications run inside the wind turbine where, for example, the protection information requires a lower network latency than the SCADA information. Based on the IEEE 1646 standard, the requirements for the time delay of the protection information is 4 ms within a substation and 8 -12 ms external to the substation, as explained in Section 4.2.

Fig. 9 shows the end-to-end delay for 10 scenarios
where the link capacity is configured at 100 Mbps and 1 Gbps. In the case of the WPF with 10 wind turbines, the results indicated that the end-to-end delay for the protection and control information was of about 11.74 ms using a link capacity of 100 Mbps. The results showed stable performance with a lower end-to-end delay of about 1.12 ms using a link bandwidth of 1 Gbps.

Increasing the number of turbines from 10 WTs to 12 WTs affects the network performance where a 100 Mbps link capacity is used. Fig. 10 shows the end-to-end delay for 12 WTs, and the average end-to-end delay for the protection information increases to 14.11 ms, which does not fulfill the requirements of the power system. Therefore, we do not consider a link bandwidth of 100 Mbps in the case of 24 WTs or 48 WTs. The remaining scenarios are configured for a link capacity of 1 Gbps. In the case of 48 WTs, Fig. 11 shows that the end-to-end delay for the protection and control information is of about 5.58 ms.

4.5 End-to-End delay from LCC to CCC

The communications network for remote WPFs represents a hierarchical architecture that is divided into three levels: WPF LAN, public communication WAN, and CCC LAN. Within the WPF and the CCC, the communication networks are regarded as a local area network, while the connection between the WPF and the CCC is seen through a wide area network, as shown in Fig. 12. In this case, the WPF has its own local control center while the CCC collects data from all of the WPFs. The main function of the CCC is that of the energy management system that occurs by managing and supervising different WPFs.

This section shows the end-to-end delay between the WPF and the CCC that uses a shared network solution. The LCC of each WPF is directly connected to the CCC with a dedicated link through routers using a leased line (public networks). The network performance with respect to the end-to-end delay is evaluated for a small-size WPF consisting of 10 WTs. Two different scenarios are considered for the public communications network: direct data transmission and full data transmission. Fig. 13 shows the OPNET network model for the scenario with direct data transmission.
transmission. The link bandwidth between the WPF and the CCC is configured as OC-1 (51 Mbps) and OC-3 (155 Mbps).

Table 4 shows the ETE delay between the WPF and the CCC for the direct data transmission. At the control center, only one SCADA server is used. The maximum value of ETE for SCADA is of about 21.5 ms and 9.64 ms using OC-1 and OC-3, respectively. The meteorological mast delay is of about 5.1 ms. For the individual wind turbines (WT1ÆWT10), the details of the ETE delay of the SCADA traffic are given in Figs. 14 and 15.

This section shows the end-to-end delay between the WPF and the CCC with full data transmissions, as shown in Fig 16. We configured one workstation (workstation_CC) in order to transmit the traffic from LCC to the CCC. The amount of traffic is equal to that received at the LCC servers, as shown in Fig. 17. The workstation at the LCC is directly connected to the CCC with a dedicated link through routers using public networks, and the link

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Link Capacity</th>
<th>SCADA Max.</th>
<th>SCADA Min.</th>
<th>Met. Mast</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>51 Mbps SONET-OC1</td>
<td>21.5 ms</td>
<td>21.08 ms</td>
<td>5.1 ms</td>
</tr>
<tr>
<td>E</td>
<td>155 Mbps SONET-OC3</td>
<td>9.64 ms</td>
<td>9.44 ms</td>
<td>2.5 ms</td>
</tr>
</tbody>
</table>

transmission delay is given in Table 5.

Table 5. ETE delay among WPF, LCC and CCC (full data transmission).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>WPFÆLCC (Fast Ethernet)</th>
<th>LCCÆCCC (SONET-OC3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg. ETE delay</td>
<td>Avg. ETE delay</td>
</tr>
<tr>
<td>SCADA</td>
<td>8.7 ms</td>
<td>11.7 ms</td>
</tr>
<tr>
<td>PCI</td>
<td>11.7 ms</td>
<td>1.9 ms</td>
</tr>
<tr>
<td>Met. Mast</td>
<td>1.9 ms</td>
<td>0.73 ms</td>
</tr>
</tbody>
</table>
bandwidth between LCC and CCC is configured as OC-3 (155Mbps). The network performance in view of the end-to-end delay is evaluated for a WPF with 10 WTs, as shown in Table 5.

5. Conclusion

In this work, we have proposed a hierarchical communications network architecture for large-scale WPFs. The OPNET modeler was used to model and simulate the network, and the communications network models were validated by measuring the amount of traffic received at the control center servers. The performance of the proposed architecture was evaluated for the large-scale WPF. We investigated the network delay according to different link bandwidths of 100 Mbps and 1 Gbps. The results showed that the link bandwidth at 100 Mbps cannot guarantee the end-to-end delay of the protection and control information. Considering a small-scale WPF with 10 wind turbines, the end-to-end delay of the protection and control information was of about 11.74 ms. When the network capacity was increased to 1 Gbps, the end-to-end delay for different wind turbine applications decreased. In case of the large-scale WPF with 48 wind turbines, the end-to-end delay for the protection information was of about 5.58 ms. In order to monitor the data transmission between the WPF and the CCC, two scenarios were studied: direct data transmission and full data transmission. The simulation results showed that the channel capacity of the OC-3 satisfies the timing requirements of the power systems for different applications. Our future work is to extend the network model for a large-scale WPF by using a wireless-based solution, such as WLAN/WiMAX.

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References


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