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Technologies of Data Transmission in Modern Systems of Relay Protectioin and Automation and Their Quality Indicators

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Abstract: The study describes the quality indicators (Ping and BER) of RS-485 and Ethernet traditional interfaces, as well as advanced technology of xPON-networks used in the construction of the collection and transmission systems in power industry. The technical and economic aspects of passive optical networks use in power industry on the example of GPON networks are analyzed in this study. The study proposes the use of well-known GPON technology for the systems of information collection and transmission, when solving the problems of construction of centralized systems of relay protection, automation and signaling as well as the organization of technological information collection from microprocessor units of relay protection, mechanization and automation in electrical installations of different voltage classes.

Key words: The system of information collection and transmission, relay protection and emergency control equipment, centralized system of relay protection, automation and signaling, RS 485 interface, industrial ethernet, technologies of passive optical networks xPON, GPON, IEC 61850, data transmission quality indicators, Ping, Bit Error Rate (BER)

INTRODUCTION

In recent years, the systems and devices of microprocessor relay protection and automation (microprocessor relay) come to replace electromechanical and static relays. According to the cited statistics of the installed microprocessor relays in the United States of America in 2007, the amount of devices was from 30% (differential busbar protection) to 65% (generator protection) (Baghchesaraei *et al*., 2015). According to the data given in the "Concept of development of relay protection and automation of electric grid complex" (Baghchesaraei *et al*., 2014), in Russia in 2015, 18.43% of microprocessor devices were in operation (from the total amount of devices of Relay Protection and Automation (RPA)). According to the market growth forecast report (Baghchesaraei *et al*., 2016) of microprocessor relay protection from 2016 till 2021, the world's capitalization will amount from $3.31-4.54 billion, reflecting the continuing trend to increase the number of microprocessor relay as part of relay protection and automation systems worldwide.

Modern microprocessor relays are not only the devices that protect electricity-generating equipment of different voltage classes but also have the ability to perform the functions of SCADA-systems, the systems of monitoring and control of relay protection and Emergency Automation (EA). These functions are implemented while scanning the microprocessor relays by selected channels of communication of Information Acquisition and Transmission Systems (IATS). The development prospect of "digital substation" concept determines the need to deploy a single interplant IATS for the systems of relay protection and automation, SCADA and other automation systems according to IEC 61850 (Fig. 1) (Chao, 2007).

Against the background of growth in the number of functions performed by microprocessor relays, the equipment and communication channels are imposed increasingly high demands for reliability, productive efficiency, redundancy as well as electromagnetic compatibility including the creation of substation networks with zero loss of data packets (Jiali and Congju, 1991). The economic aspect is also an important component of the possibility of innovative solutions introducing. In most cases, the solutions, providing qualitative technological effect but leading to significant increase in cost, can not find wide application for a long time. So, urgent is the direction of search for compromise solutions which contain the benefits of new technologies, eliminating the disadvantages of the old methods and providing additional functions that will improve the productive efficiency and reliability of the systems as a whole while being economically feasible.

Often, for the objects of medium voltage class, the cost of IATS deploying correlates with the cost of the objects themselves. For the objects of high voltage class the cost of deploying of such systems is justified,

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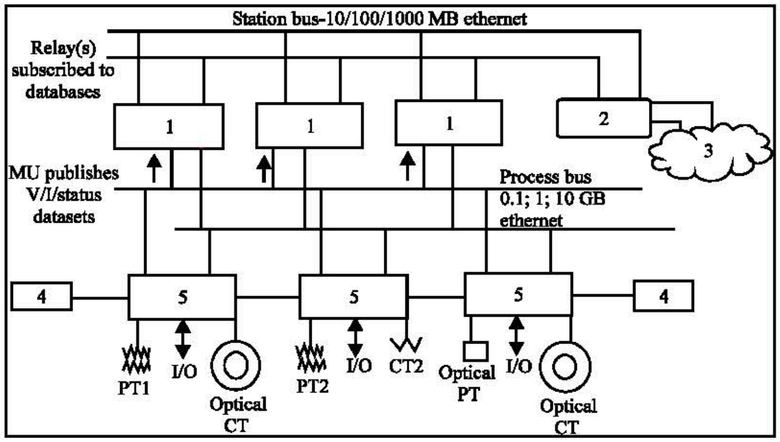

Fig. 1: The model of electric substation according to IEC61850; 1: relay, 2: remote access, 3: network, 4: clock, 5: merging unit, PT: Power Transformator, Optical CT: Optical Circuit Transformator, CT: Circuit Transformator

because the emergency situations and connected with them power interruption are unacceptable for the requirements of reliability and quality of electric supply of large industrial and municipal consumers, for the requirements of providing network operating modes, as well as on grounds of significant economic damage.

When deploying IATS at electricity generation facilities, it also needs to consider the impact of complex electromagnetic environment inside the high-voltage electrical equipment through which or next to which communication channels are routed and IATS equipment is installed. Despite the fact that all devices and communication channels are not put into operation without checking for compliance with the electromagnetic compatibility standards, to eliminate completely the influence of interference is not possible (Xin, 2004). This problem is relevant all over the world: for example, according to the report of Japanese manufacturing companies (Yan, 2003) about the defectiveness of microprocessor relay systems from electromagnetic influences, the number of temporary and permanent damages is an average of 6 cases per year.

Traditionally, communication channels, on the basis of RS-485 and Ethernet, mostly based on twisted pair, are used now in most cases between the microprocessor relays for data communication in IATS on the facilities of different power voltage. However, more and more, the manufacturers, at the request of the customer, install the optical interface converters for RS-485 or high-speed optical Ethernet ports. These solutions make it possible to take advantages of optical transmitters:

- Reliability of the communication channels
- High speed of data transmission
- Interference protection
- Wide bandwidth
- The possibility of use of wavelength-division multiplexing (the organization of full-duplex communication, using a single waveguide)
- Fire safety
- Guaranteed bandwidth (using the synchronous/plesiochronous digital hierarchy of the network (SDH/PDH)
- The ability to create long lines of communication

Despite the obvious benefits, for the organization of the network, based on optical communication channels, it is necessary to have complex active communications equipment-optical switches which cost is several times higher than their conventional counterparts and now this fact limits the widespread use of optical solutions, increasing the reliability of power supply and control by power facilities in general.

It should be noted, that at present, economically feasible for medium voltage objects, becomes the construction of relay protection systems or signaling systems, not on the base of separate microprocessor relays (protecting its own feeder) but as a single for the entire object of centralized system of control, protection and signaling, that is a set of microprocessor devices, highly reliable IATS and centralized subcontrol. IATS in this case is the basic unit, determining the reliability, quality and functional operation of the centralized system, which in turn imposes significant requirements as to the communications channels installed at the object as well as to the reliability and to noise immunity of information collection and transmission devices.

COMPARISON OF DATA TRANSMISSION CHANNELS INDICATORS

The main indicators of data transmission quality are the following:

- Jitter: an absolute difference of propagation delays of two consecutive received packets, belonging to the one information flow
- Ping: the time, need for a data packet to reach the selected device via the network and then come back to the source device
- BER (Bit Error Rate): the ratio between the transmitted information bits, correctly and incorrectly transmitted

Quality parameters of the RS-485: RS-485 interface is one of the most common communication interfaces in the industry and, in particular, in the energetic. Its wide use is caused by the flexibility, ease of programming and relatively high data rates (up to 10 Mbit/sec). There are the factors limiting, under certain conditions, the possibility of this interface:

- Cable length
- Cable design
- Cable impedance (capacitance and inductance smooth the pulses wave form, that increases the probability of error occurrence, in the process of data transfer)
- Interference margin
- Steepness of driver input voltage
- Approval of termination load (good conditioning reduces signal reflections to minimum, improving the quality of information exchange as a whole)

Let's consider the main indicators of quality of RS-485 interface: maximum bypass time of the packet by the primary path T_{max} is defined by the following equation [8]:

$$T_{max} = \left(\frac{8+2}{10^{-6}} + 10^{-3} + \frac{3\times 2}{3\times 10^{8}}\right)\times 5 = 0.005\ c \quad (1)$$

where T_{max} is the time of sending the package (c), delaying time on the input registers (1 msec), time of the message delivery over a twisted pair (c), N_p+2: the size of the message packet (bit) including start and stop bits, N_k: the number of nodes in the ring, l: the average distance between nodes (m).

This delay is acceptable for delivering of control signals and for signals of microprocessor relay automated scanning. However, for the automatic protective communication channels and for critical communications between the microprocessor relays, this threshold should not exceed 5-10 msec (Weidong *et al*., 2005).

Jitter and BER: As an example, let's consider the research of the indicators of maximum communication system efficiency, based on RS-485 interface. For the test, twisted pair of category 5 was used; the transfer was carried out at a speed from 1-39 Mb/sec with the length of the cable from 90-270 m. According to the test results, reported in during the study of RS-485 interface indicators, RS-485 networks were capable to provide communication speed up to 52 Mbit/sec with cable lengths reaching hundreds of meters without repeaters or interface converters.

Despite all the advantages of the RS-485 interface, the requirements for channels and communication interfaces in energetic are higher every year. This trend is related to the constant load increase and complexity of electrical networks schemes, the emergence of variety of relatively low-power generation in various points of the network. Also, there is a tendency to the creating of new communication protocols (for example, communication protocols within the framework of international standard IEC 61850), leading to complication of microprocessor relays, improving protection algorithms and introducing of new functions. On top of that, there is noticeable increase in interest to rising "clarity" and controllability of electricity generation facilities which can not be implemented using conventional technologies, primarily due to the limited capacity and its vulnerability to electrostatic discharges, taking place at electricity generation facilities.

In light of this situation, the urgent task is introducing new solutions allowing to perform reliable high-speed exchange of data packets at the electricity generation facilities of different voltage classes.

Ethernet quality indicators: The use of Ethernet networking technology at the power engineering facilities for control and monitor of the modes in real-time, now is possible due to the development by leading manufacturers of network equipment, capable to operate in severe conditions of electromagnetic environment and standards, describing interaction rules of communication network elements. Industrial Ethernet (IE) communication protocol has been adapted to the peculiarities of control devices such as the RTU, microprocessor relay, the devices of power facilities automation systems.

Industrial Ethernet technology has been selected for the implementation of IEC 61850 in the power industry.

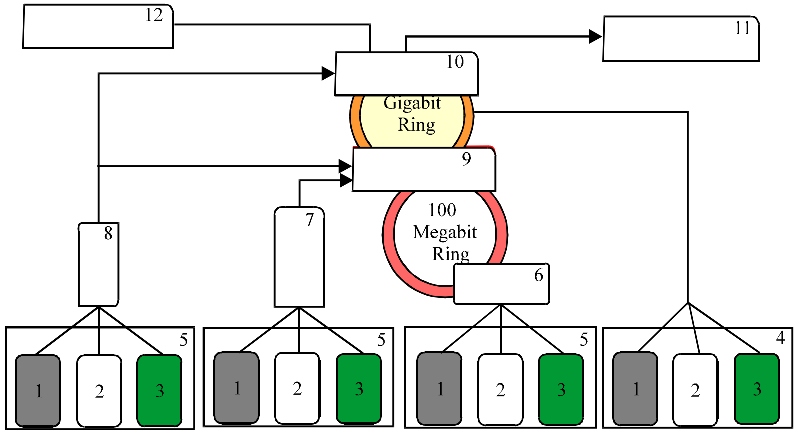

Fig. 2: Ethernet base substation network; 1: Relay, 2: RTU, 3: IED, 4: IEC 61850, 5: Non IEC 61850, 6: RS 232/422/485 to ethernet interface converter, 7: Communication gateway, 8: Terminal server, 9: Second level Ethernet switch, 10: Third level ethernet switch, 11: Workstation, 12: Scada HMI

One of the features of IEC 61850 is the organization of so-called internal buswork of technological process, connecting field devices, digital transmitters with microprocessor relays, emergency control devices and automation systems at the substation which are according to the standard terminology, the Intelligent Electronic Devices (IED). Internal substation network based on ethernet is shown in Fig. 2. Let's consider the main indicators of communication channels quality, based on Ethernet, for the communication system IEC 61850:

Where, T_{max} the time of sending the package (c), delaying time in the multiplex equipment (5 msec), the time of the message delivery via the optical fiber (c), N_p: the size of the message packet (byte), N_k: the number of nodes in the ring, l: received average distance between the nodes (m), nov: refractive index of the optical fiber (1.45-1.55).

The standard length of GOOSE packets is 1500 bytes, Sample Value packets (SV, IEC 61850-9-2 (LE)) is 163 bytes, the number of nodes in the ring is <3 m, the average distance between the nodes l within the substation is 5 m.

Then, for the transmission of SV packets, the maximum time will be T_{max} = 56 msec; for the GOOSE messages it will be T_{max} = 377 microseconds. Received values are acceptable in terms of rapid response in emergency cases and that according to the requirements of IEC 61850 should not exceed 4 msec.

According to the report of the New Hampshire University laboratory, the ethernet equipment of the IEEE 802.3 standards, demonstrates the functional characteristics and concedes errors in packages, approved in the process of their design with an accuracy of 95%. In particular, the number of errors and therefore the number of incorrectly transmitted frames, to a large extent depends on the specific hardware, network configuration, security of communication channels and external conditions. However, the mechanism of Forward Error Correction (FEC), implemented in one or another form, allows to reduce the already small number of them to zero, reducing overall bandwidth of the network.

Providing reliable high-speed connectivity within the substation on the basis of ethernet today is completed task, but the creation of a full-fledged network with all security measures, redundancy and quality of the transmitted data is a very expensive task, particularly because of the high price of industrial switches, routers and gateways.

GPON quality indicators: Currently, due to the creation and widespread acceptance in telecommunication sphere the cheaper solutions based on xPON technologies (Passive Optical Network; PON), the construction of networks with fiber-optic communication lines, becomes relatively affordable. In particular, one of the most successful in this field is a standard GPON (Gigabit PON). The key features of GPON is the use of only one transceiver (Optical Linear Terminal) for information receiving and transmitting to the plurality of receiving devices (Optical Network Unit or Optical Network Terminal) (Fig. 3). Moreover, unlike traditional networks, based on optical fiber, there is no need to install the active devices in the network nodes; instead of this, the branch lines are made from the main cable, using the optical splitters and therefore the network topology is a "tree with passive nodes".

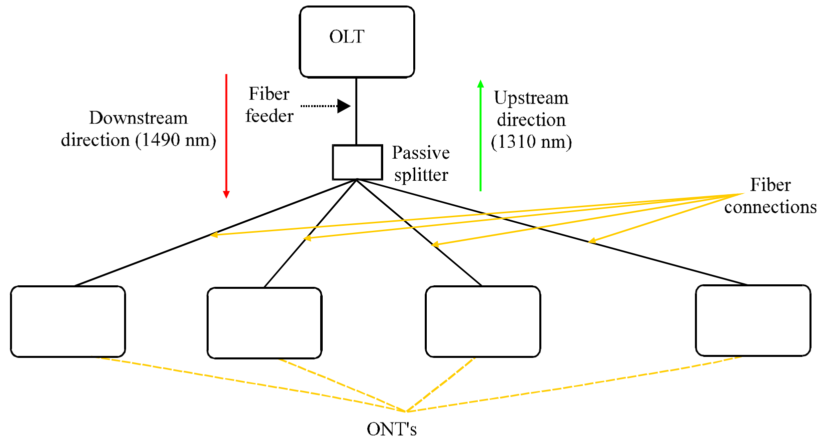

Fig. 3: GPON network architecture

The key aspects of this technology, allowing it to be implemented at the facilities of electric power industry are the following:

- The ability to install modular compact transceivers in the format of SFP standard (Small Form-factor Pluggable) in microprocessor relays or in bay-controllers SCADA for organization of communication channels IATS
- Compactness of splitter allows them to be placed in tight spaces, to the extent of relay protection and automation units in cells of medium voltage
- Independent format of transmitted units
- Packets routing is implemented in the receive-transmitted devices, due to the mechanism of the data management GTC
- GPON standard supports the following speeds: downstream traffic (from OLT) is transmitted at a speed of 1.25-2.5 Gbaud, ascending from (ONT) speeds of 0.155 - 1.25 GBaud

Delayed delivery of the messages:

$$=125 \text{ msec} \quad (3)$$

where, the time of sending the package of standard length 38880 bytes (c) is equal to 125 msec; guard time that is formed from T_{laser}: laser on-of time (25.7 nsec) and T_{pad}: preamble and delimiter time (70.7 nsec); the time of message delivery via the optical fiber (c); l is the distance to the farthest receiver (m); nov is refractive index of optical fiber (1.5) where, the time of sending the package of standard length 19440 bytes (c) is equal to 125 msec; guard time that is formed from T_{laser} laser on-of time (25.7 nsec) and T_{pad} preamble and delimiter time (70.7 nsec); the time of message delivery via the optical fiber (c); l is the distance to the farthest receiver (m); nov is refractive index of optical fiber (1.5).

The delayed time of the message delivery depends on the size of the buffer: when the buffer has a small size, for example 10 MB, the delayed time can be up to tens of milliseconds, as shown in the research of dynamic bandwidth of GPON technology.

The analysis of the GPON signal quality: Next, consider the results of the research of the GPON network signal quality, 2.5 GBaud. For the study a simulation model in software Optisystem was used, comprising a random number generator, a pulse generator NRZ, Mach-Zehnder modulator, a continuous source of laser radiation, a low-pass filter, BER-analyzer, optical Bessel filter, 3R regenerator.

According to the results of GPON networks simulation, obtained in the study (with one OLT and plurality of ONT) at a wavelength of 1550 nm, at a length of optical fiber portion of 20 km, parameters BER were obtained for ONT OLT 1.29×10^{-12} and 4×10^{-8}, respectively. Also eye diagram was obtained, showing a low level of noise and jitter.

CONCLUSION

The application of Industrial Ethernet standard in IATS at the substations is rapidly gaining its popularity, as can be seen by the number of solutions, presented on the market but their implementation is limited by the cost of the active equipment. Solution, based on passive optical network is an alternative which can solve this problem. The quality indicators of communication channels of GPON technology satisfy all the requirements for its using in communication channels in the relay protection and automation, in SCADA-systems and in relay protection and emergency monitoring systems. The features of GTC-mechanism of data transmission allow the passage to GPON without any problems because this mechanism is largely similar to the SDH-technology, which is already successfully used in the power industry. One of the advantages of GPON technology is built-in high-precision synchronization and guarantee of messages delivery within 125 msec that is critical important for the transmission of emergency signals, relay protection signals and maintaining the stability of the electricity grid as a whole. A particularly important advantage of this technology is the maintaining of SFP-modules of various configurations, allowing to create as communication channels on a single optical fiber using WDM technology and on the two separate fibers for the downlink and uplink traffic, that is important for creating alternate communication channels.

The application of GPON technology for creating IATS in centralized systems of control, protection and signaling at the power facilities of medium voltage classes can provide highly reliable, interference-free and high-speed data transfer between connected devices and the central node in a cost-effective manner.

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