Fault Resilient Communication Network Architecture for Monitoring and Control of Wind Power Farms

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Abstract— **Real time monitoring and control of wind power farm (WPF) require a highly reliable communication network infrastructure. The monitoring and control can be guaranteed through the communication network by using redundant resources and ensuring quality of service (QoS) for different applications. In this paper, we study and simulate fault-resilient network architecture for monitoring and controlling of WPF. First, communication network topologies are explored. Then we propose a fault-resilient communication network architecture which consists of three different levels: (1) data generation level, (2) data aggregation level, and (3) control center level. Each level is defined by its function, physical location, network topology, communication link bandwidth, redundant nodes, and links. In accordance to IEC 61400-25 standard, the monitoring traffic of wind turbine is classified into critical and non-critical data according to the required QoS. Due to low cost, non-proprietary standard, and guaranteed real-time services, the Ethernet technologies are currently used in various industrial applications. Several network failure scenarios based on Ethernet technology are used to simulate the network architecture through OPNET. The performance of the network architecture is evaluated on the basis of the amount of received data, end-to-end delay, and data loss at control center. The simulation results show that the communication network architecture can guarantee the transmission of WPF critical data.**

Keyword— **Communication Networks; IEC61400-25; Monitor and Control; Reliability and Resiliency; Wind Power**

I. INTRODUCTION

WIND is a natural and low cost resource that is never depleted and can be used for an environment friendly renewable energy production. These characteristics of wind lead to a fast increase in WPF around the world. Mountains and offshore locations are the suitable choices for wind power because of stable and strong wind with space availability. Some European countries such as Germany, Denmark, and United Kingdom are rapidly installing offshore WPF with larger size wind turbines (WTs) and higher power capacity. The offshore wind power generation is facing several issues: high construction cost, offshore installation, and maintenance cost. The construction and installation are considered to be initial investment expenditure. However, the maintenance and repair need a special attention because it is a long term and continuous task. The communication networks can play a significant role in the reduction of maintenance and repair expense by providing real time monitoring and control mechanism to these WPF. Communication networks can enable the control center (CC) to monitor the status of WTs in real time. The CC then controls the operation of the WT with control commands. Currently, various monitoring techniques such as sensor and infrared camera based monitoring are used [1,2]. Fig.1 shows a schematic diagram of WPF communication network. In this figure, the monitoring and control system for WPF is divided into three parts. In the first part, all WPF are connected to a remote terminal through a wired communication link. The second part is the communication network by using wired or wireless according to the requirements. At the third part, there is a CC with different monitoring and control servers system. An efficient monitoring and control operation strongly relies on the high availability of data with a minimum latency. In view of communication network, the resiliency can be defined that the communication network should be able to route the traffic via secondary resources to ensure the data transmission under any failure of device and link. The issues in communication network that can influence the WPF system include plane maintenance, component failure and accident/disaster [3]. Therefore, designing a fault-tolerant communication network is highly required for WPF. In this regards, several communication architectures have been proposed in the literatures. The authors in reference [4] proposed an Ethernet passive optical network (EPON) based communication network architecture. The communication network was modeled through optical network unit (ONU) and optical line terminal (OLT). In reference [5] a resilient communication network for large-scale offshore wind farm was proposed with the focus on redundant resources in the network. An open shortest path first (OSPF) protocol and rapid spanning tree protocol (RSTP) was used for avoiding loop in the network.

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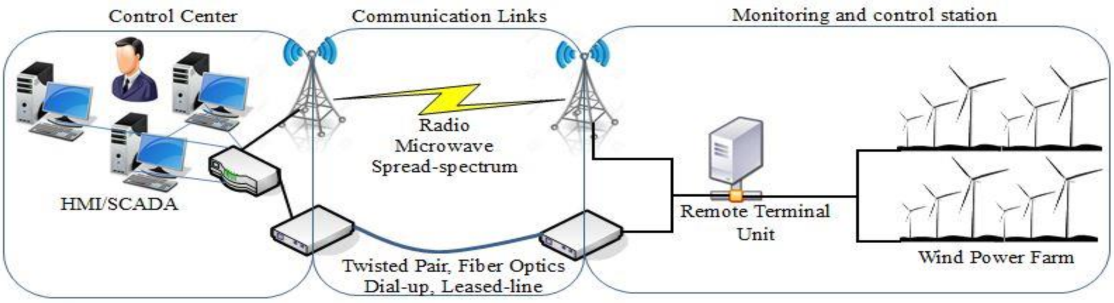


Fig. 1. Schematic diagram of communication network for wind power farm monitoring and control

Resilient wireless communication network architecture for smart grid in building area network (BAN) was proposed by the authors in reference [6]. To achieve resiliency with high degree, the paper focused on wireless mesh network among the different communicating entities in BAN. To the best of our knowledge, simulation study towards the fault-resilient communication network for monitoring and control of WPF has not been considered.

In this paper, we extend our previous work titled "Simulation Studies of Resilient Communication Network Architecture for Monitoring and Control Wind Power Farms" [7]. First, we explore various topologies that can be applied to the communication network for WPF. The advantages and disadvantages of each topology are discussed. Then, fault-resilient communication network architecture with hybrid topology is proposed. To achieve fault-tolerance in the network with a higher degree, we considered redundant resources at WPF, offshore platform, and control center level. The IEC 61400-25 standard is used for monitoring various components of WT. The standard mapped the physical components of WT into different logical nodes (LNs). Some of the LNs are mandatory while the others are optional. These different kinds of LNs have different QoS requirements. According to the IEC 61400-25 standard optional and mandatory LNs, the monitoring data are classified into critical and non-critical data to satisfy the QoS requirements. Several network failure scenarios are simulated through OPNET to evaluate the proposed architecture performance. The performance of the communication network architecture is analyzed in terms of end-to-end delay, data loss, and the amount of received data.

The rest of this paper is organized as follows: related work is discussed in Section II. The different network topologies and the proposed communication network architecture are presented in Section III. WPF communication network with data modeling and simulation set-up is given in Section IV. Simulation results and discussion is presented in Section V. Finally, Section VI summarizes the paper with concluding remarks and related future work.

II. RELATED WORK

A. *The Horns Rev Communication Network*

Elsam, a Danish energy company, installed the first largest offshore WPF in the North Sea. It consists of 80 Vestas V80-2.0 MW unit WTs with 160 MW power capacities. The 80 WTs are connected in 10 rings with a total of 8 WTs in each ring. The network architecture is designed with a primary wired and secondary wireless radio communication channels [8]. Fig 2 shows the Horns Rev communication network diagram. The network is equipped with redundant devices both at offshore (WPF site) and onshore (CC) locations. All the communication is made through the primary wired link. This wired link uses a single mode fiber with link bandwidth of 1Gbps to support the 80 WTs traffic and cover longer distance between WPF and CC. An open platform communication (OPC) interfaces are enabled within the network equipment. The data is transmitted through file transfer protocol (FTP), serviced by TCP/IP. The secondary wireless radio communication channels use a 34Mbps channel bandwidth. The secondary wireless channel has the advantages of low installation cost, simple configuration, and is easy to deploy. When the primary link fails the traffic is routed to the secondary wireless channels for data transmission. However, some of the limitations associated with this architecture are: According to the IEC 16400-25 standard LNs, a WT generates approximately 1.8 Mbps of monitoring data [9]. In the case of Horns Rev WPF the fiber link has a huge capacity of 1Gbps which is not utilized. Also, the secondary wireless channels have a limited bandwidth of 34 Mbps. The limited channel capacity may result in data loss with an increased latency. Furthermore, different applications require different service qualities but the Horns Rev WPF do not consider any QoS requirements.

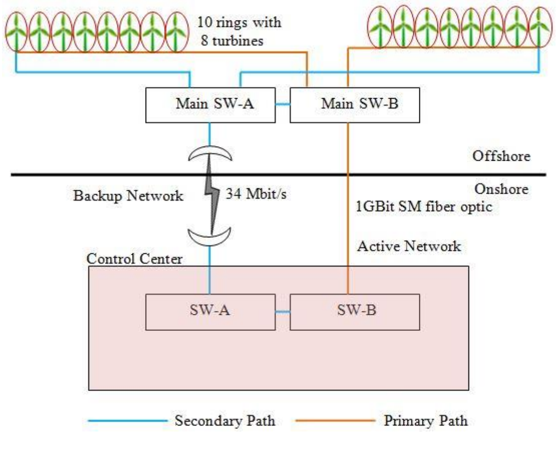


Fig. 2. Horns Rev Communication Network

B. *The Greater Gabbard Project Communication Network*

The Greater Gabbard project is developed by Scottish and Southern Energy (SSE) Company. The project covers a load of 40% with a total annual production of 1,900-GWh electricity. The project consists of 140 WTs with 3.5 MW power generations for a WT. The turbines are located around two sand banks called Inner Gabbard and the Galloper in the North Sea, off the coast of Suffolk in Eastern part of England. The total distance of these wind farms is about 25 kilometers off the coast. The turbines are installed in water depths of between 24 and 34 meters. The WTs are connected to two transformers located at the offshore platform via 33kv cable. The power is then exported to the onshore substation through 132kv submarine cable. The WPF is connected to the onshore substation through three different set of backbone gigabit Ethernet based communication networks. The network infrastructure consists of 8-rings connected to offshore substation with 10-20 switches. Each of the communication networks is designed to support different type of applications. A virtual local area network (VLAN) is used to isolate the traffic for each of the application. The RSTP protocols are adopted for network loop avoidance and traffic re-routing in case of any failure in the network. The details of these dedicated networks are discussed as follows.

- ✧ **Balance of plant network**: This network is called as “substation protection and control network” with the main function to connect all the protection and control IDE’s at WTs, offshore and onshore substation.
- ✧ **Wind turbine generator network**: The WT controllers are connected to central supervisory controlled and data acquisition (SCADA) control system through Ethernet communication link.
- ✧ **Telephone and security network**: The video surveillance cameras and IP telephony services are provided by this network.

All these networks are connected to the onshore substation through gigabit Ethernet backbone with redundant switches and routers [10]. The network provides resiliency with higher degree using ring topology and redundant network resources. The QoS can be achieved through independent network for each application. However, some of the associated limitations are: the physically connected network is logically separated through VLAN for three different types of applications. The VLAN can cause an increasement in the delay of sensitive or time critical data. Another limitation is the cost factor, because the network infrastructure is fully connected with a bundle of resources (network switches and links) which associates a high cost. Hence, in view of cost it cannot be considered as an optimized solution.

III. PROPOSED FAULT RESILIENT COMMUNICATION NETWORK ARCHITECTURE FOR WPF

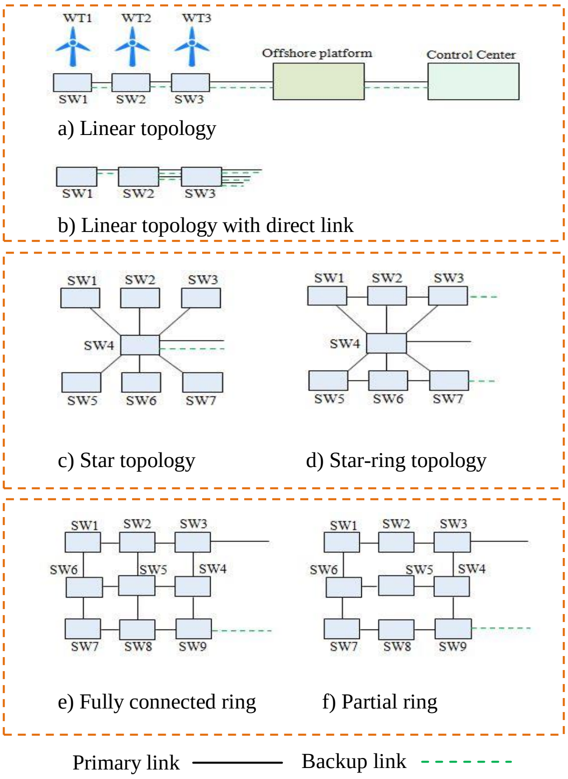
In this section, we discuss various communication network topologies that can be used for monitoring and control of WPF. Then, we define the level of the communication network architecture according to the network topologies.

A. Communication Network Topologies

Linear Topology: In this topology the WTs are connected in a point-to-point communication link. The communication among WTs, offshore platform, and CC is carried out through the same point-to-point links. The advantage of this type of topology is that, it is simple to install and configure. However, the failure of a node/link results in disconnecting rest of the WTs. A variation of this topology is that each of the WT is directly connected to the offshore platform with a separate dedicated link. In this case the failure of a link/node does not affect the communication of other WTs. However, in view of cabling requirements and cost, it is a complex and costly solution. Fig. 3a and Fig. 3b show the two kind of linear topology.

Star Topology: All WTs are connected to the Ethernet switch (ESW) of a central WT. This ESW operates as a coordinator for all the others WTs. The central WT has a point-to-point communication link with the offshore platform. A second kind of this topology is star-ring topology. All the WTs are connected to the central WT through a ring topology. The star topology is simple to setup and configure where the star-ring is more robust. However, failure of central WT in star topology could result in disconnecting the reaming WTs. The star-ring topology is more robust than simple star, but in this case failure of central WT results in linear topology. Fig. 3c and Fig. 3d show star topology and star-ring topology, respectively.

Ring Topology: In this topology, all WTs are connected in ring. This topology is high robust, simple, and cost effective. The failure of WT or link does not affect the communication of other WTs. A point-to-point redundant communication to the offshore platform provides a higher reliability in the network. Ring topology can be a fully connected or partially connected. The fully ring-topology is more reliable and robust but require more cables, devices and ports. Fig. 3e and Fig. 3f show the partial and fully connected ring topologies.



a) Linear topology

b) Linear topology with direct link

c) Star topology

d) Star-ring topology

e) Fully connected ring

f) Partial ring

Fig. 3. WPF Communication Network Topologies

B. Three Level Communication network architecture

In this study, we consider an Ethernet based resilient communication architecture for WPF. A schematic diagram is shown in Fig 4. To obtain reliability with a higher degree, the aforementioned architecture is divided into three levels: data generation level, data aggregation level, and control center level. Each level is based on a specific function, location, and network topology. To maintain fault-tolerance in the network, each level has redundant network resources. The WPF and offshore platform are located at offshore site while the CC is located at onshore. Rapid spanning tree protocols (RSTP) are adopted to avoid loop in the network. The following section describes these levels in detail.

Data generation level (DGL): Embedded sensors continuously monitor the components of WTs at DGL. Each WT has a WT controller (WTC) at its bottom. An ESW located at WTC maintains communication with previous and next WTC through an Ethernet link. The WTs within the WPF is connected through partial ring topology. The partial ring topology provides resiliency with higher degree at the DGL. The WPF is connected to the offshore platform through point-to-point connection. The resiliency between WPF and offshore platform is achieved through a secondary point-to-point link. The traffic is routed to the alternate backup link if the primary link fails.

Data aggregation level (DAL): DAL is the middle level of the communication network architecture between WPF and CC. The function of this level is to aggregate the WPF data to the CC. The offshore platform has redundant resources to maintain primary and secondary links. Primary ESW maintains a point-to-point primary link while the secondary ESW is reserved for backup. To provide resiliency with higher degree the primary and secondary ESW at this level are also connected through point-to-point link.

Control center level (CCL): The CC collects data through the offshore platform for processing. Control commands are then transmitted to WTs within WPF for appropriate action using primary and/or secondary link. At CCL the SCADA systems are connected through LANs using star topology. The resiliency at this level is achieved through redundant switches and links. The secondary network resource is used with the failure of primary network resources.

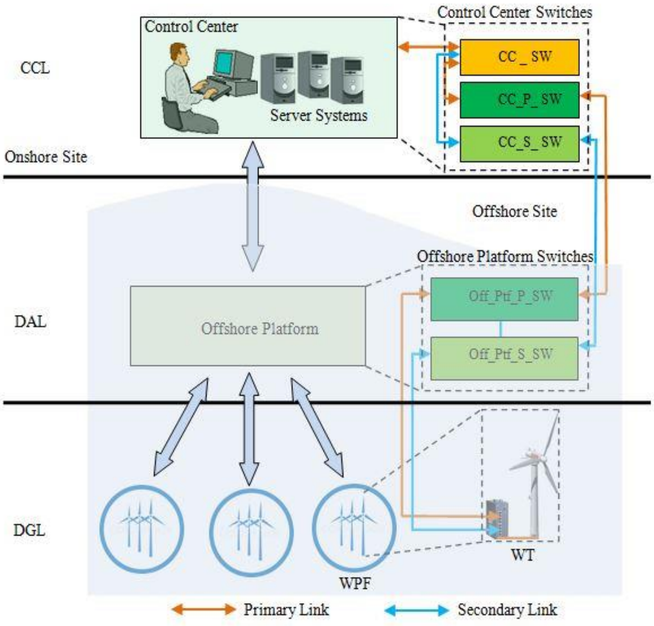


Fig. 4. Schematic diagram of network architecture with three levels

C. *Proposed fault-resilient communication architecture*

The proposed communication network architecture is based on hybrid network topology. The proposed architecture is shown in Fig 5. A partially connected ring topology is used to connect WTs within the WPF at the DGL. The WPF, offshore platform, and CC communicate through a point-to-point linear link.

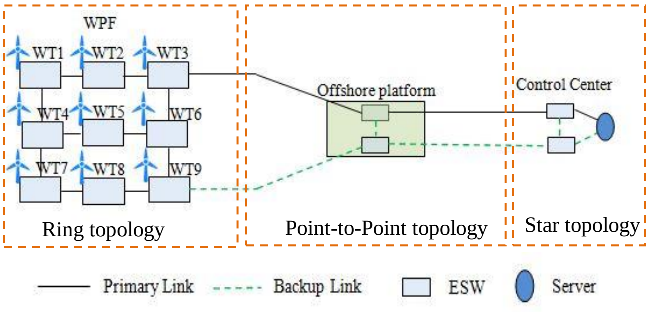


Fig. 5. Proposed architecture with hybrid communication network Topology

Within the CC the devices are connected through local area network using star topology. All the monitoring and control operations are performed through primary ESWs and links. For resiliency reserved backup network resources are used at each level of the architecture.

IV. WPF NETWORK MODELING

A. *Traffic Modeling*

The integration of WPFs into electricity grid explores new requirements in communication capabilities of WTs and electricity grid. The standard information model and communication system can make it possible to integrate the WPF into the electricity system. The IEC standard series 16400-25 defines a standardized way for accessing wind power data [11]. As discussed previously that this standard relates the components of WT into LNs. This work considers nine LNs including WROT, WTRM, WGEN, WCNV, WNAC, WYAW, WTOW, WTRF, and WMET. These LNs are categorized into status, analogue, and control information. Each category is sub-divided into different attributes. Table I shows the details about WROT and its associated attributes [12]. In accordance to the mandatory and optional LNs concept, we classified the WT monitoring data into critical and non-critical data to support different QoS requirements. Table II shows the critical and non-critical data for one WT.

TABLE I
SUB-ATTRIBUTES FOR WROT LN

Category	Attribute	Explanations
Status Information	RotSt	Status of rotor
	BlStB1	Status of blades
	PtCtlSt	Status of pitch control
Analogue Information	RotSpd	Value of rotor speed at rotor side
	HubTmp	Temperature in the rotor hub
	PtHyPresB1	Pressure of hydraulic pitch for blades
	PtAngValB1	Pitch angle for blades
Control Information	BlkRot	Set rotor to blocked position
	PtEmgChk	Check emergency pitch system

TABLE II
CLASSIFICATION OF WT CRITICAL AND NON-CRITICAL DATA

LN Class	Description	M/O	Type
WROT	WT rotor information	M	Critical Data
WGEN	WT generator information	M	
WNAC	WT nacelle information	M	
WYAW	WT yawing information	M	
WTOW	WT tower information	O	Non-critical Data
WMET	WPF meteorological information	O	
WTRF	WT transformer information	O	
WCNV	WT converter information	O	
WTRM	WT transmission information	O	

TABLE III
WT MONITORING MEASUREMENTS

Measurement	Sampling Frequency	Number of Channels	Data Transmissions(bytes/s)	No. of Measurement Devices
Temperature	1 Hz	1	2	16
Speed	3 Hz	1	6	3
Pressure	100 Hz	1	200	7
Pitch Angle	3 Hz	1	6	6
Vibration	200 Hz	3	1200	2
Voltage	2048 Hz	3	12288	12
Current	2048 Hz	3	12288	6
Power	5 Hz	1	10	2
Power Factor	1 Hz	1	2	2
Humidity	1 Hz	1	2	3
Wind Direction	3 Hz	1	6	3
Wind Speed	3 Hz	1	6	3
Displacement	10 Hz	2	40	2
Oil Level	1 Hz	1	2	4
Frequency	10 Hz	1	20	1
Torque	50 Hz	3	300	1
Status	1 Hz	1	2	29
Temperature	1 Hz	1	2	16
Total				**102**

The WT monitoring traffic depends on the sampling frequencies, the number of channels, and the number of sensors nodes. Table III shows monitoring measurements for 102 sensors. In our previous work we, proposed multilayer communication network architecture for WPF [13]. We considered 102 sensors that generate a total of 225,602 byte/sec (approximately 1.8 Mbps) monitoring traffic for a WT. The following formula is used to calculate the monitoring traffic for one WT.

$$\text{Data rate} = 2 * N_C * F_S$$

Where N_C is the number of channels or measurements devices (sensors) and F_S is the sampling frequency of each device. Each sample is of 2-byte in size. For example the vibration sensor generates 200 samples/sec, thus the total amount of traffic is 1200 byte/sec for 3 channels with 2 byte of data for each sample. Based on mandatory and optional data shown in Table I, the WT critical and non-critical monitoring traffic can be calculated. Table IV shows the critical and non-critical traffic for stand-alone WT.

TABLE IV
WT CRITICAL AND NON-CRITICAL TRAFFIC DATA

Traffic calculation for mandatory LNs		
LN Classes	**No of sensors**	**Data transmission byte/s**
WROT	14	642
WGEN	14	73764
WNAC	12	112
WYAW	7	220
Sub-total	**47**	**74,738 byte/sec**
Traffic calculation for optional LNs		
LN Classes	**No of sensors**	**Data transmission byte/s**
WTOW	4	8
WMET	7	228
WTRF	12	73740
WCNV	14	74060
WTRM	18	2828
Sub-total	**55**	**150,864 byte/sec**
Total	**102**	**225,602 byte/s ≈ 1.8Mbps**

By considering the above classification for critical and non-critical data, Table V shows the amount of traffic for single WT and for a small scale WPF consisting of 12 WTs. The overall traffic is then summed up as cumulative traffic.

TABLE V
CRITICAL AND NON-CRITICAL TRAFFIC FOR SMALL SCALE WPF

WT/WPF	**No of WTs**	**WT/WPF monitoring data in Mbps**		
		Critical data	**Non-critical data**	**Total**
Stand-alone WT	1	0.57	1.15	1.8
Small Scale WPF	12	6.84	13.81	20.64

B. *Network Modeling*

The communication network for WPF can be defined on the basis of electric power system topologies. The authors in reference [14] defined various electric topologies for WPF. To achieve high reliability the proposed communication network architecture in this paper follows hybrid topology. Fig 5 shows the OPNET [15] topology of a small scale WPF. It consists of 12 Ethernet work stations. Each workstation represents one WT. Offshore platform consists of primary and secondary ESWs. WPF is connected to primary ESW through primary link while the secondary link maintains a secondary connection. The CC uses three ESWs. The primary ESW maintains a primary connection with offshore primary ESW. The secondary ESW is used for backup/secondary connection. Both the primary and secondary ESWs are connected to the CC central ESW. The SCADA servers are connected to the central ESW. A link bandwidth of 100Mbps is used for the primary connection to support the WPF monitoring traffic. Similarly, link bandwidth of 10Mbps is used for the secondary connection. A low link bandwidth for the secondary link provides a cost effective solution. The SCADA servers system supports critical and non-critical data of WPF. In order to execute the network topology, different type of OPNET objects are needs to be configured. In our simulation scenarios, the following objects are used:

1. Application configuration: The application object is used to define and configure the traffic according to the user requirements. This object defines six common applications including: HTTP, E-mail, video, FTP, Voice, and database. In this work, we used this object as *WT_Application* and configure for two FTP applications (i.e. critical_app & non_critical_app) to generate two different types of WT monitoring traffic at application layer of the OSI model.

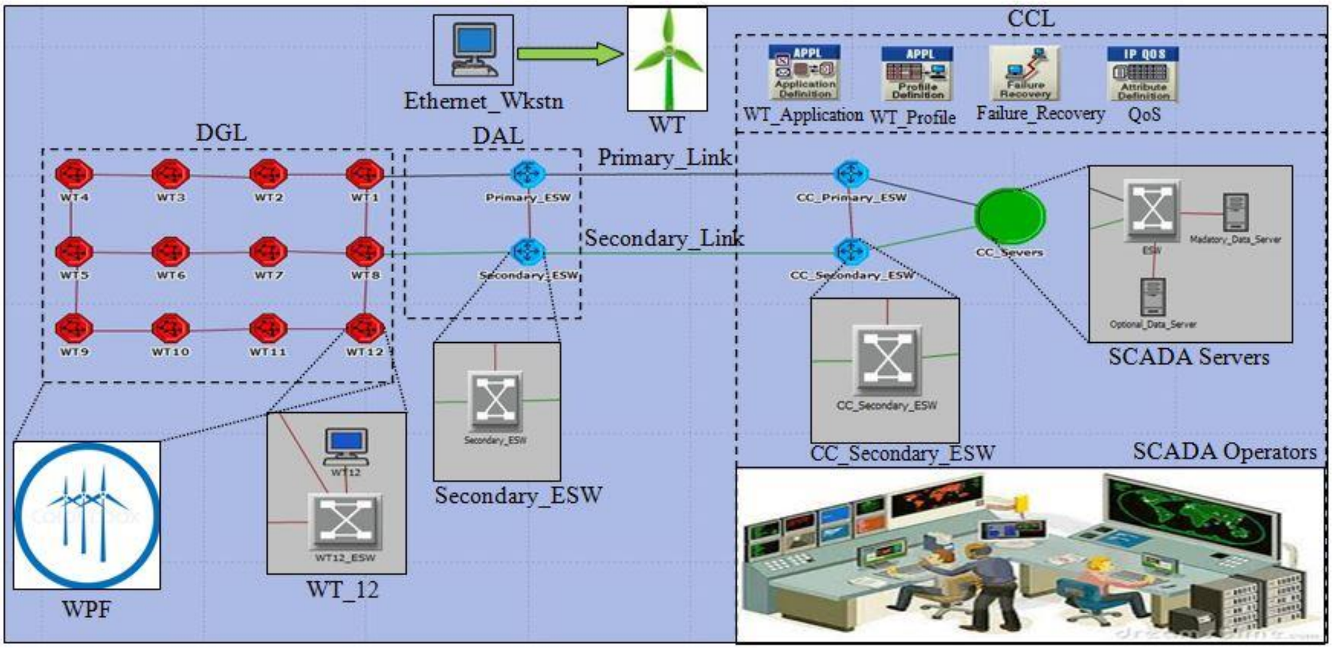


Fig. 5. OPNET Model for WPF Communication Network

2. Profile configuration: The profile object is used to create user profiles, which can support one or more application. The profile configuration defines the type of application to be used for the transmission of the traffic between the communicating nodes. It provides the starting and ending time for each application within the profile. In our work, we used the profile object as *WT_Profile*. This WT_Profile supports both critical and non-critical FTP applications. All the Ethernet work stations and server system support this profile. It enables the transmission and receiving of the WTs monitoring data between work stations and server systems across the network.

3. Failure recovery configuration: The failure recovery object is used to configure different failure points for link and nodes. The configuration of this object defines the type of failure, the time of failure (failure point), and the time of recovery (recovery time). In our simulation we used this object as *Failure_Recovery*. It is configured for primary link failure and recovery at three different times.

4. QoS configuration: This object is required for resource allocation to support the different QoS requirements. This object mainly deals with the three queuing policies: First in First out (FIFO), Priority queuing (PQ), and weighted-fair queuing (WFQ). These policies are discussed as follows.

4.1 FIFO Queue: The FIFO queuing discipline is simple as the first packet that arrives at a node is the first packet to be transmitted. The buffer space is finite and the nodes (Switch or router) discard an incoming packet if the buffer is full. This policy does not care, whether a packet is important or not. Hence it cannot support any QoS requirements.

4.2 Priority Queue (PQ): In the PQ configuration each packet is marked with a priority in the IP Type-of-Service (ToS) field. The communicating nodes then maintain multiple FIFO queues, one for each priority class. Within each priority class, the packets are still managed in a FIFO manner. This queuing discipline allows packets with a high priority to be transmitted before those with a low priority. The PQ policy supports the QoS requirements for different application.

4.3 Waited-Fair Queue: In the weighted-fair queuing (WFQ) discipline multiple queues are maintained by the nodes. For each packet a weight is assigned in the ToS field of the IP header. This weight effectively controls the percentage of the link bandwidth. According to the link bandwidth, it transmits the data with high priority. The nodes manage the WFQ services through round robin manner. In our simulation model we configure the *WFQ* queuing policy to prioritize the critical data over the non-critical data. Thus, the transmission of critical data is guaranteed with secondary link in case of primary link failure.

V. SIMULATION RESULTS AND DISCUSSION

The performance of the proposed fault-resilient communication network architecture is analyzed through end-to-end delay, data loss, and data received. Several link failure and recovery scenarios are simulated. The first scenario is normal network operation without any failure. The result in Fig. 6 shows that the amount of data received, which is 6.84 Mbps and 13.81 Mbps for critical and non-critical monitoring traffic, respectively. These results are validating our simulation according to the numerical calculation in Table V. The Fig. 7 shows that the end-to-end delay is 6.5 ms and 9.5 ms for critical and non-critical monitoring data, respectively.

The second scenario considers link failure. In this scenario, the primary link is failed and recovered at three different points. Fig. 8 shows the cumulative transmitted and received traffic. The result indicates data drop in the received traffic with the failure of primary link. This data drop is in total (cumulative) traffic, and it difficult to differentiate whether critical or non-critical data are lost. This is because in this scenario no QoS requirements are considered. This data drop is due to the fact, that with the primary link failure the traffic diverts to the secondary link. The peak lines in the figure shows the retransmission of the data packets in the waiting queue. The third scenario considers QoS of requirements. The WFQ policy configuration is adopted to prioritize the critical data. In this scenario, the primary link is also failed and recovered at three points. Fig. 9 shows the amount of received traffic for critical and non-critical monitoring data. The result clearly indicates that with failure of primary link the non-critical data is dropped. The transmission of critical data is guaranteed. Thus the non-critical data are sacrificed for the transmission of critical data. The result in Fig. 10 shows that the end-to-end delays are 69 ms and 353 ms for critical and non-critical data, respectively. There are two main reasons for this increased delay. First, the secondary link has a lower link capacity. Second, the queuing delay is increased by the packets waiting for retransmission at the time of primary link failure.

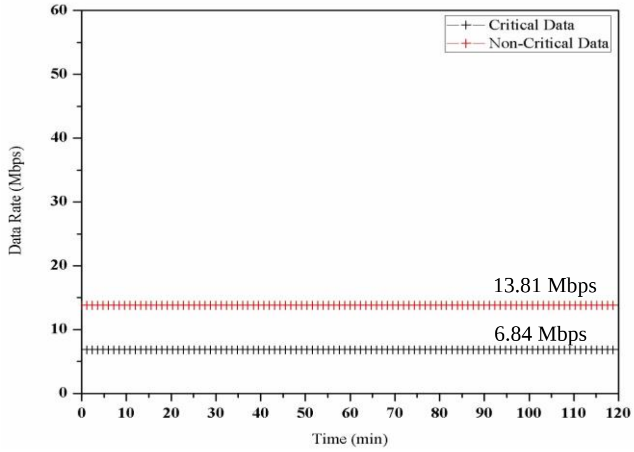


Fig. 6. Total amount of received data without failure

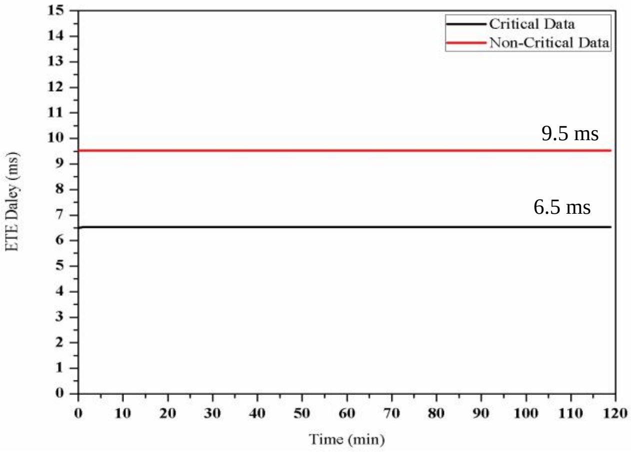


Fig. 7. ETE delay under normal operation

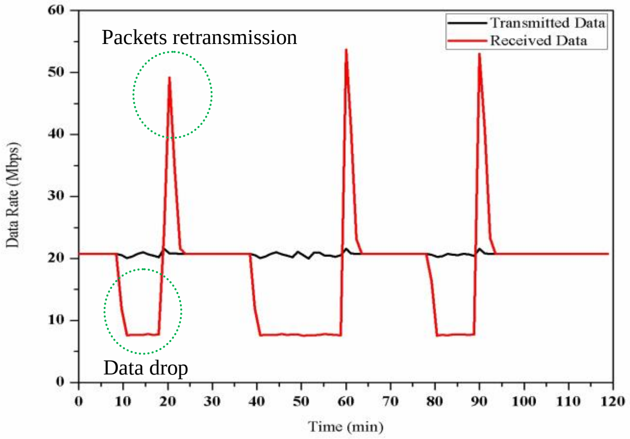


Fig. 8. The impact of primary link failure

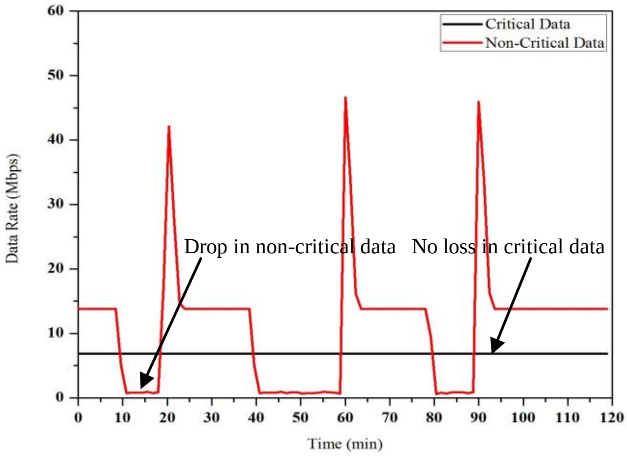


Fig. 9. Total amount of received data with primary link failure

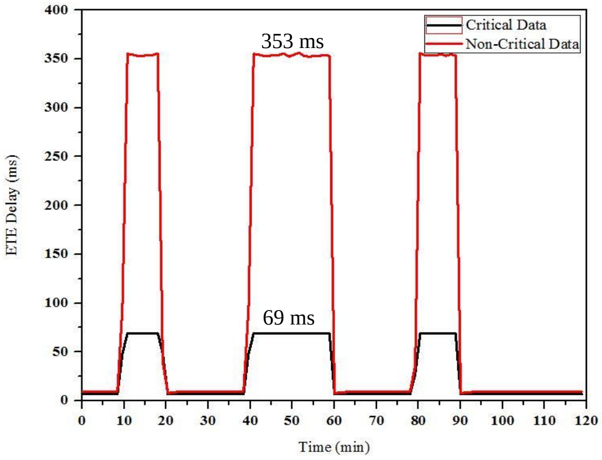


Fig.10. ETE delay with primary link failure

VI. CONCLUSION

In this paper, we proposed fault resilient communication network architecture for monitoring and control of WPF in real time. The proposed architecture was based on a hybrid topology consisting of three levels: DGL, DAL, and CCL. At the DGL, the WTs are connected in a ring topology. DAL supports the connection through point-to-point linear topology between the WPF and CC. The communication network architecture was designed with different link bandwidth of 100Mbps and 10Mbps for primary and secondary link, respectively. The traffic of LNs was modeled into critical and non-critical data according to the IEC 61400-25 standard. The monitoring data was prioritized by WFQ policy according to the required QoS. We investigate the end-to-end delay, data loss, and data received with different scenarios. Under the normal, operation the end-to-end delay was about 6.5 ms and 9.5 ms for critical and non-critical data, respectively. In the case of primary link failure the data was lost. However, considering the QoS the critical data (6.84 Mbps) was successfully received. The non-critical data sacrificed for the transmission of critical data. Thus it can be concluded that in the case of network fault the proposed fault-resilient communication architecture can support the transmission of critical data. In future, the work will be extended for large scale WPF.

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