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Communication Network Architectures for Southwest Offshore Wind Farm

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ABSTRACT

With the increasing of the penetration rate of large-scale wind farms, a reliable, highly available and cost-effective communication network is needed. As the failure of a WF communication network will significantly impact the control and real-time monitoring of wind turbines, network reliability should be considered into the WF design process. This paper analyzes the network reliability of different WF configurations for the Southwest Offshore project that is located in Korea. The WF consists of 20 WTs with a total capacity of 60 MW. In this paper, the performance is compared according to a variety of indices such as network unavailability, mean downtime and network cost. To increase the network reliability, partial protection and full protection were investigated as strategies that can overcome the impact of a single point of failure. Furthermore, the reliability performances of different network architectures are analyzed, evaluated and compared.

Key Words : Wind Farm, Communication, Network Reliability, Protection, Simulation, OPNET

Ⅰ. Introduction

Along with an increasing emphasis on the reduction of the greenhouse gas emissions, wind energy has received a great amount of attention among the available renewable energy resources. The development and growth of wind energy has enabled the installation of large-scale wind farms (WF) that cover large geographic areas in remote locations where abundant wind resources are available. As wind energy is intermittent by nature, it will be a major challenge to integrate large-scale WFs into the electric power grid and operate the power grid securely and reliably. In this regard, communication systems will play an important role in the monitoring and control of both wind turbines (WTs) and the electric power system.[1,2]

In South Korea, smart renewables form one of the prime opportunities that are defined by the national smart grid road map for the creation of a large-scale renewable energy generation complex and the development of a large capacity of energy storage devices[3]. According to the Global Wind Energy Council (GWEC), 47 MW of new wind power installations in South Korea were installed by the end of 2014 bringing the total installed capacity to 609 MW, and the target plan indicates the completion of 2.5 GW offshore wind energy installations by 2019[4].

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The target for offshore wind power in South Korea is 900 MW by 2016 and 1.5 GW by 2020 [5]. The planned offshore wind projects include 2.5 GW project at the Southwest Sea, 5 GW project in Jeonnam Province and 2 GW project in Jeju Island at Tamra, Daejeong, Hallim and Haengwon[6]. Table 1 shows a list of WF projects. The complete list of projects including total capacity, number of WTs, site location and manufacturer can be found at Korea wind power industry association (KWEIA) website[7].

A typical offshore WF consists of WTs, a local WF grid, an offshore substation and a transmission system, as shown in Fig. 1. The WTs are connected in groups and are linked by submarine cables to an offshore platform. A high voltage transmission system is used to transmit the output power from the WTs to an onshore grid. Supervisory control and data acquisition (SCADA) systems are used for the remote monitoring and control of the WTs. Communication networks enable the SCADA systems to transmit the measured information and control signals between the WTs and the remote control center. Different SCADA systems with a variety of operational functions are used within a WF such as turbine SCADA system, the plant SCADA, and the security SCADA.

Numerous publications present studies regarding offshore WFs from the perspective of the electric power system. However, only a small number of studies involved an investigation of the communication networks[1,7-9]. In [1], several communication technologies are presented for the grid integration of renewable energy resources including power line communication, wireless local area networks (LAN), and wireless wide area networks (WAN); also, the communication system for a real WF project (Bear Mountain WF, Canada) is presented. In [7], the role of communication infrastructure for large-scale WFs is discussed, whereby a greater emphasis is placed on the balancing of the plant SCADA system. In [8], the design requirements and considerations for the deployment of an Ethernet-based WF network are discussed; additionally, the network topology of a real offshore WF project in the UK is described. The WF communication infrastructure consists of a Switch-based network where Ethernet Switches have been located in every WT. Communication links were used for the connections between the WTs and the control center. In [9,10], a comprehensive review regarding the grid integration of wind energy is given. The review covers the communication technologies (wired/wireless) and protocols that are used in a variety of network segments (WT internal network/WT external network). Due to the importance of the WF communication infrastructure, the network should remain working in the case of a device/link failure[11].Therefore, the communication network should be designed with redundant architectures.

Table 1. WF projects in operation in South Korea

Project	Capacity (kW)	WTs	Location
Haengwon	9,795	15	Jeju-do
Jeonbuk	7,900	10	Jeollabuk-do
Hangyeong	21,000	9	Jeju-do
Maebongsan	8,800	9	Gangwon-do
Yeongdeok	39,600	24	Gyeongsangbuk-do
Yongdae	61,500	41	Gyeongsangbuk-do

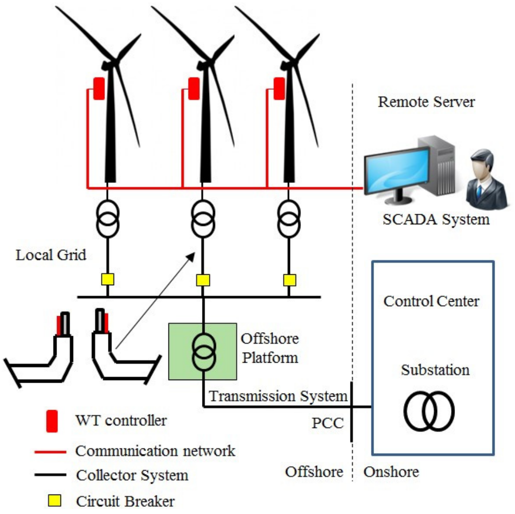

Fig. 1. Layout of offshore WF.

The design of a WF communication network must ensure a high level of availability. Special consideration must be taken into account in case of offshore installation. The main design requirements that should be considered are environmental issues, electromagnetic interference (EMI), redundancy, etc. Detailed requirements when designing communication network for a wind farm are given in Ref. [8].

The purpose of this paper comprises the following:

- Design of a reliable communication network architecture for an offshore WF
- Reliability analysis of different configurations with and without protection schemes
- Evaluation of network performance in consideration of network availability, mean downtime and network cost
- Modeling and simulate of different communication network architectures using OPNET Modeler

Ⅱ. Related Work

2.1 Offshore Wind Farm Layout

This section gives an overview of WF layout. It describes different designs of WF collector system. Typical configurations of WTs in a WF are combination of radial and star topologies. Different topologies (radial, radial-loop, star, etc.) may be considered for the design of a WF collector system, as shown in Fig. 2, whereby a tradeoff is made between the economic costs and the technical performance [8,9].

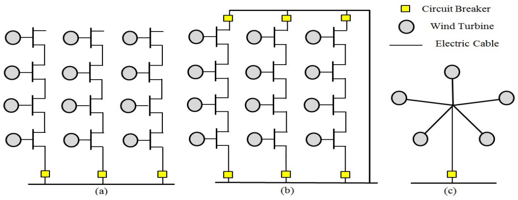

Fig 2. Different options of WF collector system (a) Radial (b) Radial-loop (c) Star

2.1.1 Radial Design

All of the WTs are connected in a series to a single feeder, and the maximum WT number is determined by the cable rating and the generator rating. The major disadvantage of this design is a poor reliability in cases where the feeder link is disrupted.

2.1.2 Radial-Loop Design

Redundancy is provided by the establishment of a looped circuit between the WTs. A cable that is installed from the outermost WT in the feeder to the collector hub must be capable of carrying the entire power flow of the feeder if a fault occurs at a point between the first WT and the hub.

2.1.3 Double-Sided Ring Design

This is another version of the looped design, whereby the two feeders are connected in parallel to provide redundancy. In the event of a fault at the first feeder, the full output power of the WTs in the faulted feeder must be delivered through the other feeder.

2.1.4 Star Design

This design allows for a reduced cable rating and improved security since a cable outage will only affect one WT. The drawback of the star design is the increased expense from longer diagonal cables and a more complex switchgear requirement.

2.2 Wind Farm Communication Network

The communication network here is defined by the wiring and configuration of the communication system between the WTs and the control center. The optical fiber cables are integrated with the medium voltage cable, allowing the network layout to follow the electrical topologies of the WF. However, the fiber cable layout may be designed in a different way due to the redundancy, safety and stability requirements. The main types of communication networks are cascaded, ring and star, while the other topologies comprise combinations of these three types. The following explanation provides a brief overview of the advantages and limitations of different topologies[10].

2.2.1 Radial Topology

This is recommended for small installations that consist of only a small number of WTs. The WTs are connected in a daisy chain. Each turbine of the line has its own Ethernet Switch. All Ethernet Switches are connected to a central Switch. In case of failure of one Switch, the remaining turbines of the line will be disconnected as shown in Fig. 3.

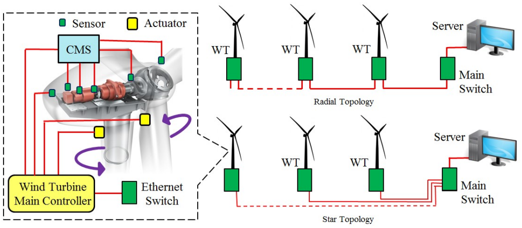

Fig. 3. Communication network architecture using various topologies

2.2.2 Ring Topology

It considered as the preferred network topology due to the corresponding compromise between reliability and safety. Each WT Switch is connected in a ring structure with a redundant path, whereby the connection is similar to that of the radial topology but features an additional alternative path. In the case of a Switch/cable failure, there is no loss in communication between the WTs and the control center.

2.2.3 Star Topology

The turbines are connected directly to the main central Switch. When a certain cable connection fails, the WT connected to that link will not function. Furthermore, the addition of turbines is easy due to the separate line of each WT, as shown in Fig. 3. This configuration requires a large amount of cabling, however, making it costly.

2.3 Case Study: Southwest Offshore Wind Farm

The Korean government announced plans to build a large-scale offshore WF on the Southwestern coast. According to the project plan, the construction of the first phase will be completed by 2018[11,12]. The project is divided into the following three phases:

- First phase: 60 MW test bed for verification.
- Second phase: 400 MW demonstration site.
- Third phase: 2000 MW large-scale WPF.

The aim of this work is the design of the communication network for the first phase of the Southwest project. A total of 20 WTs, each with a turbine capacity of 3 MW, will be connected to an offshore substation. We designed the communication network for the first phase of the Southwest offshore WF project based on the electric topology layout.

Ⅲ. Communication Network Architectures for Southwest Offshore Wind Farm

3.1 Communication Network Architecture

The communication network is an important part of a large-scale WF design, as it enables the control center operator to remotely monitor and control the generated power from the WTs. The communication network can be divided into the following two levels: WT internal network and WF external network. The WT internal network represents the communication network inside the WT itself, which consists of sensor nodes, actuator nodes and a local turbine controller. The WF external network represents the communication network between the WTs in the WF. Conventional network architectures are based on the Switch-based Ethernet. In this work, the cascaded topology and star topology are considered. We designed the communication network for the first phase of the Southwest offshore WF project based on the electric topology.

The following three different cases for the electric topology, which are shown in Fig. 4, are considered: Case (1) with five feeders, Case (2) with four feeders and Case (3) with three feeders. The spacing between the WTs along the rows and between the rows is equivalent to 0.8 km. The longest cable length, between the offshore platform and WT5, is approximately 2.78 km, while the shortest cable length, between the offshore platform and WT1, is approximately 0.52 km. The optical fiber cables are integrated with the submarine electric cables; therefore, the communication network follows the WF electric topology.

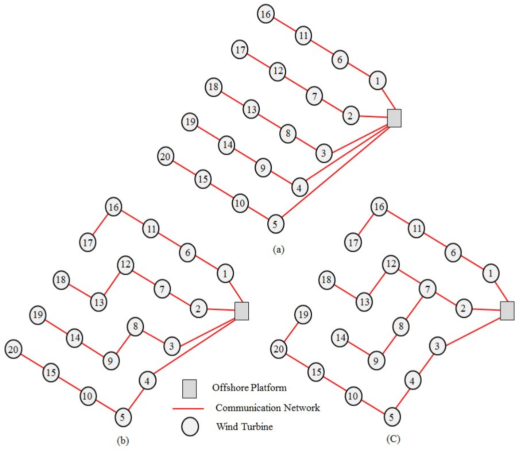

Fig. 4. Communication network options for the Southwest offshore WF (a) Case 1 with five feeders (b) Case 2 with four feeders (c) Case 3 with three feeders.

Table 2. Configuration components of architectures

Archit.	Cascaded				Star			
	#ESW (CC)	FF [km]	DF [km]	#ESW (WTs)	#ESW (CC)	FF [km]	DF [km]	#ESW (WTs)
Case(1)	1	7	12	20	1	7	24	20
Case(2)	1	4.211	12.8	20	1	4.211	32	20
Case(3)	1	2.215	13.6	20	1	2.215	40	20

3.1.1 Cascaded Architecture

The cascaded architecture begins with the main Ethernet Switch located at the offshore platform and feeder fibers provide the connections to the nearest WTs. Each WT has an Ethernet Switch at the base of the tower with at least three ports. One port is connected to the WT controller located at the nacelle, another port is connected to the next WT, and the third is connected to a previous WT. The Ethernet Switches at the WTs are connected in a chain/cascade. All of the distributed fibers between the WTs are 0.8 km. Figure 5 shows the communication network for the Case (1) cascaded architecture with five feeders, and Table 2 lists the components of the communication network.

3.1.2 Star Architecture

In this configuration, the feeder fiber connection between the main Ethernet Switch and the WTs is similar to that of the cascaded architecture. Within a feeder, each WT has a dedicated network connection that comprises individual optical fiber cables. WT1, for example, has an Ethernet Switch with at least six ports, whereby one port is connected to the WT1 controller at the nacelle and the others ports are connected to the others WTs and the offshore platform. Figure 6 shows the communication network for the star architecture of Case (1) with five feeders, and Table 1 lists the components of the communication network.

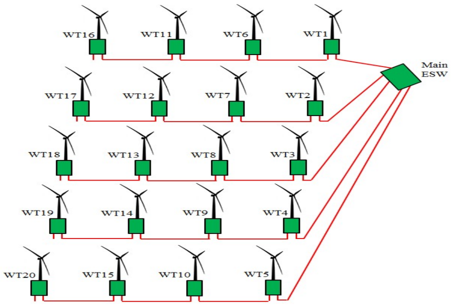

Fig. 5. Case (1): Cascaded architecture

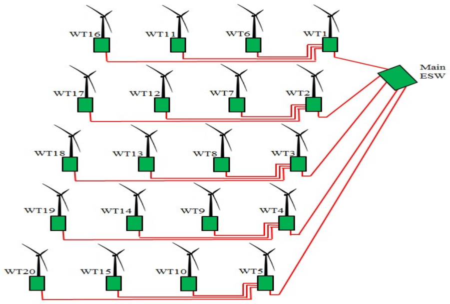

Fig. 6. Case (1): Star architecture

3.2 Network Failure and Resiliency

Several of the factors that affect the communication network such as planned maintenance, component failure, and accident/disaster can be applied to WF architecture[13].

- Planned Maintenance: The network service may be interrupted in case of an upgrading (software or hardware) of the communication network at the control center. A duplicating of the network devices at the control center (i.e., one network device is working while the other is in standby mode) enable the system operator to upgrade the network without causing a service interruption.

- Component Failure: A network outage could be caused by component/link failure. Each network component has a different impact on the network. Therefore, a redundant configuration enables a quick service recovery regarding the communication network.
- Accident or Disaster: There are many causes of accidents and disasters that can affect the communication network. For example, a ship anchor could destroy the electric power cable wherein the optical fiber cables are embedded. Natural disasters such as a flood or an earthquake may cause the catastrophic failure of the whole communication system.

To overcome the previously mentioned problems, the communication network should be designed with partial/full protection.

Ⅳ. Performance Evaluation

4.1 Reliability Analysis

This section presents the reliability analysis regarding a variety of WF network architectures. The reliability block diagram (RBD) method is used for the availability calculations[13]. Figure7 shows the RBD of the communication network between the control center and the WTs, with and without protection. Each block represents either a component or a fiber link. Each WT has an Ethernet Switch and all of the WTs are connected to the main Ethernet Switch located at the offshore platform.

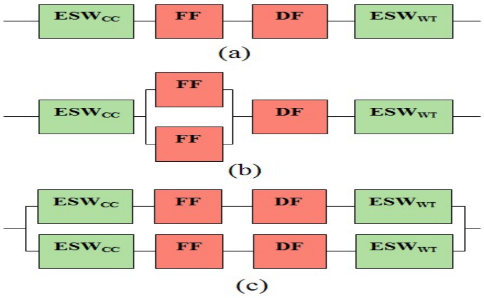

Fig. 7. Reliability block diagram for the connection between CC and WTs (a) Unprotected architecture (b) Partial protection architecture (c) Full protection architecture

The unavailability(U_x) is defined as the probability that a component (device/link) is unavailable at any time and is expressed in terms of failure-in-time (FIT) and mean-time-to-repair (MTTR).

$$U_x = (FIT^*MTTR) \ / \ 10^9 \qquad (1)$$

The FIT parameter represents the number of observed failures in 10^9 hours. The mean downtime (MDT_X) for a component x is calculated as follows:

$$MDT_x \ (min/year) = U_x{}^*365^*24^*60 \qquad (2)$$

Equation (3), Equation (4) and Equation (5) are used for the calculation of the connection unavailability (U) between the ESW-CC (Ethernet Switch at offshore platform) and ESW-WT (Ethernet Switch at turbine side), with and without protection. $U_{ESW\text{-}CC}$, U_{FF}, U_{DF}, and $U_{ESW\text{-}WT}$ represent the unavailability of ESW-CC, FF(feederfiber), DF(distributedfiber) and ESW-WTs, respectively.

$$U_{NP} = U_{ESW\text{-}CC} + U_{FF} + U_{DF} + K.\ U_{ESW\text{-}WT} \qquad (3)$$

$$U_{PP} = U_{ESW\text{-}CC} + (U_{FF})^2 + U_{DF} + K.\ U_{ESW\text{-}WT} \qquad (4)$$

$$U_{FP} = (U_{ESW\text{-}CC} + U_{FF} + U_{DF} + K.\ U_{ESW\text{-}WT})^2 \qquad (5)$$

The Switch-based architectures without redundancy include Ethernet Switches and optical fiber cables. For partial protection (PP), feeder fiber (FF) cables are duplicated. For full protection (FP), all of the network links and devices are duplicated to provide a high reliability in the case of network failure. We calculated the unavailability for 18 different configurations using reliability data of Table 3. Table 4 and Table 5 show the unavailability and expected downtime for the cascaded topologies and star topologies, respectively. In the case of the cascaded architecture, Case (3) has the lowest MDT of approximately 437 min/year, whereas Case (1) has the highest MDT of approximately 460 min/year. In the case of the star architecture, Case (1) has the lowest MDT of approximately 547 min/year, whereas Case (3) has the highest MDT of

Table 3. Component unavailability of WPF network.

Level	Components	FIT	MTTR	Ux
Offshore Platform	ESWCC	1,250	12	1.5E-05
WF Area	ESWWT	1,250	24	3.0E-05
	Fiber (/km)	570	24	1.37E-05

Table 4. Network components of cascaded topology

Cascaded Topology	Net. Arch.	#ESW (CC)	FF [km]	DF [km]	#ESW (WTs)	U_X	MDT_X (min/yr)
Case (1)	NP	1	7	12	20	8.74E-04	460
	PP	1	14	12	20	7.792E-04	410
	FP	2	14	24	40	3.062E-06	2
Case (2)	NP	1	4.2	12.8	20	8.476E-04	446
	PP	1	8.4	12.8	20	7.901E-04	416
	FP	2	8.4	25.6	40	2.87E-06	2
Case (3)	NP	1	2.215	13.6	20	8.313E-04	437
	PP	1	4.430	13.6	20	8.011E-04	421
	FP	2	4.430	27.2	40	2.765E-06	2

Table 5. Network components of star topology

Star Topology	Net. Arch.	#ESW (CC)	FF [km]	DF [km]	#ESW (WTs)	U_X	MDT_X (min/yr)
Case (1)	NP	1	7	24	20	1.039E-03	547
	PP	1	14	24	20	9.434E-04	496
	FP	2	14	48	40	4.319E-06	3
Case (2)	NP	1	4.211	32	20	1.11E-03	584
	PP	1	8.422	32	20	1.053E-03	554
	FP	2	8.422	64	40	4.932E-06	3
Case (3)	NP	1	2.215	40	20	1.193E-03	627
	PP	1	4.430	40	20	1.162E-03	611
	FP	2	4.430	80	40	5.688E-06	3

approximately 627 min/year.

Redundant architectures (partial/full) have shown a greater improvement in terms of both the MDT and availability. In the case of the cascaded architecture, Case (1) has the lowest MDT of approximately 410 min/year, whereas Case (3) has the highest MDT of approximately 421 min/year. In the case of the star architecture, Case (1) has the lowest MDT of approximately 496 min/year, whereas Case (3) has the highest MDT of approximately 611 min/year.

4.2 Network Cost

The communication network cost can be divided into the following two parts: active devices (Ethernet Switch) and passive components (fiber cable). For this paper, the costs of the Ethernet Switch and the fiber cable are (200 component + 100 per port) US$ and 160 US$ per km, respectively[11]. Note that the network installation cost is not considered because the optical fibers are integrated with the electric power cables. The communication network cost is calculated as follows:

$$COST_{WFNetwork} = C_{ESW} + C_{Fiber} \tag{6}$$

where C_{ESW} and C_{Fiber} represent the costs of the Ethernet Switches and optical fiber cables, respectively.

We compared the configurations of the cascaded architecture and the star architecture, whereby the three following scenarios were considered: five feeders, four feeders, and three feeders. Table 6 shows the network costs of the cascaded architectures and the star architectures. In the case of cascaded architecture, the results show that Case (3) has the lowest network cost of $15,130 followed by the $15,320 cost of Case (2) and the $16,040 cost of Case (1).

The Ethernet Switch is the dominant network element here that contributes to the higher network cost. In the case of the star architecture, the results show that Case (1) has the lowest network cost of $17,960, followed by the $19,993 cost of Case (2)

Table 6. Network cost for cascaded and star architectures

Topology	Net. Arch.	Cascaded Topology			Star Topology		
		Fiber Cost($)	ESW Cost($)	Total Cost($)	Fiber Cost($)	ESW Cost($)	Total Cost($)
Case (1)	NP	3,040	13,000	16,040	4,960	13,000	17,960
	PP	4,160	13,800	17,960	6,080	15,000	21,080
	FP	6,080	26,000	32,080	9,820	26,000	35,820
Case (2)	NP	2,720	12,600	15,320	5,793	14,200	19,993
	PP	3,392	13,000	16,392	6,464	14,600	21,064
	FP	5,440	25,200	30,640	11,584	28,400	39,984
Case (3)	NP	2,530	12,600	15,130	6,754	13,800	20,554
	PP	2,884	13,000	15,884	7,108	14,200	21,308
	FP	5,060	25,200	30,260	13,508	27,600	41,108

Table 7. Traffic for WT internal network and WF external network

Application	Data rate	
	Standalone WT	Southwest WF (20 WTs)
Analogue Measurements	225,544 bytes/s	4,510,880 bytes/s
Status Information	58 bytes/s	1,160 bytes/s
Protection and Control	76,816 bytes/s	1,536,320 bytes/s

and the $20,554 cost of Case (3). We also computed the network costs for both partial and full protection. The partial protection has a small impact on the network cost due to the lower cost of the fiber cables compared with the cost of the Ethernet Switches.

4.3 Network Modeling and Simulation

This section evaluates and compares the performances of a variety of WF communication networks using OPNET Modeler. The network performance is evaluated in terms of the end-to-end (E2E) delay. The details of the OPNET models for the WTs and the control center are given in Fig. 8.

Each WT is modeled into one subnet that consists of an ESW and a WT controller, and the WT consists of a workstation and an Ethernet Switch. The workstation represents the WT controller that is responsible for collecting the monitoring data from different sensor nodes. The total number of measurements in a WT is 102[12]. All of the WTs are configured to transmit the monitoring data to the control center servers (SCADA servers). The workstation is configured according to different profiles (analogue measurement, status information and protection information).

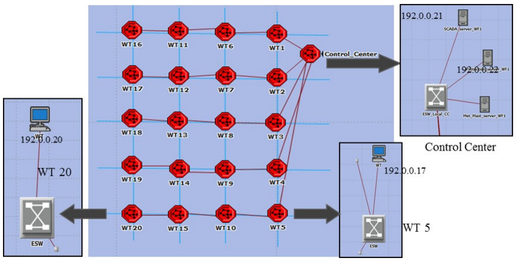

Fig. 8. OPNET model for radial topology with 5 feeders

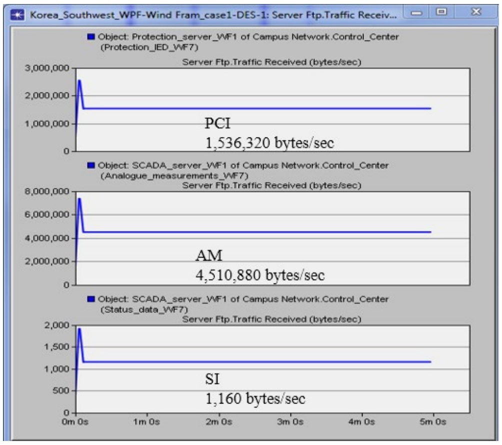

Fig. 9. Amount of upstream traffic for WPF

In OPNET workspace, we assign the network scale with 10 km to X Span and 10 km to Y Span. We considered 6 cases of configurations. The locations of the WTs are given by the following set of points for X and Y coordinates: {(5,1.8), (5,2.6), (5,3.4), (5,4.2), (5,5), (4.2,1.8), (4.2,2.6), (4.2,3.4), (4.2,4.2), (4.2,5), (3.4,1.8), (3.4,2.6), (3.4,3.4), (3.4,4.2), (3.4,5), (2.6,1.8), (2.6,2.6), (2.6,3.4), (2.6,4.2), (2.6,5)}. We consider the distance between adjacent WTs approximately 800 m along rows and between rows.

We verified the network model by comparing the total transmitted data (bytes/sec) with the received data at the servers. All of the received data agree with the calculations given in Table 7, as shown in Fig. 9. The received traffic at the SCADA server

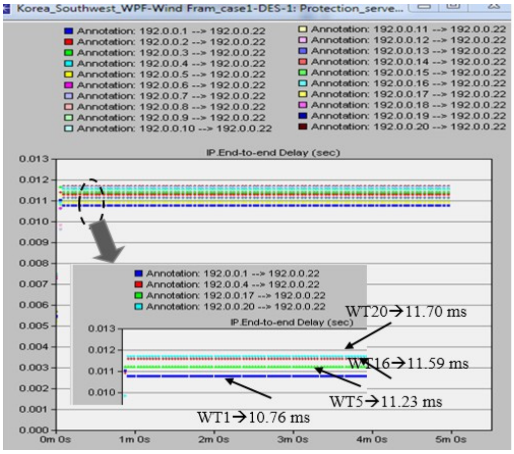

Fig. 10. End-to-end delay between CC and WTs

comprises 4,510,880 bytes/sec, as well as 1,160 bytes/sec for analogue measurements and status information, respectively. The received traffic at the protection server is 1,535,320 bytes/sec.

Figure 10 shows the end-to-end delay for Case (1), where the link capacity is configured with 100 Mbps. The end-to-end delay for WT1 is approximately 10.76 ms, while it is 11.70 ms for WT 20. Given that the requirement for the time delay of protection information is from 8 ms to 12 ms[14], the simulation results satisfy the timing requirement for the power system.

Ⅴ. Conclusions Reference

This paper proposes a variety of communication network architectures for the Southwest Offshore WF in Korea. The WF consists of 20 WTs with a total capacity of 60 MW. We evaluated the network reliability, mean downtime, and network cost for different WF configurations. The RBD approach was used to calculate the network availability for different configurations. In the case of the cascaded architecture, Case (3) with three feeders has the lowest MDT of approximately 437 min/year, whereas Case (1) with five feeders has the highest MDT of approximately 460 min/year. Redundant architectures with partial/full protection show a greater improvement of the MDT and availability. In the case of the star architecture, Case (1) with three feeders has the lowest MDT of approximately 496 min/year, whereas Case (3) with three feeders has the highest MDT of approximately 611min/year. In view of the network cost, the Ethernet Switch represents the dominant network element that contributes to the higher network cost. In the case of the cascaded architecture, the results showed that Case (3) with three feeders has the lowest network cost of $15,130 while, in the case of the star architecture, the results show that Case (1) with five feeders has the lowest network cost of $17,960. We used the OPNET Modeler for the evaluation of the communication network architectures and the investigation of the network delay. The ETE delay between the WTs and the control center satisfy the timing requirements of the power system. The proposed network model will be extended to implement resilience wireless network architecture for a large-scale WF.

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