Paper

Reliability of Communication Systems Used in Offshore Wind Farms

Tadeus Uhl[1,2]

[1] *Maritime University of Szczecin, Szczecin, Poland,*
[2] *Flensburg University of Applied Sciences, Flensburg, Germany*

https://doi.org/10.26636/jtit.2022.166022

Abstract — In the era of renewable energy, offshore wind farms play a very important role. The number of such installations in Europe is increasing rapidly. With the growing capacity of wind turbines installed in these farms (3, 5, 10 MW), the profitability of this type of energy systems plays an increasing role. The number of wind energy turbines installed at offshore wind farms is growing constantly as well. Once installed, the power plants must be under constant technical supervision, with reliability of electronic communication systems being a particularly important aspect in the operation of offshore wind farms. Considerations focusing on this subject form the very core of this paper. After an introduction to offshore wind farms, the following aspects will be discussed: redundant topologies, e.g. multiple HiPERRings, redundant switches and routers within the backbone networks, redundancy of the transmission media used, alternative transmission technologies, e.g. WLANs (IEEE 802.11h, IEEE 802.11g). Finally, requirements applicable to reliable electronic communication systems used in offshore wind farms will be formulated.

Keywords — communications technology, offshore wind farms, reliability, redundancy, telematics systems

1. Introduction

The 21st century is characterized, inter alia, by major changes taking place in the field of energy sources. Renewable energy generated with the use of wind, water, sun and biological resources is relied upon ever more widely and plays an important role in the energy mix. Wind energy offers great potential here, as this source is available virtually anywhere in the world. Consequently, many companies have been stimulated [1] to design, manufacture and operate sufficiently large and profitable wind turbines. Especially in coastal areas, such a source of energy source may be very profitable. Therefore, in recent years, many offshore wind farms have been erected in numerous coastal countries of Europe (e.g. England, the Netherlands and Germany) and all over the world (e.g. USA, China, Australia) [2]. The construction of such farms is very costly and time-consuming. It also required a significant technical effort and poses a number of logistical challenges.

Safety plays an important role in the operation of offshore wind farms. Three distinct aspects may be distinguished here:
- safety of personnel performing construction, operation, and maintenance works,
- safety of navigation through wind farms,
- reliability of communications between specific wind farms systems and components.

In the first case, the focus is on identifying specific components/elements of the wind farm, as well as on describing the escape routes and alarm systems used in the event of an accident/failure. In the second case, rules need to be developed to enable shipping along very narrow (2 km wide) corridors between water farms, especially at waterway intersections. In the third case, reliable communication needs to be ensured between components/subsystems of the wind farm, regardless of the weather conditions and of the time of year. It is this area of activity that constitutes the main topic of this work. This paper systematizes and expands on the content of the internal technical report [3].

Initially, aspects related to the construction of offshore wind farms will be presented briefly. Next, a general concept of a telematics system relied upon for ensuring communication within these farms will be described. The article will focus primarily on the techniques and methods fostering reliability of this type of communication. The “redundancy” will play a special role here. At the end of the work, requirements applicable to a reliable telematics system used in offshore wind farms will be formulated. The work will conclude with a summary and outlook concerning future work.

2. Telematics Systems in Offshore Wind Farms

Construction of wind farms in coastal areas requires intensive cooperation and coordination between wind farm operators on the one hand and manufacturing, administration, and transport companies on the other. This is a very complicated and time-consuming process. Good management is a key factor determining whether such projects turn out to be successful from the business point of view.

Figure 1 shows a typical layout of an offshore wind farm [4]. It illustrates how large such farms may be and how close are turbines located to each other (in rows!). In order for this comprehensive system to work effectively, many specialized systems supporting its management and monitoring are necessary. Reliable communication between these systems plays a key role here.

Fig. 1. Offshore projects by Bernstein and Citrin in the North Sea.

In order to ensure effective and reliable operation of offshore wind farms, all components and subsystems of these farms must remain under constant supervision. Suitable telematics systems must be designed and implemented for this purpose. Figure 2 shows a block diagram of a telematics system intended for offshore wind farm projects [3].

The telematics system presented in Fig. 2 consists of numerous hardware subsystems and software components, such as:

- WET control station. It is responsible for the controlling the operation of individual wind turbines;
- Power management. It collects measurement results concerning, inter alia, voltage and current levels, turbine power, frequency of the current generates. This system also allows to control the measured parameters of the wind farm;
- Communication connection. It serves as an interface with the telecommunications network providing access to individual subsystems of the wind farms;
- Weather station. It measures the meteorological parameters, such as wind direction and force, air temperature, etc.;
- Online portal. It collects large amount of data concerning the wind farm;
- Reporting station. It offers visualizations of the current condition of and provides an overview of the historical data related to the wind farm.

Offshore wind farms are built at a considerable distance from the coast, for example in Germany: Alpha Ventus – 43 km, Borkum Riffgrund West – 50 km, Dan Tysk – 70 km, Sandbank24 – 90 km. Due to the long distances to mainland, the farms' telematic systems are connected to public networks using optical fibers. At distances of up to several kilometers, multimode 50/125 μm optical fibers with a wavelength of 1300 μm and attenuation values of 1 dB/km are used. For longer distances, which should not exceed 30 km, however, 9/125 μm single-mode optical fibers with a wavelength of 1300 μm and attenuation value of 0.4 dB/km are used. For distances of over 30 km, 9/125 μm single-mode fibers with a wavelength of 1550 μm and attenuation factor of 0.25 dB/km are relied upon.

The technical requirements that must be met by specific wind farm components are another important aspect. All parts must function reliably in harsh environmental conditions, often over periods of many years. Electronic devices must function properly over a wide temperature range (-30°C to $+60$°C) and must also prevent the ingress of moisture and contamination. IT systems used must comply with the ISO 20653 standard [5] as well.

Telematics systems for offshore wind farms need to comply with strict reliability requirements. Due to long distances between wind farms and mainland, maintenance and servicing operations may only be performed in favorable weather conditions and are governed by numerous constraints. Thus, a high level of reliability of IT systems used in wind farms must be guaranteed. Table 1 shows an overview of the specific reliability classes according to [6].

Tab. 1. Overview of reliability classes and unavailability time.

Class	Reliability [%]	Down time, per year
Stable	99.0	3.7 days
Available	99.9	8.8 h
Highly available	99.99	52.6 min
Insensitive to errors	99.999	5.3 min
Fault tolerant	99.9999	32 s
Free of errors	99.9999	3 s

To illustrate the importance of reliability, two failure scenarios affecting offshore wind farms will be discussed. The first one assumes that errors occur without any external interference, e.g. failure of a device supplying power to electronic components. The other one involves errors caused by deliberate human action, e.g. by switching off devices while performing maintenance work. In the first case, failures may be prevented by using such equipment as uninterruptible power supplies (UPS) which are capable of supplying electricity to electronic devices for the required period of time. In the other case, reliability depends on redundant solutions implemented within the wind farms. This topic will be covered in detail in the next section.

3. Redundancy in Wind Parks

When designing and building high-quality telematics systems, special attention should be paid to the redundancy of their components. Redundant elements may be connected to each other in series or in parallel. It is known from the reliability theory that the reliability of a system relying on series connections is described by:

$$P(A \cup B) = P(A) + P(B) = P(A \cap B), \qquad (1)$$

For parallel connections, Eq (1) takes the following form:

$$P(A \cup B) = P(A) \cdot P(B). \qquad (2)$$

For example, if $P(A) = P(B) = 0.1$, then total reliability of a system made up of components connected in series

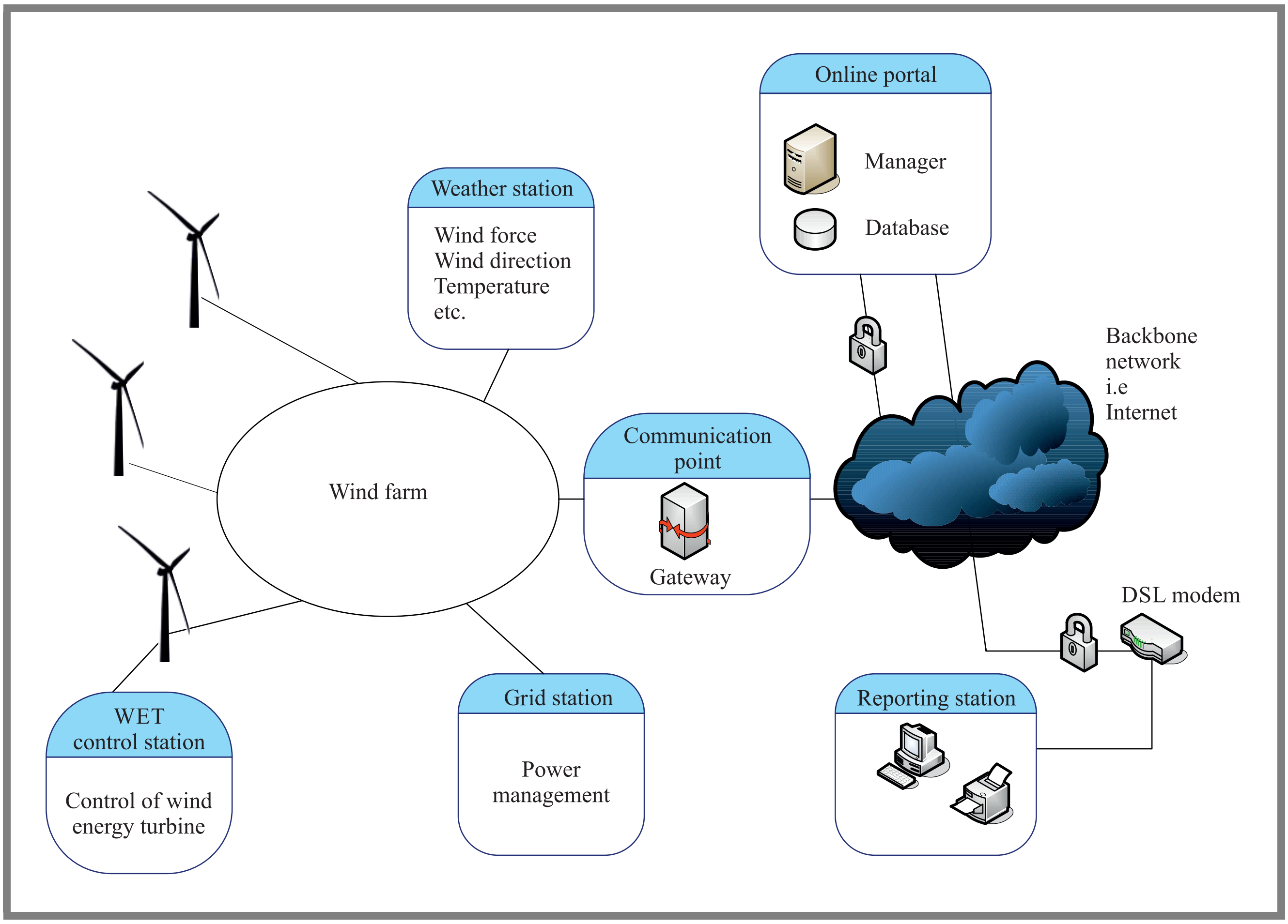

Fig. 2. Block diagram of a telematics system intended for offshore wind farms.

equals 0.81, and in the case of a parallel connection, it amounts to 0.99. This is a very convincing example, showing that in order to ensure high reliability of the entire system, its redundant elements should be connected in parallel. Therefore, parallel connections are used in redundant offshore wind farm systems.

3.1. Ring Redundancy

The individual wind energy turbines (WET) are most often positioned linearly and at equal distances from each other (see Fig. 1). Figure 3 shows a typical ring topology connection between WETs, relying on optical fibers. Two optical fibers (transmit and receive) are sufficient for a basic connection between WETs. Four optical fibers are required for a redundant WET connection. Since Ethernet data transfer between two points can only take place using an unambiguous connection path, the primary ring structure is interrupted by a redundancy check. To overcome this problem, a redundancy manager (RM) is used. It is a functional block implemented in the switch with the smallest number and is only available once in HiPERRing [7]. If all the connections in HiPERRing are working properly, the RM transforms the ring structure into one of the linear type. Using test and control packages, the RM controls the functioning of the ring structure. If one switch fails or the optical fiber in the physical ring fails, the test packets sent via one port will not be received using the other. In this case, the RM activates the redundant connection, i.e. uses the other fiber optic path.

The reconfiguration time should be less than 500 ms. Therefore, the number of WETs in one ring is limited to approx. 10–15. If an offshore wind farm is made up of a large number of WETs, these must be linked together by multiple HiPERRings. The individual HiPERRings lead to the communications point (see Fig. 2), where they are connected to each other.

Using the multiple HiPERRing technique, it is possible to efficiently commutate redundant rings. The rings are divided into main ring and subrings. Naturally, it is possible to connect multiple subrings to one main ring. The multiple HiPERRing technique enables the start and end point of one subring to be connected to the main ring at different locations (Fig. 4).

If media redundancy protocol MRP [8] is used for commutation in the sub-rings, it must also be used in the main ring and in the LANs defined within the main ring. If a HiPERRing is used in the main rings, the MRP protocol can be used in the subrings. The formation of mesh structures between rings or their cascading are not allowed.

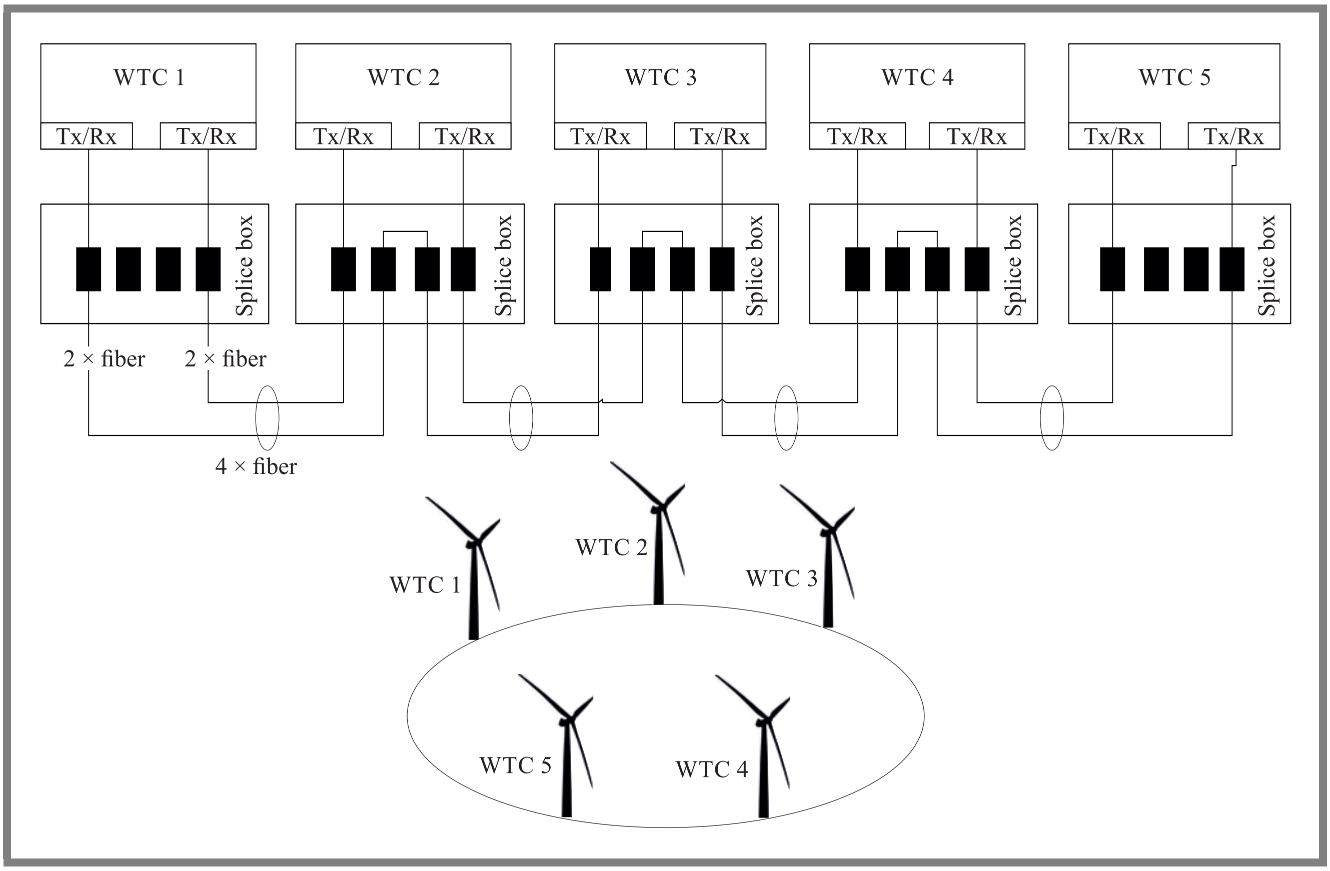

Fig. 3. Typical WET ring structure cabling layout with redundant optical fibers.

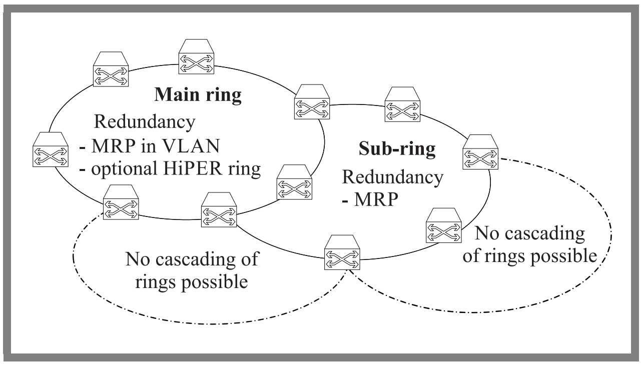

Fig. 4. Structure of a telematics system based on the main- and sub-rings concept.

By using additional cables, it is also possible to ensure a redundant connection between the two rings. Such an approach guarantees that communication may be maintained also if more than one ring element malfunctions. Access to other functioning components is possible by relying on the redundant cables existing within the structure. However, HiPERRing or MRP techniques cannot be used at the junction of the two rings, where the Rapid Spanning Tree Protocol [9]–[10] (RSTP) must be deployed.

3.2. System Redundancy

The term "system redundancy" means that multiple IT components are used. Such redundancy is not always necessary or beneficial, and always leads to increased costs and additional implementation-related efforts.

Figure 5 shows an example solution ensuring system redundancy, in which one defective HiPERRing is connected to two independent switches in the backbone network (communication point, see Fig. 2). The failure of one switch in the backbone is immediately compensated for by a well-functioning second switch. Communication between switches in the backbone could be additionally supported by relying on the link aggregation technique [10]–[11]. The use of such a technique would be another factor boosting redundancy of the system.

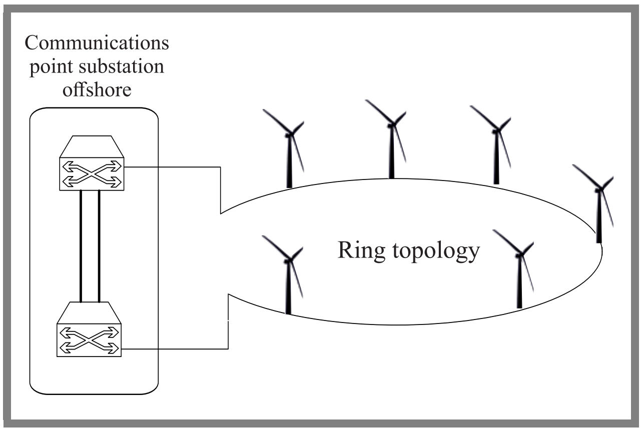

Fig. 5. Example of a solution offering system redundancy.

3.3. Media Redundancy

Media redundancy involves the use of various forms of communication. Cables are used as the primary communication medium. In practice, as an alternative, radio channels are used as well. In order for the alternative communication medium to function effectively, the system components relying on cable and radio channels must be completely independent of each other. This means that the use of different communication media leads to the creation of separate, independently functioning communication networks.

Figure 6 shows an example of the use of various communication media. Two rings are presented, with one of them based on a cable and the other on a radio link. Both rings are connected to each other via suitable coupling elements at the communication point. Since WETs are placed in rows (see Fig. 1), the radio link must always provide a WET-WET connection. As the MRP protocol is used, it would be advisable here to ensure a low reconfiguration time. On the other hand, this type of connection requires a significant implementation effort, as each WET must be equipped with two antennas. Furthermore, even if one WET fails, the radio ring is interrupted immediately. This is a major drawback of the ring structure and, therefore, such a solution is not used in offshore wind farms.

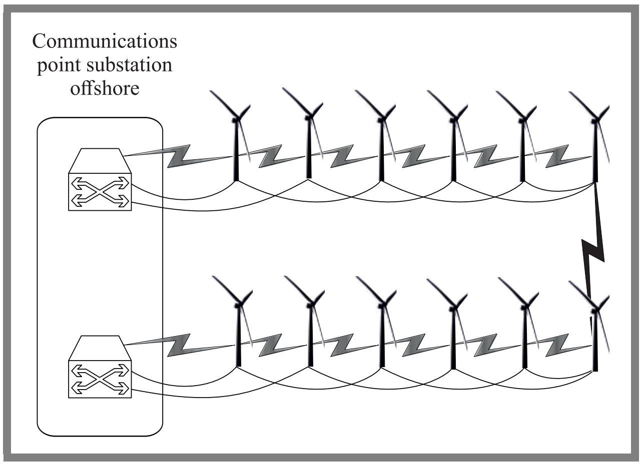

Fig. 6. Example of a ring-shaped radio network.

Figure 7 illustrates two cable-based ring networks and an additional star-shaped radio network. The radio network is controlled from a central point (master station). Hence, it is possible to communicate via radio channels with any WET device (slave station). This structure is dominated by point-to-multipoint connections. The insignificant implementation effort is an advantage here (only one antenna per WET is required only). Additionally, each WET can be individually pooled by the master station. Moreover, the failure of one WET does not affect the communication between other stations. These are the big advantages of the star topology. The drawback of star-shaped systems is the low bandwidth they are capable of achieving on dedicated radio channels. Their throughput depends on the number of WETs within the farm and on the shared medium assigned to the entire system. Additionally, it may be the case (especially in large farms) that radio waves emitted by individual WETs will interfere with each other and, therefore, communication may be difficult.

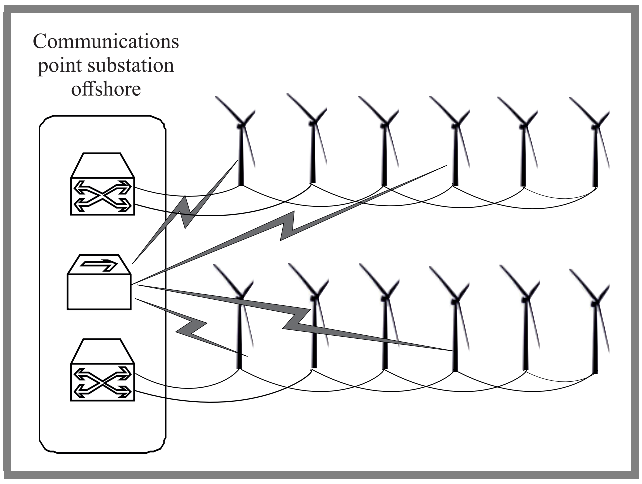

Fig. 7. Example of a star topology radio network.

The star topology seems to be a suitable solution for offshore wind farms. It is easy to implement and offers good reliability of the entire system. Radio networks may be based on a number of well-known standards, such as IEEE 802.11h (up to 54 Mbps in the 5 GHz band [12]) and IEEE 802.11g (up to 54 Mbps in the 2.4 GHz band [13]). Upcoming standards, such as IEEE 802.11n (248 Mbps gross bitrate in the 2.4 and 5 GHz [14] bands) and IEEE 802.11s (for radio mesh networks [15]) should be taken into account as well. When using these types of systems, one should bear in mind that the total capacity of the system is shared among all installed stations. In addition, data transfer speeds may be significantly reduced due to interference (e.g. generated by radar working in the 5 GHz band). Weather conditions also exert a negative impact on radio channels, causing interference and, consequently, degrading the range of the networks. Finally, it should be emphasized that in the case of radio networks, the transmitted data must be secured by technologies such as wired equivalent privacy (WEP) [16] and Wi-Fi protected access (WPA) [17].

4. Requirements for Telematics Systems in Wind Farms

Based on the information presented in the previous chapters, one may specify the requirements applicable to telematics systems used in offshore wind farms. The highlights of such a specification include the following:

- IT components must be adapted to the prevailing environmental and operational conditions (i.e. temperature, air chemistry, mechanical impacts, humidity, etc.). The most stringent ISO standards have to be respected;
- Components of telematics systems must be implemented redundantly. Parallel connections between individual elements of the telematics system should be used;
- The communication networks used should be redundant, i.e. should be based on main and subring topologies;

- When designing and building telematics systems, attention should be paid to the use of various types of transmission media (cables, radio links). It should be noted here that media redundancy involves the construction and operation of communication systems operating independently;
- State-of-the-art data security solutions must be implemented;
- When designing and building telematic systems, international standards applicable to IT systems need to be observed.

5. Summary and Outlook

This paper is devoted to the reliability of telematics systems used in offshore wind farms. After a short introduction, the main characteristics of such systems and the data network structures most frequently used in wind farms are described. Next, the general concept of a telematics system used for communication in offshore wind farms is presented, and techniques boosting the reliability of communication are shown. The notion of redundancy and its important role are described as ell. At the end of the article, a catalogue of safety- and reliability-related requirements applicable to electronic communication systems used in offshore wind farms is created.

A summary of this paper was presented at the 12th International Scientific Conference EXPLO-SHIP 2022 “Problems Concerning the Operation of Vessels and Port Facilities” [18].

The reliability of telematics systems used in wind farms, as analyzed in this study, is only one of the three important aspects guaranteeing the security of offshore wind farms. The remaining crucial aspects include the safety of navigation and personnel. There is still much room for improvement in these fields. Research concerned with the safety of navigation in offshore wind farms is facilitated by maritime navigation simulators. They allow to create conflict situations and identify the potential solutions. The Flensburg University of Applied Science operates a very modern Nautical Center equipped with five captain bridge simulators. Similar simulators are also available at the Maritime University in Szczecin. It would be advisable to establish cooperation in this particular field of research. Further research focusing on this topic is planned in the future.

References

[1] –, Wind turbine manufacturers, `http://en.wikipedia.org/wiki/List_of_wind_turbine_manufacturers`.

[2] –, List of offshore wind farms, `http://en.wikipedia.org/wiki/List_of_offshore_wind_farms`.

[3] N. Struve, “Planung- und Konzeptionierung eines Kommunikationsnetzes für Offshore Windpark Thornton Bank (Belgien)”, (in German) *Internal technical report, Flensburg University of Applied Sciences*, 2010.

[4] –, Offshore-projects by company BARD, `http://www.windkraft-journal.de/2011/10/20/tuv-sud-zertifiziert-520-mw-offshore-projekte-von-bard`.

[5] –, Standard ISO 20653, `http://en.wikipedia.org/wiki/IP_Code`.

[6] –, High availability stages, `http://en.wikipedia.org/wiki/High_availability`.

[7] Hirtschmann: Anwender-Handbuch (in German). Hirschman Automation and Control GmbH, Neckartenzlingen, 2010.

[8] –, Standard IEC 62439-2, `http://en.wikipedia.org/wiki/Media_Redundancy_Protocol`.

[9] –, Standard IEEE 802.1w, `http://www.ieee802.org/1/pages/802.1w.html`.

[10] K. Nowicki and T. Uhl, “Ethernet End-to-End”, *1th Edition, Shaker-Publisher*, Germany, 2008 (ISBN: 978383832271404).

[11] –, Standard IEEE 802.1AX, `http://ieee802.org/3/axay`.

[12] –, Standard IEEE 802.11h, `http://en.wikipedia.org/wiki/IEEE_802.11h-2003`.

[13] –, Standard IEEE 802.11g, `http://en.wikipedia.org/wiki/IEEE_802.11g`.

[14] –, Standard IEEE 802.11n, `http://en.wikipedia.org/wiki/IEEE_802.11n`.

[15] –, Standard IEEE 802.11s, `http://en.wikipedia.org/wiki/IEEE_802.11s`.

[16] –, Wired Equivalent Privacy, `http://en.wikipedia.org/wiki/Wired_Equivalent_Privacy`.

[17] –, Wi-Fi Protected Access, `http://en.wikipedia.org/wiki/Wi-Fi_Protected_Access`.

[18] –, “Problems of vessels and port facilities operation”, *12th International Scientific Conference EXPLO-SHIP*, 2022.

Tadeus Uhl received his M.Sc. in Telecommunications from the Academy of Technology and Agriculture in Bydgoszcz, Poland in 1975, his Ph.D. from the Gdańsk University of Technology, Poland in 1982 and his D.Sc. from Dortmund University, Germany in 1990. Since 1992, he has been working as a Professor at the Institute of Communications Technology, Flensburg University of Applied Sciences, Germany and, in addition, since 2013, as a Professor at the Institute of Transport Engineering and Economics, Maritime University of Szczecin, Poland. His activities focus on the following areas: traffic engineering, performance analysis of communications systems, measurement and evaluation of communications protocols, QoS and QoE by triple play services, Ethernet and IP technology. He is an author or co-author of five books and 130 papers dealing with LAN, WAN and NGN.

`https://orcid.org/0000-0001-6849-9168`

E-mail: t.uhl@pm-szczecin.pl, tadeus.uhl@hs-flensburg.de

Maritime University of Szczecin, Szczecin, Poland

Flensburg University of Applied Sciences, Flensburg, Germany