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Some Aspects of Process Bus Configuration for Digital Substation.

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ABSTRACT

This article discusses some aspects of process bus configuration for digital substation. Results of field tests of process bus are presented in terms of estimation of bus bandwidth and data transfer delay time. A prototype device for data steam merging which is aimed at reduction of number of received streams via process bus at the bay/unit level.
Keywords: Digital substation, process bus, analog sampled values, bandwidth, digital streams, IEC 61850.

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INTRODUCTION

What is a digital substation?

Digital substation is a power unit with high automation level of engineering process controlling equipped with dedicated data engineering and controlling systems and means, where all processes of data exchange between the substation units is carried out in digital form on the basis of IEC 61850 protocols.

Peculiar features of digital substation are as follows:

- Existence of intelligent microprocessors built-in into primary equipment;
- Application of local networks for communications;
- Digital approach to data, its transfer and processing;
- High degree of automation of substation operation and its process control.

Automation system based on the principle of digital substation is subdivided into three levels:

- Field level (process level);
- Bay/unit level;
- Station level.

The field level is comprised of:

- primary sensors for acquisition of discrete data and transfer of control commands to switching devices;
- primary sensors for acquisition of analog data, digital transformers of current (CT) and voltage (VT).

The bay/unit level is comprised of intelligent electronic devices (IED):

- terminals of relay protection and local emergency automation;
- control and monitoring devices (bay controllers, multifunctional instrumentation, monitoring systems of transformers and others).

The station level is comprised of:

- higher level servers (database server, SCADA server, telemetry servers and so on);
- workstations of substation personnel.

Now let us consider in details the aspects related with optimum configuration of interrelations between the process level and the bay/unit level.

Requirements to data transfer time via process bus

One of the main tasks upon embedding of digital substation as a power unit is optimum configuration of local networking for interrelation between the process level and the bay/unit level, that is, process bus. Optimization is meant in terms of hardware and logic structure of the process bus. Process bus configuration influences the most important speed performances, in their turn influencing the response speed of protecting devices and automatics at the bay/unit level and determining operation efficiency of overall automation system in the case of emergency. The method of process bus configuration influences the time of data transfer from one device to another, as well as limitation on data array participating in the exchange.

Let us consider in details the aspects related with the process bus bandwidth and the data transfer time via the bus.

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According to IEC 61850-5 [1] the levels and logical interfaces inside one electrical substation or another single power unit are determined as follows:

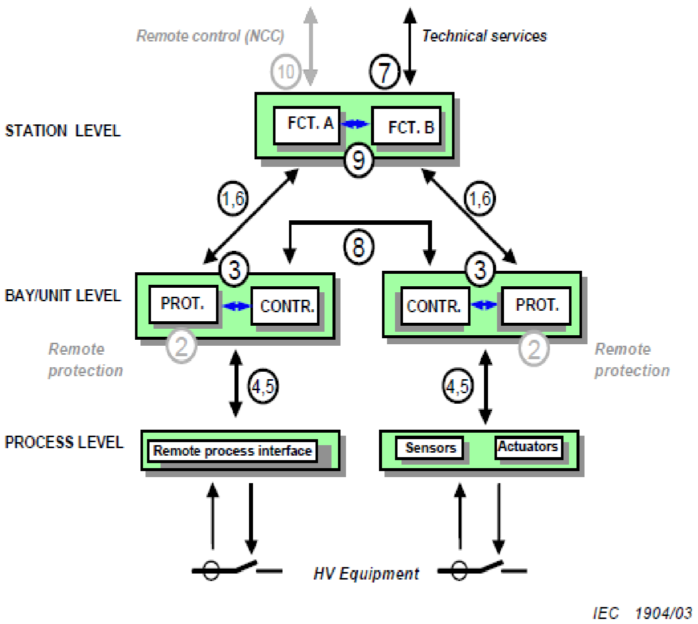

Fig. 1. Levels and logical interfaces in automation system of substation (IEC 61850-5).

The process bus maintains the relations between the process level and the bay/unit level) as well as two logical interfaces 4 and 5, illustrated in Fig. 1.

Interface 4 - CT and VT instantaneous data exchange (especially samples) between process and bay level.

Interface 5 - control-data exchange between process and bay level.

IEC 61850-5 defines the following message types:

- Type 1 – Fast messages;
- Type 1A – "Trip";
- Type 1B – "Others";
- Type 2 – Medium speed messages;
- Type 3 – Low speed messages;
- Type 4 – Raw data messages (sampled values);
- Type 5 – File transfer functions;
- Type 6 – Time synchronization messages (no requirements are set for transfer time of this type of messages; requirements are set to precision class);
- Type 7 – Command messages with access control.
- Herewith, IEC 61850-5 highlights three performance classes for protection and control:
- P1 is usually applied to low and medium voltage networks, where moderate requirements are set for performance;
- P2 is usually applied to bay of high voltage networks and are used by default, unless another class is defined by the customer;
- P3 is usually applied to bay of high voltage networks with high requirements to performance and synchronization.

For measurements and quality control of electric power IEC 61850-5 highlights three performance classes: M1, M2, M3. They have limitations in terms of measurement accuracy, but no requirements to message transfer time.

Table 1 summarizes the requirements to maximum transfer time of messages of various types and performance classes for devices exchanging via the process bus. The message transfer time is the time interval between the occurrence of event in one device to the start of processing of this event in another device. We have three possible reasons of event occurrence in transferring device:

- calculation result of processing function;
- variation of discrete input state with account for delay for debouncing of input contact ;
- variation of analog input state with account for delay for filtration of input circuits.

Table 1. Requirements to message transfer time with the use of process bus

Signal type	Examples	Maximum message transfer time (ms)		
		P1	P2	P3
Type 1A – "Trip"	Tripping, logical blocking, commands	10	3	
Type 1B – "Others"	Interaction with primary process (less strict requirements)	100	20	
Type 3 – Low speed messages	Messages for high time tolerant functions of automatic control, event recording, setting of ultimate values	500		
Type 4 – Raw data messages (sampled values)	Output data from digitizing transducers and digital instrument transformers independent from the transducer technology	10	3	
Type 5 – File transfer functions	Files with data for recording in the control system and others	1000		

As can be seen in the table, the most stringent requirements to maximum time of data transfer are applied to messages of Type 1A and Type 4.

Messages of Type 1A – these are the messages related with operation of relay protection and emergency automation. Stringent time limitations for such devices are caused by peculiar features of their functioning, requiring activation in emergency cases in the time ranges of commercial frequency period. In automation systems of substations at the level of process bus the messages of such type are transferred as a rule by GOOSE mechanism described in IEC 61850-8-1 [2].

Messages of Type 4 – these are the messages related with data transfer from digital current and voltage transformers irrespective to physical principles of measurements. The most stringent requirements in terms of transfer time of such data are related with peculiar features of operation of relay protection and emergency automation, which in the scope of digital substation should provide better response times in comparison with widely applied devices of such type without process bus. Such data are transferred using Sampled Value (SV) mechanism, described in IEC 61850-9-2 [3].

TESTING OF PROCESS BUS

Message structure

It should be mentioned that the standard defines the upper limit of allowable data transfer time equaling to 3 ms. In fact, in actual automation systems of substations the data transfer time does not exceed 1-1.5 ms for the most time critical messages.

The data transfer time is comprised of three main components:

- Operation time of communication unit of transferring device;
- Transfer time via network environment;
- Operation time of communication unit of receiving device.

Operation time of communication units depends on configuration of equipment by manufacturer and cannot be optimized. Transfer time via network environment depends on the speed of applied network equipment and configuration of process bus. Only this time can be optimized.

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The most time critical data are transferred via the process bus by means of two main transfer methods: GOOSE for discrete data, SV mechanism for analog data. Both methods are based on the use of multicast transmission at the channel (second) level of OSI model — this approach provides high rate of data publication into network.

GOOSE data transfer in steady mode (at consistency of transferred data) occurs usually with the period of several seconds, and only in the case of modification of the value of transferred data the period increases from several milliseconds to the established value.

Sampled values for the purposes of relay protection (80 points per period) are transferred at constant period of 250 µs, which is 100 times more frequent that the GOOSE data transfer. Therefore, for estimation of network bandwidth and data transfer time it is sufficient to consider only transfer of analog sampled values.
IEC 61850-9-2 describes the communication profile of sampled value transfer protocol and the structure of relevant messages, however, it describes neither the structure of data model of devices, nor the structure of transferred data set, nor the discretization frequency of measured signals, nor the time synchronization method of devices.

There emerged a necessity of certain agreement between manufacturers, customers and other involved parties. Under the auspices of UCA International Users Group the agreements were reached arranged as technical specifications titled “Implemetation Guidelines for Digital Interface to Instrument Transformers using IEC 61850-9-2”, “IEC 61850-9-2LE” (Lite Edition) in abbreviated form [5]. These specifications do not contradict with the provisions of IEC 61850-9-2, and only stipulate some aspects, such as:

- Structure of data model of device;
- Set of transferred data (4 currents and 4 voltages);
- Discretization frequencies of measured signals (4000 Hz for relay protection and commercial electricity accounting, 12800 Hz for quality control of electric power).

According to IEC 61850-9-2LE a standardized Ethernet frame is generated. MAC address of receiver in the range from 01-0C-CD-04-00-00 to 01-0C-CD-04-01-FF. Tag Protocol Identifier (TPID) has the value of 0x8100. User priority, priority of transferred traffic, is 4. Message identifier (Ethertype), the message type, is 0x88BA. Application identifier (APPID) is 0x4000.

The structure of applied protocol data unit APDU for IEC 61850-9.2LE messages of 80 samples per period is illustrated in Fig. 2.

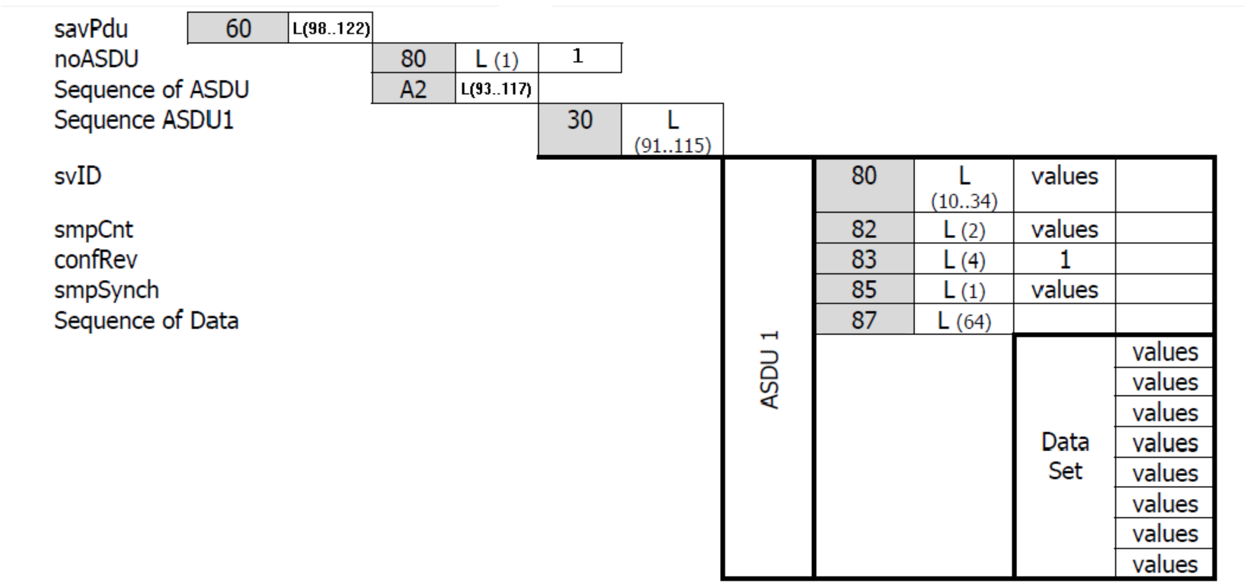

Fig. 2. Structure of applied protocol data unit APDU for 80 samples per period.

Syntax of message transfer is in accordance with ASN.1 (Abstract Syntax Notation One) [4]. For SV messages of 80 samples per period the data about one measurement period is transferred by means of 80 single packets, each with 1 sampled value. For SV messages of 256 samples per period the data about one measurement period is transferred by 32 single packets, each with 8 sampled values.

svID field – Sampled value identifier, defines the name of SV stream. The field length is from 12 to 36 byte.
smpCnt field – The current number of samples within a second.
confRev field – Configuration number.
smpSynch field – Mark of synchronization existence.

The Sequence of Data field contains data about sampled values of currents and voltages of A, B, C phases and N neutral. The field length is 66 byte. Each measured value is ciphered by 8-byte code. The frame format for one sampled value (4 currents, 4 voltages). is illustrated in Fig. 3.

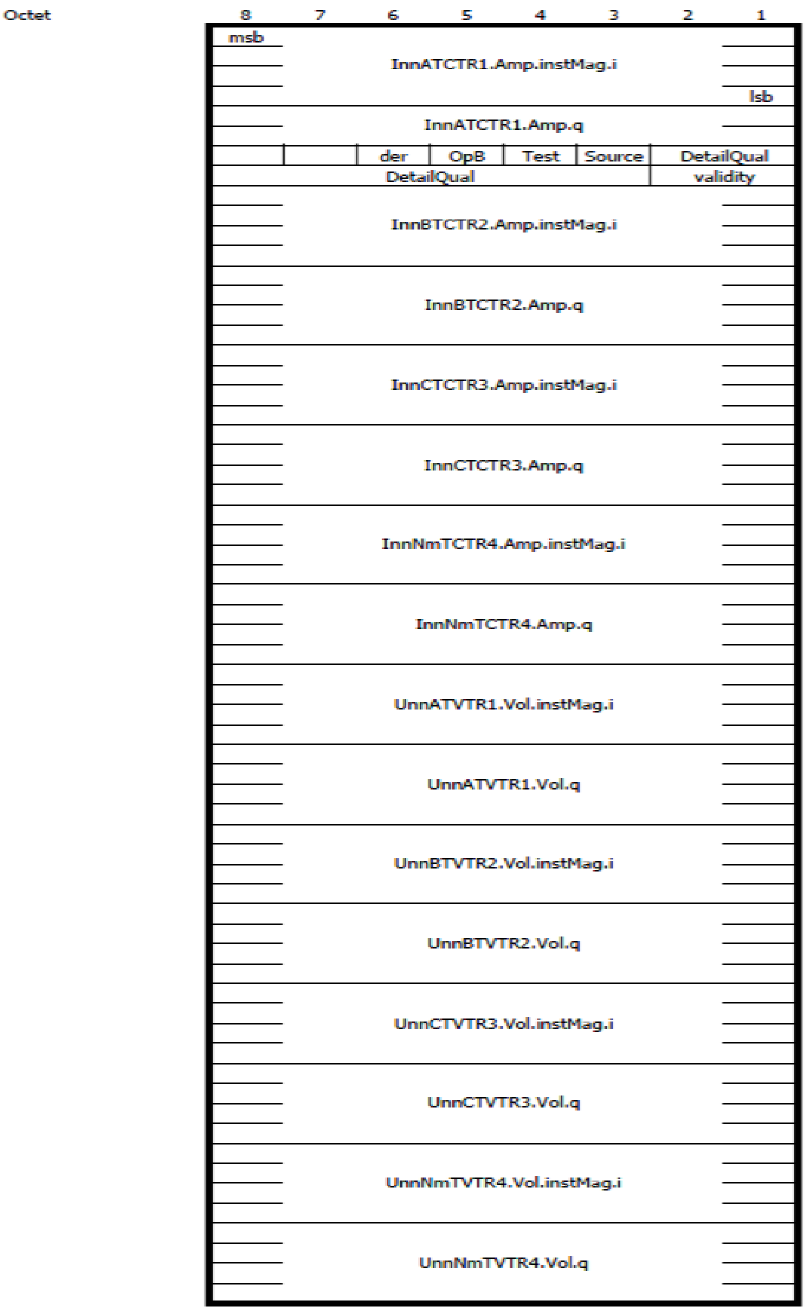

Fig. 3. Frame format for one sampled value.

InnxTCTRy.Amp.instMag.i field – amplitude of current sampled values, where x is the A, B, C phase or Nm (neutral). Scaling coefficient: 1 bit = 1 mA. The field length is 4 byte. y=1,2,3,4.

InnxTCTRy.Amp.q field – additional data on sampled values of current, where x is the A, B, C phase or Nm (neutral). The field length is 2 byte, default value is 0x0000. y=1,2,3,4.

UnnxTVTRy.Vol.instMag.i field – amplitude of sampled values of voltage, where x is the A, B, C phase or Nm (neutral). Scaling coefficient: 1 bit = 10 mV. The field length is 4 byte. y=1,2,3,4.

UnnxTVTRy. Vol.q field – additional data on sampled values of voltage, where x is the A, B, C phase or Nm (neutral). The field length is 2 byte, default value is 0x0000. y=1,2,3,4.

der field – identifier. Indicates, whether the sampled values are the results of measurements (0xb0) or calculations (0xb1).

OpB field – identifier of blocking, set in the case if the operator blocks further updating of the values. If this identifier is set, the oldData flag of detailQual identifier should also be set.

Test field – identifier for indication of test value which is not intended for use in operational purposes but for testing of functioning.

Src field – identifier of value origination. The value can be obtained from the process (process, 0b0) or can be set by user (substituted, 0b1).

DetailQual field – additional identifier of quality.

Validity field – quality identifier can be good, questionable, or invalid. Default value: good – 0b00.

At existence of a flag of DetailQual identifier the Validity identifier should be set to invalid (0b01) or questionable (0b11).

If the values of current and/or voltage are not measured, then zero values are transferred and the quality identifier should be set to invalid.

Process bus bandwidth

Let us estimate possibilities of bandwidth of Ethernet 100 Mb, the most widely applied solution for configuration of process bus. Faster network are rarely used due to high costs of both communication equipments and communicating units of devices. The load on local network, the amount of transferred data per second (Mbit/s), can be estimated as follows:

$$\frac{L \times N \times 8}{1024 \times 1024}$$

where L is the length of single packet in bytes, N is the number of transferred (received) packets per second. Such estimation of bandwidth completely corresponds to actual results obtained at testing site of NTC FSK digital substation and in laboratory environment. The testing site of digital substation operated with RTDS complex with GTNET cards for generation and receiving of packets of analog sampled values [6]. In laboratory tests the packets were generated and received by proprietary software running on PC.

The test results were as follows.

The stream of 80 counts per period (network frequency 50 Hz) provides the load ≈ 4.4 Mbit/s, with the packet length of 140 byte. The packet length depends on the number of symbols in the stream name and amounts from 136 byte to 160 byte.

The stream of 256 counts per period (network frequency 50 Hz) provides the load ≈ 9.8 Mbit/s, with the packet length of 800 byte. The packet length depends on the number of symbols in the stream name and amounts from 789 byte to 981 byte.

The use of unmanaged or managed switches, as well as of devices of RedBox type in fact does not influence the bandwidth but only the time of data transfer.

While increasing the amount of simultaneously generated streams, connecting higher amount of data sources, the reliability of data transfer was verified by comparison of transferred and received data. When the load on receiving device exceeds 80 Mbit/s (80% of bandwidth of 100 Mbit/s channel) steady data skipping is recorded. In the case of 80 counts per period this results in 19 streams. For 256 counts per period this results in 8 streams. The test results on RTDS complex are illustrated in Figs., 5, 6, and 7. Black color designates initial reference signal. red color -- received signal after transfer via process bus.

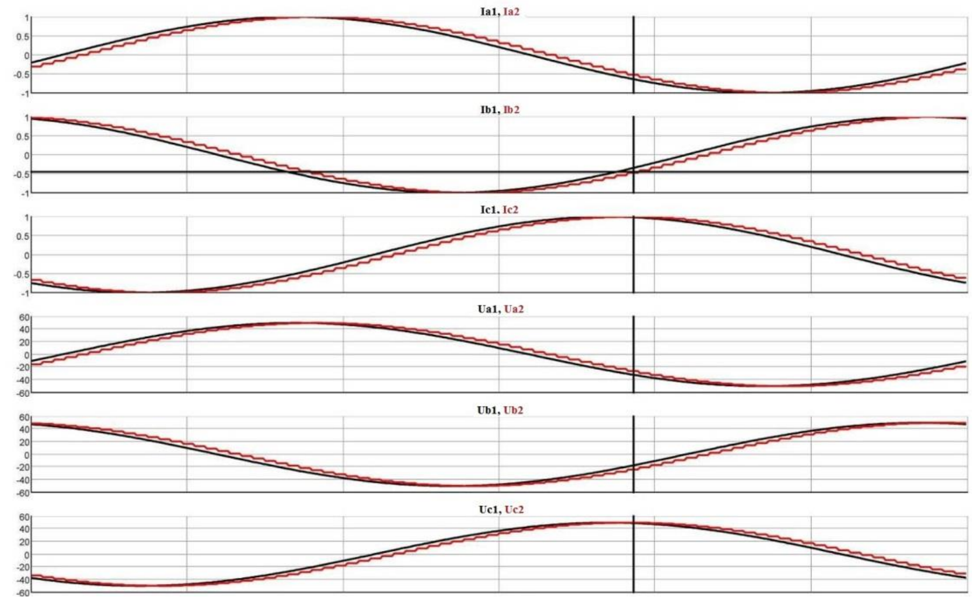

Fig. 4. Oscillograms of sent and received signals at 16 streams of 80 points per period.

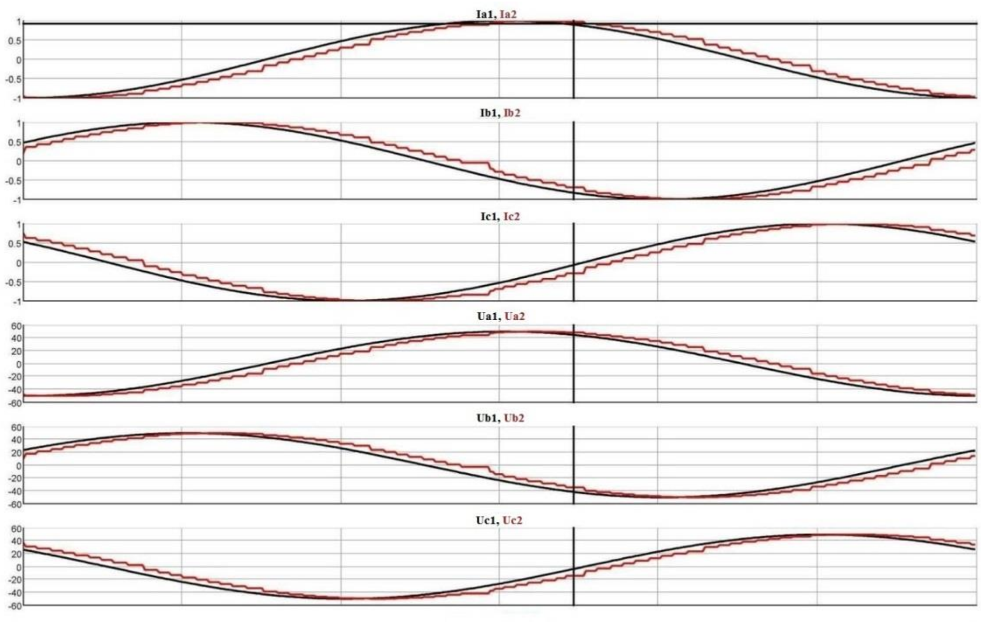

Fig. 5. Oscillograms of sent and received signals at 22 streams of 80 points per period.

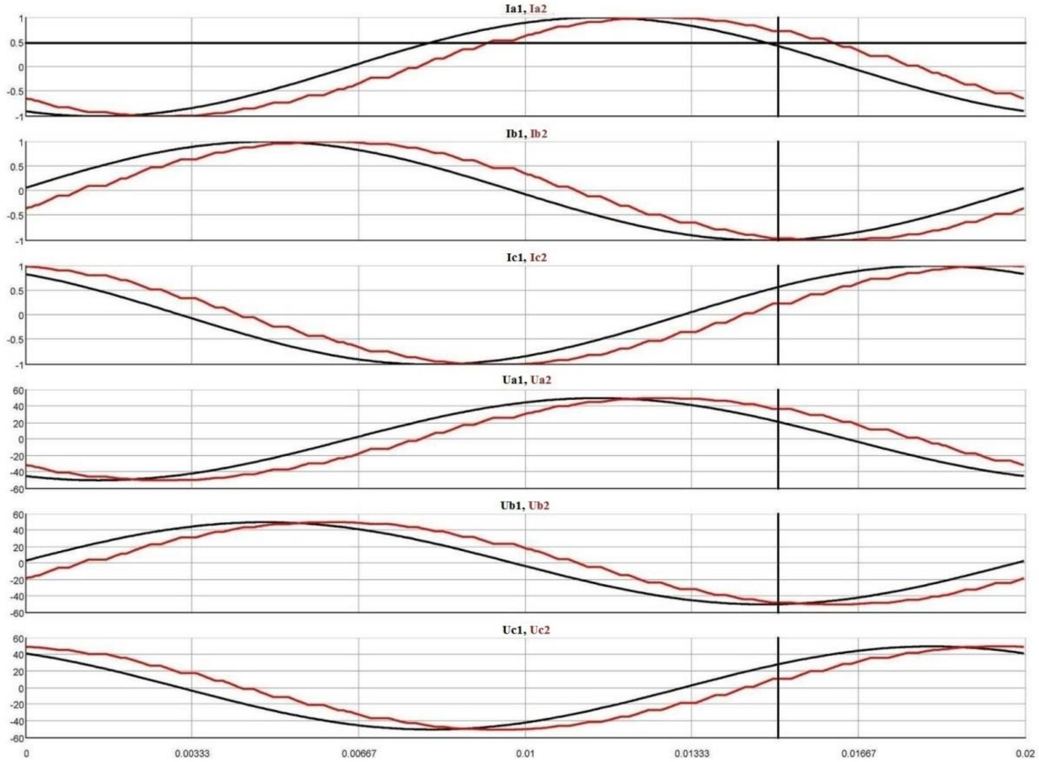

Fig. 6. Oscillograms of sent and received signals at 4 streams of 256 points per period.

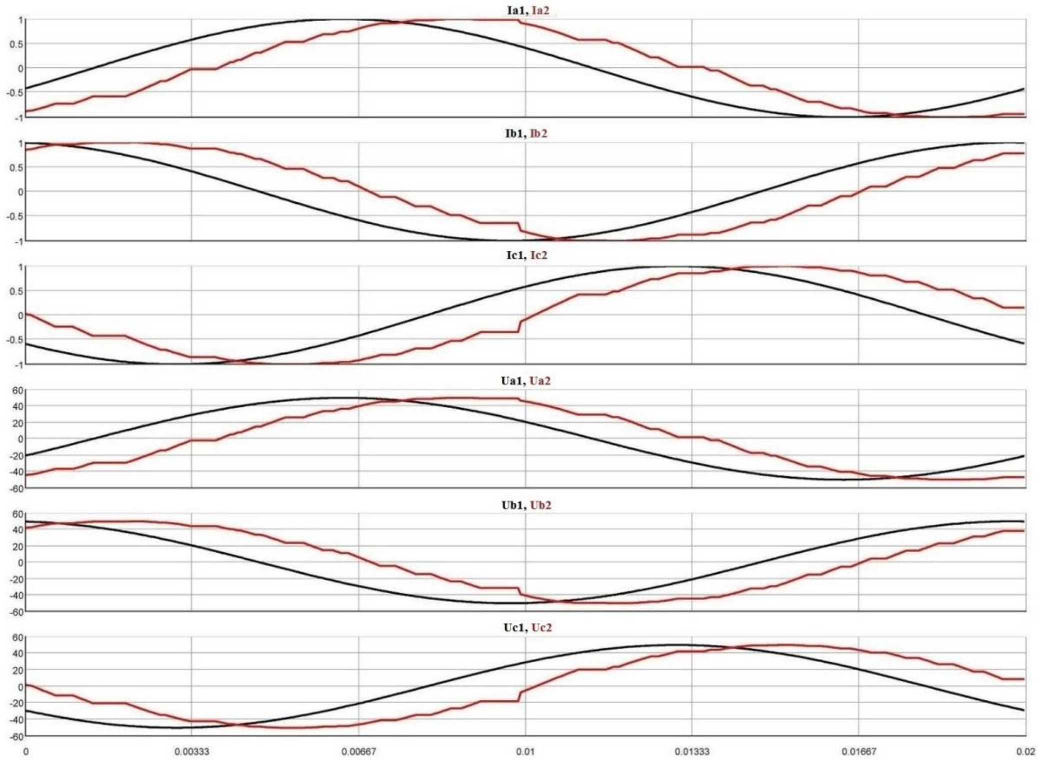

Fig. 7. Oscillograms of sent and received signals at 10 streams of 256 points per period.

In practice, using Ethernet in order to guarantee data transfer it is not recommended to exceed 60% of channel bandwidth. The obtained results of 80% are slightly in excess of the recommended ones, they are related with regular, steady and time synchronized load which uniformly employs the equipment.

In the case of combining of streams of 80 counts per period and 256 counts per period the situation remained nearly the same; when the bandwidth exceeds 80% there occurs data loss.

Delay time for packet transfer

Let us consider the time delays occurring in active network equipment (switch). The most critical to transfer time data are transferred via process bus by means of multicast at the channel (second) level of OSI model.

Manufacturers of the equipment in the specifications do not declare the characteristics reflecting delay time of data packet transfer from switch input to output port. This time is comprised of the frame receiving to input buffer, operation time of switch internal logics (searching in address table, data transfer from input buffer to output ones, and so on) and the time of frame transfer from output buffer. It is obvious that the times of receiving and transfer depend on the frame length and Ethernet bandwidth, and the time of internal operation depends on architecture of switch configuration (shared memory, common bus, communication matrix) [7].

While operating on the test site and in laboratory with Ruggedcom and Hirschman managed switches (the most widely applied equipment for configuration of process buses on substations) the delay time was experimentally determined upon transfer of multicast delivery with the length of 140 byte (IEC 61850-9-2LE stream of 80 points per period). Transfer time of such packets via one switch is 70-100 µs. This results turned to be unexpectedly high. This is an evidence that upon configuration of process bus these delays should be taken into account, and the number of switches should be limited on the route from data source to consumer in order to provide complete time of data transfer in the required range of 1-1.5 ms.

Methods of configuration of process bus

As a rule, process bus is created separately without connection to station bus. At present the process bus is configured by means of various methods: from point-to-point connection between the devices to merging of total bus into unified local network [8].

Point-to-point connection involves minimum amount of active network equipment, but high amount of digital connections via optical or electric cables. It has the most excessive composition of field equipment and high requirements to possible amount of switches for this equipment. Any modification of process bus configuration requires for new mounting of digital connections, for instance, HardFiber System (GE and Alstom Grid) [9].

Configuration of process bus as a single (non-segmented) local network is suitable for minor power units, usually with low voltage. This is the most optimum variant in terms of amount of active network equipment and simplicity of adjustment.

For the power units of medium and high voltage the configuration of segmented process bus is more often applied. It is based on physical segmentation of local network (for instance, by voltage sections), logical segmentation using VLAN or combination thereof. The process bus is divided into segments on the basis of primary layout of substation and communication logics between the devices, so that to restrict as much as possible the packet exchange at the interfaces of individual segments, thus minimizing the data exchange between the segments.

For instance, the cell maintaining outgoing 110 kV line has at least five devices at the bay level: main and standby protection line, switch control device, terminal of bus differential protection for connection, metering device of electricity quality. In addition, there are devices at the process levels: field controllers of circuit breakers, disconnectors, earth switchers, analog meters of current and voltage. Excluding redundancy of process bus local network there are at least 10 Ethernet ports to active network equipment.

Let us consider the actual substation: Leningradskaya 750 kV (Russia). Medium size 110 kV bay of this substation has 8 line feeders, 1 section switch unit, 3 transformer feeders: 12 units in total. The amount of required Ethernet ports at active network equipment for connection of devices of only process level and bay level is at least 120. After addition of ports for connection of active equipment into the network we need at least 6 managed switches, each of 24 ports. The delay time for data transfer via 6 switches in ring structure results in sufficient value of ≈0.6 ms, which cannot be neglected in configuration of process bus.

MERGING OF DIGITAL DATA STREAMS

Let us consider one more aspect of configuration of process bus in terms of topological distribution of measuring points and initiated there streams of digital data. According to IEC 61850-9-2LE data frame contains a fixed set of transferred data: 4 currents and 4 voltages, and in case of no currents or voltages their values are transferred as zero including relevant value in the quality field.

Voltage transformers are installed on section buses, and current transformers on corresponding feeders. These points on substation are located at significant distance between each other (from several tens to hundreds of meters depending on the voltage level). In this case in order to generate complete digital stream (4 currents and 4 voltages) it is required to merge both current and voltage circuits in one device. This contradicts with the concept of creation of digital substation process level maximally integrated into primary equipment. That is maximum approaching to measuring point in order to minimize analog circuits of secondary commutation, which are highly susceptible to electromagnetic noises.

Another approach to solution of this problem is to generate two streams of digital data: one for currents and another for voltages. This method has its significant drawback: receiving such data device, should process two digital streams (each half filled by useful data). This sets increased requirements to communication unit of receiving device in terms of processing speed and algorithms, as well as increases load on equipment of process bus.

An alternative method of generation of complete digital stream for feeder is proposed. At first two digital streams are generated: one for currents and another for voltages. Then, at the nearest common switch the streams are merged and afterward there exists only one merged complete digital stream (4 currents and 4 voltages).

The algorithm of merging is very simple: two synchronous messages are awaited, one with current values and another with voltage values, then the common stream is generated which includes currents and voltages. Synchrony means equality of values in smpCnt field – the current number of samples within a second. Since the devices initiating two initial digital streams are synchronized in time and the period of data output is the same (80 or 256 points per period of commercial frequency), then the respective packets to switch will arrive nearly simultaneously to input ports.

At present the proposed method has been tested using PC of moderate power (Intel, 2 MHz) connected to one of the ports of switch, where by means of VLAN configuration the data were redirected from two ports receiving initial digital streams. The merged stream is transferred via the same switch port for transferring to devices receiving this information. Testing of such method of stream generation revealed that the delay time for merging of the streams does not exceed 60 µs (for streams of 80 points per period).

Various methods of commercial implementation of such approach are possible:

- In portable specialized device connected to a switch port;
- Directly in the switch by means of additional computing module. Implementation by means of central processor of the switch is possible, though, this is an abnormal task for it.

At any variant of implementation the additional time delay should not exceed 100 µs, which is similar to occurrence of one more managed switch in the sequence of devices from the source of digital stream to its receiver.

The merging algorithm can be expanded by addition of supplemental intelligent functions, for instance, automatic switching to another digital stream from standby voltage transformer as well as for standby current transformer. It is possible to implement in one device simultaneous merging of several pairs of digital streams, their diagnostics and so on. Application of such intelligent stream processing would decrease the number of digital streams at the bay level and simplify data receiving and processing in the devices.

CONCLUSIONS

Upon configuration of process bus of digital substation it is necessary to account for limitation of Ethernet bandwidth and significant time delays (up to 100 μs) in each active network device. While commissioning an automation system it is required to provide specialized full scale testing for verification of time delays and absence of data loss in process bus. In the case of non-complete set of process level and bay level devices during such tests it is recommended to use imitators for simulation of absent data streams [10,11].

A prototype device of intelligent processing of digital streams is proposed aimed at reduction of amount of received streams at bay level and decrease in load on the process bus. Time delays for such processing are comparable with the time of message transfer via a unit of active network equipment.

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