Contribution of Hardware, Software, and Traffic to the Wams Communication Network Availability

M. I. Uspensky
•
Komi SC UB RAS, Syktyvkar, Russian Federation.
uspensky@energy.komisc.ru

Abstract

Modes of the power system can now be controlled by use of a Wide Area Measurement Systems (WAMS). It is based on the Phasor Measurement Unit (PMU), connected by an information network covering a significant territory. The hardware reliability of such a network is determined to a big extend by the reliability of storage media (optical fiber, radio waves, etc.) and by the devices that ensure their operation - Phasor Data Concentrator (PDC). The paper proposes an approach to determining the parameters of reliability on the example of a 10-bus power system. The ways to improve the hardware reliability of the information network are considered.

Key words: reliability, availability, WAMS communication network.

I Introduction

The need for a correct assessment of the power system state has led to the creation of a Wide Area Measurement Systems (WAMS). It is based on the measuring technology of phasors (phase vectors), on the Phasor Measurement Unit (PMU) by the signal of global navigation systems, which ensures simultaneous measurement of phasors [1]. WAMS includes measuring transformers, PMUs, Phasor Data Concentrators (PDCs) and equipment of the local information network. It allows controlling the behavior of power system by continuously observing system events. The reliability of WAMS the operation is determined by the monitoring system reliability of each element.

The paper considers the WAMS network structure, proposes the assessment of its reliability based on the network links. The network reliability includes four components, as follows:

1) Hardware or technical reliability associated with the failure (destruction) of the transmission channel elements or the integrity of communication lines;
2) Traffic reliability, determined by time loss or data corruption without element failure of channel transmissions;
3) Software reliability due to errors in the development of exchange execution programs; and
4) Resistance to external targeted influence on the transmitted information.

This paper considers first three components of the network reliability. The paper includes the example of an application for assessing the network availability of a 10-bus power system for the positions under consideration is given. Optical fiber or high frequency channels on power lines adopted in the example as carriers.

II The structure of the WAMS communication network

An important part of the WAMS are communication networks combining PMUs with PDCs. Concentrated PDC information then goes to the upper level of the WAMS to determine the actions of the automation or the dispatcher, depending on the modes and processes in the power system. Communication networks are divided:

- By hierarchy: the upper level is monitoring and control centers of the system, regional dispatch organizations; middle level is data concentrators and means of their delivery to the upper level; lower level is synchronous data collection in the buses of the system (fig. 1);
- According to the remoteness of the information sources and receivers: the lower level is the connection of the PMU with the PDC usually lies within hundreds of meters to kilometer, the upper one is the connection of the PDC with dispatch centers – from units to hundreds of kilometers;

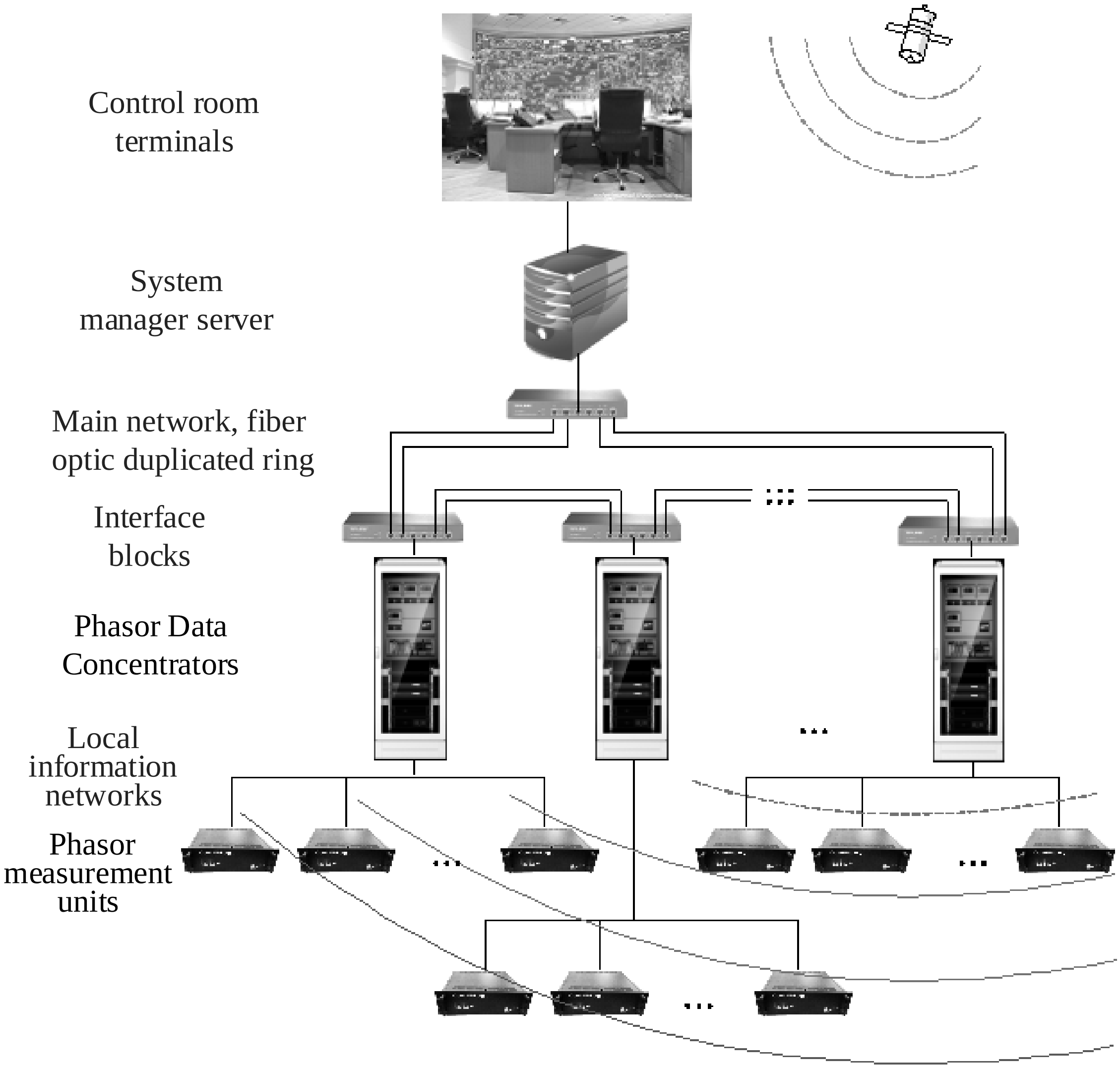


Fig. 1. Example of a hierarchical WAMS system.

- According to the network diagram: a star, a star with backup, a ring, a ring with backup, the first type of scheme being applied to the lower level of the hierarchy for linking PMU with PDC, since the distances and volumes of information here are relatively small. PMUs are installed with redundancy in such a way that when one of them comes out, its information can be restored using PMUs remaining in the work. If this is not possible, then the second or third scheme is used. A

backup ring scheme is usually used to communicate with the upper level;
- By type of information carrier: optical fiber, wire pair, microwave or high frequency radio waves. The choice of one or another carrier is determined by its distance, cost, and noise immunity;
- By affiliation: own and third party (commercial). An example of third-party media is the Internet.

From the point of view on the operation reliability of the WAMS network, four aspects should be considered:

1) The element reliability of electronic devices and the reliability of information carriers (wires, optical fiber, ether) in the sense of physical failure (change in the parameters of the medium under the influence of external factors, for example measures, open circuit) namely hardware reliability;
2) Software reliability due to errors in the development of exchange execution programs;
3) Traffic reliability, determined by the temporary loss or distortion of data without failure of the transmission channel element;
4) Opposition to an external targeted effect on the transmitted information.

III Determination of the network WAMS hardware reliability

The WAMS network hardware e is made up by the PDC electronics. Since the operation of the central processor units and the PDC communication interface during backup is similar to the operation of these elements in the PMU, we use the reliability estimate of these units in [2], which obtained from the system of Markov equations of state probabilities, taking into account different lengths of the main and backup communicate channels. Then the network channel availability, A_{ch}, consisting of a duplicated information source (PMU, PDC or, if necessary, an intermediate amplifier) and communication channel can be defined as

$$A_{ch} = A_{PDC} \cdot A_{com}, \tag{1}$$

where

$$A_{PDC} = \frac{\mu_{PDC}^2}{(\mu_{PDC}+\lambda_{PDC})^2}, \tag{2}$$

since PDCs are the same type, and

$$A_{com} = \frac{\mu_{lm} \cdot \mu_{lb}}{(\mu_{lm}+\lambda_{lm})(\mu_{lb}+\lambda_{lb})}. \tag{3}$$

Here A_{PDC} is the availability of the duplicated information source; λ_{PDC} and μ_{PDC} are the failure and recovery rates of the source, respectively. The physical availability of information carriers (twisted pair, optical fiber, high-frequency channel), each element of which is characterized by the length l_i, specific failure rate λ_{lm} for main and λ_{lb} for backup line and average recovery time r_{lm} for main and r_{lb} for backup line i per unit length. Since the reliability indicators of communication lines λ_l and r_l approximately linearly depend on the their length, and $\mu_l = 1/r_l$, then the working state probability of the information carrier element (availability) is easy to evaluate as

$$A_{ln,i} = \frac{\mu_{ln,i}}{(\mu_{ln,i}+\lambda_{ln,i})} = \frac{1/(r_{ln,i} \cdot l_i)}{1/(r_{ln,i} \cdot l_i)+\lambda_{ln,i} \cdot l_i} = \frac{1}{1+\lambda_{ln,i} \cdot r_{ln,i} \cdot l_i^2}\,. \tag{4}$$

It should be noted that $r_{ln,i}$ includes two components: the distance-searching violation variable, and the recovery-related constant. Since the second component has small values, we neglect it. Consequently, the availability of a communication line is inversely proportional to the square of its length. Unlike duplication in electronics, where the backup device usually repeats the basic one, duplication of storage media is most often provided by elements of various reliability indicators. This is due to the fact that in normal mode, communication is provided via the shortest line in the communication network, and in the case of the backup mode, information goes through the remaining in the communication network, which can be significantly longer than the main one. Moreover, the approach in solving such a problem is the same as when duplicating electronic units (2), only taking into account the different values of λ_j and μ_j for the j-th connection (3).

The algorithm for the calculation is as follows. After setting the initial data on the known link lengths of the information channels and the necessary reliability parameters, a table of the link participation in the formation of the main and backup channels is compiled (see the example of table 1 below). Further, the reliability characteristics of the links (λ_j, μ_j and A_j for the j-th link), the same parameters are determined for the main and backup channels of information exchange and the availability and channel characteristics with redundancy are calculated. At the same time, the initial data and the link participation table determine all changes in the network configuration. The estimated part remains unchanged.

IV An example of calculating the reliability of a WAMS network

Let us consider the described approach using the example of a 10-bus system considered in [3], fig. 2 and fig. 3. Without dwelling on the optimal composition of the PMU, assign them to each network bus and select the locations for PDC in nodes 4 and 9. We will determine the main and backup communication channel from the PMU of each node to its PDC, table 1 and fig. 3. In fig. 3a, such connections are without reservation, and in 3b, with back up. For communication lines on fiber, the specific indicators from the table 12.4 in [4] and the data from [5, 6] λ_l = 0.01752 failure /(km·year); r_l = 0.2088 hour/(km·recovery). Reliability indicators of electronic devices with their reservation are as follows: $\lambda_{PMU} = 1.539 \cdot 10^{-3}$ failure/year, μ_{PMU} = 5.922 recovery/year, A_{PMU} = 0.999740 [2], $\lambda_{PDC} = 2.673 \cdot 10^{-6}$ failure/year and μ_{PDC} = 740 recovery/year, A_{PDC} = 0.999999996 [2].

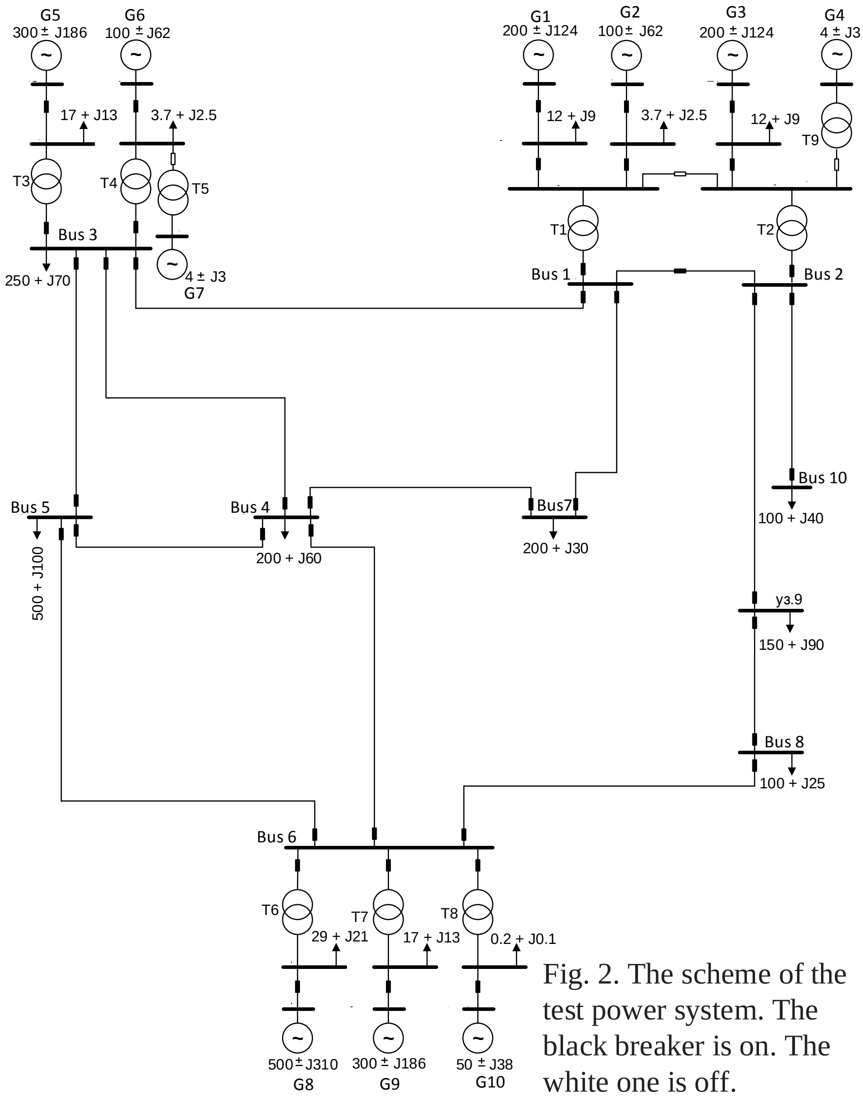


Fig. 2. The scheme of the test power system. The black breaker is on. The white one is off.

In the table 2, the link availabilities of the information exchange channel are determined, each of which includes an information source (PMU or PDC) and the actual fiber-optic connection, taking into account the fact $\mu_{con} = \frac{8760}{r_{con}}$ recovery/year. Then the availability of individual information channel is defined as the availability product of sequential links, which corresponds to a nonreserved channel, and the availability of the i-th channel with redundancy is defined as

$$A_{ch,i} = 1-\left(1- A_{m\_ch,i}\right)\cdot\left(1-A_{b\_ch,i}\right), \tag{5}$$

where $A_{m\_ch,i}$ is i-th main channel connection availability, $A_{b\_ch,i}$ is i-th backup channel connection availability. The individual channel availabilities are given in the table 3 according to the connection table 1 and according of the channel availabilities with back up.

Let us agree to call a separate information line as "connection", a line with the source of information (PMU or PDC) - as "link", and a set of connections from the source node to the dispatch server - as "channel".

The table 3 shows that when using a single communication channel, its availability spread lies in the range from one to three nines after the decimal point. With reservation, the communication availability is maintained at the level of three nines after the point, even at a source sufficiently far from the control room, such as nodes 1 and 2.

Table 1. **Routes for the main and backup channels of information exchange**

Source node	Main channel	Backup channel
1	1-7-4	1-9-8-6-4
2	2-7-4	2-9-7-4
3	3-4	3-5-4
5	5-4	5-6-4
6	6-4	6-5-4
7	7-4	7-6-4
8	8-6-4	8-9-7-4
9	9-7-4	9-8-6-4
10	10-2-7-4	-

For communication lines using a high-frequency signal on power lines, specific indicators from the table 12.3 [4] λ_l = 0.0196 failure/(km·year); r_l = 0.19 hour/(km·recovery), the rest of the data is the same. Then the channel link availability and information exchange channels are given in table 4 and table 5, respectively.

As a comparison of tables 2, 3 and 4, 5 shows, the difference in availability between fiber and high frequency transmission is negligible. In the last table, as for optical fibers, only the main channel determines the availability of node 10.

Considering the sequential link inclusion of the main or backup information channel, as well as the parallel operation of these channels on the server, we determine the failure rate λ_Σ and the recovery rate μ_Σ for information exchange channels with optical fiber. Then, $\lambda_{i,\Sigma} = \sum_j \lambda_{i,j}$, where i is the main or backup information channel, j is the link element of this channel. Further, we determine $\mu_{i,\Sigma} = \frac{\lambda_{i,\Sigma}\cdot A_{ch,i}}{1-A_{ch,i}}$ from the relation $A = \frac{\mu}{\mu+\lambda}$ and find $\mu_\Sigma = \sum_i \mu_{i,\Sigma}$ and $\lambda_\Sigma = \frac{\mu_\Sigma(1-A_{ch,i})}{A_{ch,i}}$. The resulting λ_Σ and μ_Σ for fiber and power lines are summarized in table 6.

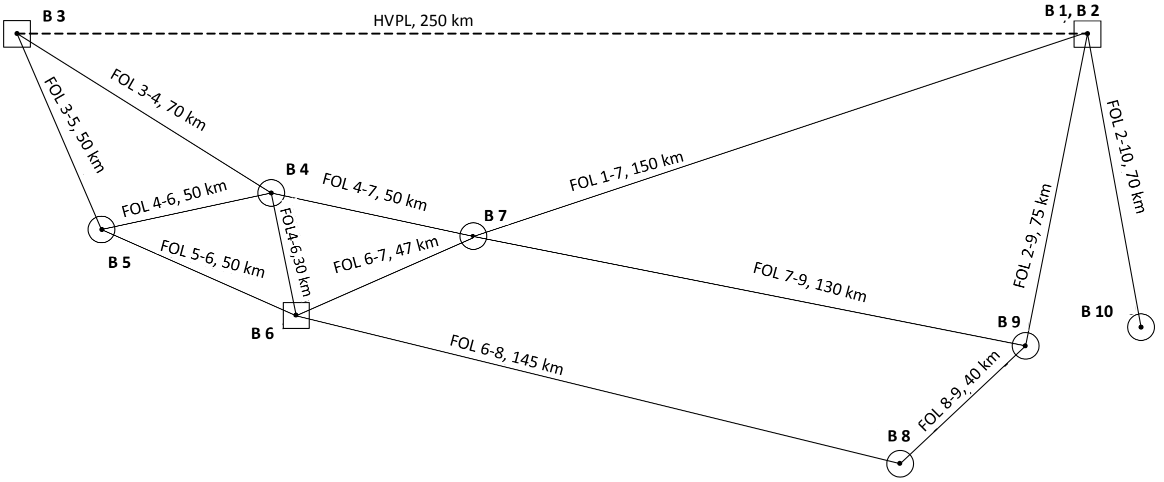
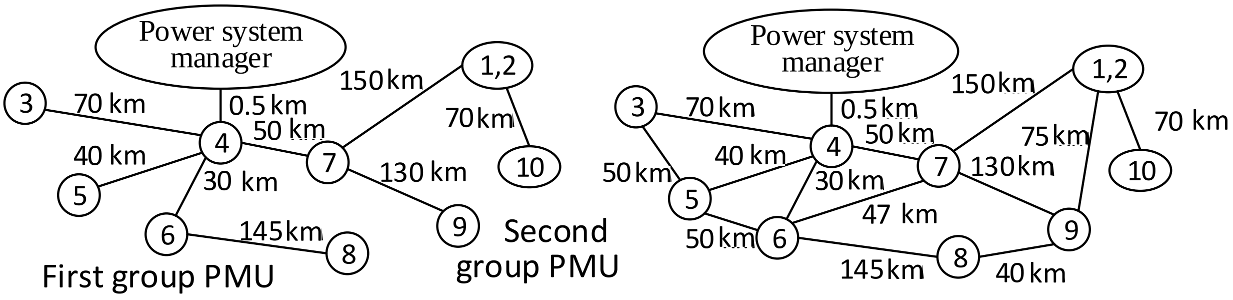


Fig. 3. The geographical location of the test power system. Scale 1 cm = 17 km. Rectangle nodes have generation. Circular nodes have only a load.



a) b)

Fig. 4. Communication channels: a) without redundancy, b) with redundancy.

Table 2. **Fiber optic link availability of the information exchange channel**

Link	l, km	$\lambda_{св.}$, failure/year	$r_{св.}$, h/ recovery	A_{link}	Link	l, km	$\lambda_{св.}$, failure/year	$r_{св.}$, h/ recovery	A_{link}
1-7	150.0	2.628	31.32	0.990433883	4-6	30.0	0.5256	6.264	0.999364399
1-9	75.0	1.314	15.66	0.997397114	4-7	50.0	0.876	10.44	0.99869736
2-7	150.0	2.628	31.32	0.990433883	5-6	50.0	0.876	10.44	0.99869736
2-9	75.0	1.314	15.66	0.997397114	6-7	47.0	0.82344	9.8136	0.998818611
2-10	70.0	1.2264	14.616	0.997698469	6-8	145.0	2.5404	30.276	0.991038641
3-4	70.0	1.2264	14.616	0.997698469	7-9	130.0	2.2776	27.144	0.99273384
3-5	50.0	0.876	10.44	0.99869736	8-9	40.0	0.7008	8.352	0.99907246
4-5	40.0	0.7008	8.352	0.99907246					

Table 3. **Fiber optic channel availability**

Bus #	$A_{main\ channel}$	$A_{backup\ channel}$	A channel with backup	Bus #	$A_{main\ channel}$	$A_{backup\ channel}$	A channel with backup
1	0.989400945	0.987684744	0.99986947	7	0.990433883	0.998443352	0.999985109
2	0.989400945	0.989374459	0.999887379	8	0.990666305	0.991036328	0.999916336
3	0.997698469	0.998030512	0.999995467	9	0.991698503	0.99000482	0.999917025
5	0.99907246	0.998322147	0.999998444	10	0.987380523	0	0.987380523
6	0.999364399	0.998030512	0.999998748				

Table 4. **Link availability of the information exchange channel for power lines**

Link	l, km	$\lambda_{св.}$, failure/year	$r_{св.}$, h/ recovery	A_{link}	Link	l, km	$\lambda_{св.}$, failure/year	$r_{св.}$, h/ recovery	A_{link}
1-7	150.0	2.94	28.5	0.990268019	4-6	30.0	0.588	5.7	0.999357643
1-9	75.0	1.47	14.25	0.997355058	4-7	50.0	0.98	9.5	0.998678619
2-7	150.0	2.94	28.5	0.990268019	5-6	50.0	0.98	9.5	0.998678619
2-9	75.0	1.47	14.25	0.997355058	6-7	47.0	0.9212	8.93	0.998802048
2-10	70.0	1.372	13.3	0.997661811	6-8	145.0	2.842	27.55	0.990883459
3-4	70.0	1.372	13.3	0.997661811	7-9	130.0	2.548	24.7	0.992608673

3-5	50.0	0.98	9.5	0.998678619	8-9	40.0	0.784	7.6	0.999060456
4-5	40.0	0.784	7.6	0.999060456					

Table 5. **Channel availability on power line**

Bus #	$A_{main\ channel}$	$A_{backup\ channel}$	$A_{channel\ with\ backup}$	Bus #	$A_{main\ channel}$	$A_{backup\ channel}$	$A_{channel\ with\ backup}$
1	0.98921669	0.987469907	0.999864884	7	0.99026802	0.998420046	0.999984624
2	0.98921669	0.989189439	0.999883426	8	0.99050449	0.990880875	0.999913409
3	0.99766181	0.997999793	0.999995323	9	0.99155486	0.989831215	0.999914123
5	0.99906046	0.998296664	0.9999984	10	0.98716037	0	0.98716037
6	0.99935764	0.997999793	0.999998715				

With a complex network of information connections, it can find a backup connection from the server node to the node with the failed connection, excluding the latter. To do this, we use the search algorithm first in depth and then in broadwise, as proposed in [7]. It allows taking to find a backup path into account the failed connections, if one exists, or to warn about its absence. When searching, the column "Reserve channel" is built in the table 1 and then the hardware reliability is evaluated for the found path.

These backup routes are stored in table 1 in order of decreasing a availability. A similar operation is performed in the process of network building. In real mode, if necessary, a backup channel with operational connections and highest availability is used.

Table 6. **Resulting values λ_Σ and μ_Σ of communication channels**

Bus source	Fiber optic channel		Power line channel	
	λ_Σ	μ_Σ	λ_Σ	μ_Σ
1	0.09589628	734.572164	0.109127394	807.5486398
2	0.083695895	743.08248	0.095243883	816.9324165
3	0.006031754	1330.67373	0.006854215	1465.551612
5	0.002472612	1588.79738	0.00280486	1752.642178
6	0.00203475	1625.44545	0.002306221	1794.935514
7	0.016936974	1137.37422	0.019264457	1252.864972
8	0.062884682	751.569245	0.071559069	826.33357
9	0.062221822	749.824533	0.070804518	824.418488
10	0.077536602	642.210362	0.088232547	706.0262268

V Traffic reliability

Traffic reliability is information transfer in a timely manner, without losses and associated with the exchange channel loading the distortions. Losses due to traffic are induced by an unacceptable delay or loss of some information due to an overload of the information channel, but are not associated with the failure of the device elements of this channel, which is taken into account in hardware reliability. Therefore, the traffic reliability is determined by the choice of bandwidth, taking into account the delay in the transmitted information.

The information frame from the generation unit or power line, formed by each PMU, combines 9 vector measurements: 3 currents and 3 voltages (magnitude and phase), 3 power (active and reactive components); 2 analog values: generator current and voltage; the state of the PMU device and the state of the switching elements. In addition, the transmission package includes the frequency and speed of its change, the time stamp and the binding for interaction with the information network in the standard C.37.118-2011. The structure of the data frame is given in table. 7.

Table 7 **C37.118-2011 frame structure**

Field	**Size**
Sync byte (SYNC)	2 bytes
Byte number of frame (FRAMESIZE)	2 bytes
Identifier PMU (IDCODE)	2 bytes
Second counting (SOC)	4 bytes
Fraction of a second/quality flag (FRACSEC)	4 bytes
Status flag (STAT)	2 bytes
Vectors (PHASORS)	$8 \cdot n$ bytes (floating point)
Frequency (FREQ)	4 bytes (floating point)
Frequency change rate (DFREQ)	4 bytes (floating point)
Analog data (ANALOG)	$8 \cdot m$ bytes (floating point)
Digital data (DIGITAL)	$2 \cdot l$ bytes (discrete values)
Cyclic Redundancy Check (CHK)	2 bytes

l – number of discrete information sources; m – number of analog information sources; n – synchronized vectors (magnitude and phase).

Then the amount of information from one PMU takes $b_{in} = 8 \cdot 9 + 2 \cdot 8 + 2 + 2 = 92$ bytes. The amount of information per frame of one node is $b_{fr} = 6 + 8 + 8 + 2 = 24$ bytes. Depending on the number of PMU - sources of measurement information, and transmitted measurements per second, the packet volume often have the range of 100 - 400 bytes. The approximate channel bandwidth in kbit/s, depending on the number of source devices and the sampling rate, taking into account a margin of 10%, is given in table 8, [8]. In this case, 1kbit = 1024 bits. Information delay is caused both with the type of the exchange channel and with the time of unloading its receive buffer. Packet delivery to a receiver requires time consuming T_d, which, in the general case, is determined by the propagation time of the signal T_{pc}, the time of transmission of the packet over the communication line T_{tp} and the waiting time of the packet in the queue in the communication unit T_{wp}

Table 8. **Required channel bandwidth, kbit/s**

Samples per second	Number of PMU's			
	2	10	40	100
25	50	249	997	2392
50	100	499	1994	4984
100	200	997	3988	9969

$$T_d = T_{pc} + T_{tp} + T_{wp}. \tag{6}$$

The propagation time, T_{pc}, of the signal in most communication systems is determined by the propagation time of the electric (electromagnetic field) or optical signal. The pulse delay in the optical fiber is (3.5–5) $\cdot\, l$ (ns) [6], and in the copper wire $5 \cdot l$ (μs) [9], where l is the channel length in km.

The packet transmission time, T_{tp}, depends on the data transfer rate on the communication line v_{tr} (kbit/s) and the volume or length of the packet L_p (kbit)

$$T_{tp} = L_p/v_{tr}. \tag{7}$$

Obviously, the propagation speed depends only on the channel material; therefore, the propagation time along the channel is constant. Transmission time depends only on the packet length.

The main task in designing a data transmission network is to ensure a balance between traffic (the flow of requests λ, in our case, the measurement frequency), the amount of network resources (bandwidth) and the quality of the service (service flow μ, parameter of request processing). In solving this problem, two levels of the open system interaction model (OSI) are considered: network and channel.

Network level. Traffic transit routes on the network are considered at the network level. For this, it is convenient to describe the communication network as the graph model [10] (in this case, non-oriented), in which the network nodes (routers) correspond to the graph vertices, and the communication lines to the graph arcs. The transmission time to the receiving node is the time that the packet spends on the network line. This time is to some extent random.

The load intensity on the arcs of the network graph ρ_{ij}, determined by the ratio of the request flow intensity the from the source node information *i* to the intensity of the service flow by the destination node *j* (λ_i/μ_j), depends on the number of devices and the amount of information from each device. In our case, the request flow rate is determined by the frequency of parameter measurement in the nodes of the power system: $\lambda = f_{msr.} = \frac{1}{T_{msr.}}$, service flow intensity – by the revers of the packet delivery time: $\mu = \frac{1}{T_d} = \frac{1}{L_p/v_{tr}+T_{pc}}$, and since this time in our case is shorter than the request period, $T_{wp} = 0$. On the other hand, the receiver electronics creates an additional delay, T_{re}, of about 5 μs on average. Then

$$\rho_{ij} = \frac{L_p/v_{tr}+T_{pc}+T_{re}}{T_{msr.}}\,. \tag{8}$$

Channel level. At this level, it is required to evaluate the necessary bandwidth of communication lines between network nodes. In the general case, an approximate formula can be used to estimate the probability of losses [11]

$$q_{ij} = \frac{1-\rho_{ij}}{1-\rho_{ij}^{N_j+1}}\rho_{ij}^{N_j}, \tag{9}$$

where N_j is the section number of the receiver accumulator *j*; ρ_{ij} is the load intensity of line *ij*.
The loss absence is defined as

$$p_{ij} = 1 - q_{ij}. \tag{10}$$

It is clear that such an assessment corresponds to one information line connecting two nodes. Taking into account the sequence of switching on the communication lines of two nodes passing through the intermediate nodes, the overall assessment of the probability of information loss is defined as

$$P_\Sigma = \prod_{ij} p_{ij}. \tag{11}$$

We estimate the WAMS information channels for the electric power system fig. 2, cited in detail in [3]. The scheme of information links with the distance scale is shown in fig. 3. Define the conditions and characteristics of the network. All information connections are made with fiber optic with propagation delay T_{pc} = 5 ns. Electronics delay is T_{re} = 5μs. Transmission rate is v_{tr} = 1Mbit/s = 1048576 bit/s [12]. The measurement transmission frequency is 10 Hz or $T_{msr.}$ = 0.1 s. Since the dispatch center is defined in four node of the system, the information routes in the normal and emergence mode for several information transmission line is given in table 1. The last column shows the connection of the source node with node 4 in case of failure for one of the link components bypass routes. Note that 10-2 communication failure leads to a complete loss of information exchange with node 10. The initial data for the calculations are summarized in table 9. b_{in} and b_{fr} are directly related to the corresponding line in the third and fourth columns, and Σb^{nr} and Σb^{em} are byte batches, including intermediate packets for the communication, both in normal mode and in emergency one, associated with the failure of one from the lines. *N* is determined by the maximum frames in normal mode and equals five.

The simulation results are given in

Table 9. **Input data on the information network**

Link	*l*, km	b_{in}	b_{fr}	$\sum b_{in}^{nr}$	$\sum b_{fr}^{nr}$	$\sum b_{in}^{em}$	$\sum b_{fr}^{em}$
1-7	150	2	1	2	1	5	3
2-9	75	2	1	3	2	5	3
10-2	70	1	1	1	1	1	1
3-4	70	6	2	6	2	6	2
3-5	50	0	0	0	0	6	2
9-7	130	1	1	4	3	6	4
9-8	40	0	0	0	0	6	4
8-6	145	1	1	1	1	7	5
7-4	50	1	1	7	5	7	5
6-5	50	1	1	0	0	7	3

6-4	30	6	2	7	3	13	7
5-4	40	1	1	1	1	8	4
7-6	50	6	2	0	0	7	5
2-7	150	0	0	0	0	5	3
1-9	75	0	0	0	0	5	3

tables 10 and 11 from which it can be seen that with the calculated loads, the probability of information loss is very low.

Let us consider the dependence of the information loss probability on the load intensity ρ by the example of a 7–4 connection under the remaining conditions. In the same example, we consider the influence of the number of sections drive *N*, tab. 12.

Table 10. **Loads and Probabilities of information loss for a separate link**

Link	$\rho_{ij}^{\text{н}}$	$q_{ij}^{\text{н}}$	$\rho_{ij}^{\text{а}}$	$q_{ij}^{\text{а}}$
1-7	0.01593	1.008E-09	0.04065	1.0643E-07
2-9	0.02477	9.099E-09	0.04064	1.0638E-07
10-2	0.00890	5.545E-11	0.00890	5.5455E-11
3-4	0.04583	1.929E-07	0.04580	1.9296E-07
3-5	–	–	0.04583	1.9289E-07
9-7	0.03363	4.154E-08	0.04949	2.8233E-07
9-8	–	–	0,04949	2.8221E-07
8-6	0.00891	5.557E-11	0.05835	6.3671E-07
7-4	0.05834	6.364E-07	0.05834	6.3645E-07
6-5	–	–	0,05468	4.6204E-07
6-4	0.05468	4.619E-07	0.10412	1.0961E-05
5-4	0.00890	5.541E-11	0.06353	9.6904E-07
7-6	–	–	0,05834	6.3644E-07
2-7	–	–	0,04065	1.0649E-07
1-9	–	–	0,04064	1.0638E-07

Table 11. **Probabilities of no loss for route information**

Route	$Q_{\Sigma\text{м}}^{nr}$	Route	$Q_{\Sigma\text{м}}^{em}$
1-7-4	6,37E-07	1-9-8-6-4	1,199E-05
2-9-7-4	6,87E-07	2-7-4	7,429E-07
3-4	1,93E-07	3-5-4	1,162E-06
5-4	5,54E-11	5-6-4	1,142E-05
6-4	4,62E-07	6-5-4	1,431E-06
7-4	6,36E-07	7-6-4	1,16E-05
8-6-4	4,62E-07	8-9-7-4	1,201E-06
9-7-4	6,78E-07	9-8-6-4	1,188E-05
10-2-7-4	6,37E-07	–	–

Table 12. **Influence of load intensity and number of sections on the probability of information loss q and error-free operation p for communication 7-4**

#	ρ	N	p	q	#	ρ	N	p	q
1	0.01	0	0	1	5	0.3	7	0.9998469	0.0001531
2		1	0.99009901	0.00990099	6		10	0.999995867	4.13344E-06
3		3	0.99999901	9.9E-07	7		100	1	0
4		5	1	9.9E-11	1	0.5	0	0	1
5		7	1	9.88098E-15	2		1	0.666666667	0.333333333
6		10	1	0	3		3	0.933333333	0.066666667
7		100	1	0	4		5	0.984126984	0.015873016
1	0.05834	0	0	1	5		7	0.996078431	0.003921569
2		1	0.944874979	0.055125021	6		10	0.99951148	0.00048852
3		3	0.999813008	0.000186992	7		100	1	0
4		5	0.999999364	6.36452E-07	1	0.7	0	0	1
5		7	0.999999998	2.16628E-09	2		1	0.588235294	0.411764706
6		10	1	4.30211E-13	3		3	0.864587446	0.135412554
7		100	1	0	4		5	0.942856074	0.057143926
1	0.1	0	0.000000000	1.000000000	5		7	0.973782312	0.026217688
2		1	0.909090909	0.090909090	6		10	0.991354799	0.008645201
3		3	0.999099909	0.000900090	7		100	1	1.11022E-16
4		5	0.999990999	0.000009000	1	0.9999999	0	0	1
5		7	0.999999909	0.000000090	2		1	0.500000025	0.499999975
6		10	0.999999999	9.00007E-11	3		3	0.750000038	0.249999962
7		100	1.000000000	0.000000000	4		5	0.833333375	0.166666625
1	0.3	0	0	1	5		7	0.875000044	0.124999956
2		1	0.769230769	0.230769231	6		10	0.909090955	0.090909045
3		3	0.98094566	0.01905434	7		100	0.990099059	0.009900941
4		5	0.998297759	0.001702241					

It is clear that at $N = 0$ the probability of information loss equals 1, because there is simply nowhere to take it. With increasing N, the q value drops rather steeply, turning almost to zero already at $N = 10$. It is also obvious that the greater is the load intensity ρ, the greater is the probability of information loss q, and the increase is quite fast, requiring an increase in the number of sections of the receiver drive N.

VI The network software availability

The failure of the software (SW) is associated with its inconsistency with the set tasks. There are many definitions of a software error. The most acceptable definition seems to be [13]: *Software reliability is probability that the program will work without failures for a certain period, taking into account the degree of their influence on the output results.*

The frequency occurrence of errors from the statistical data, reduced to 100% errors, is given in table 13, with the position "Incomplete or erroneous task" disclosed in more detail.

The software is not the subject to wear and tear and its reliability is determined only by development errors. Thus, over time, this indicator should increase if the correction of the detected errors does not introduce new errors.

Table 13. **Frequency occurrence of errors for certain types** [14]

Cause of error	**Fraction**, %
Deviation from the task	12
Neglecting programming rules	10
Incorrect data sampling	10
Erroneous logic or sequence of operations	12
Erroneous arithmetic operations	9
Lack of time to resolve	4
Incorrect interrupt handling	4
Invalid constants or source data	3
Inaccurate recording	8
Incomplete or erroneous task	28
⇓	
Errors in numeric values	12
Insufficient accuracy requirements	4
Erroneous characters or signs	2
Registration errors	15
Incorrect hardware description	2
Incomplete or inaccurate development basics	52
Ambiguity of requirements	13

For critical applications, which should include the WAMS SW, by the time the system is delivered to the client, it may contain from 4 to 15 errors per 100,000 lines of program code [4]. For clarity, we note that the code line number of WINDOWS XP more than 45 million, NASA - 40 million, Linux 4.11 kernel more than 18 million. When evaluating the WAMS program of 10 million lines of code, the number of errors at the beginning of operation of the program $E = (V/100000) \cdot 4 = 400$ errors. Then, using the formula for the mean time between failures of the software, we get

$\lambda_{SW} = \beta \frac{E}{V} = 0.01 \frac{400}{10^7} = 4 \cdot 10^{-7}$ or

$t_{SW} = \frac{1}{SW} = \frac{10^7}{4 \cdot 8760} \approx 285$ years,

where E is the number of errors per accepted program for operation, V is the program volume in lines of code, β is the program complexity coefficient, usually in the range 0.001 ... 0.01, λ_{SW} is the failure rate and t_{SW} is the mean time between failures of the software, 8760 is the number of hours per year. With a value of one error per 1000 code lines, accepted for application software after testing with the same amount of lines $E = 10\,000$ errors

$$\lambda_{SW} = \beta \frac{E}{V} = 0.01 \frac{10000}{10^7} = 10^{-5} \text{ or } t_{SW} = \frac{1}{\lambda_{SW}} = \frac{10^5}{8760} \approx 11.4 \text{ years}$$

or about one failure in 12 years.

VII Conclusions

The correct functioning of the local information network in the WAMS is ensured by four components of operation reliability: hardware or technical reliability associated with the failure of transmission channel elements or the integrity of information transmission lines; software reliability due to errors in the development of exchange execution programs; and traffic reliability determined by temporary loss or distortion of data without failure of the elements of the transmission channel, and opposition to the external targeted influence on the transmitted information. The influence of the latter component is devoted to a number of works, for example, [15, 16], and is not considered by this paper.

Hardware reliability of such the network is largely determined by the reliability of the information carriers (optical fiber, radio waves, etc.) and the devices that ensure their work - concentrators of vector measurement data. The paper proposes an approach to determining the parameters of such reliability using the example of the 10-bus power system. So, with the proper organization of the backup, the hardware availability of the network, including information sources (PMU), exceeds three nines after the decimal point for optical fiber and is slightly less when exchanging via power lines. Ways of increasing the hardware reliability of the information network are considered.

Traffic reliability component is determined by the load intensity of each connection and the capabilities of receiving information, determined by the volume of the receiver's storage. It should be noted that the probability of information loss on the number of sections in the receiver’s drive is rather strong. Their increase in a certain range makes it possible to compensate for the growth of this probability with increasing load intensity. The availability of the test network for traffic also exceeded three nines.

In the software plan, the effect of the code line volume on the value of this parameter is noted and its estimate is shown depending on the number of commands. An important property of this indicator is its improvement with increasing operating time. However, it can be adjusted due to the introduction of new errors in the correction of those identified in operation. So for the example of the WAMS program of 10 million code lines the mean time between failures should be 285 years.

References

1. Phadke A. G. and Thorp J. S. Synchronized Phasor Measurements and Their Applications. New York: Springer, 2008, 260 p.
2. Uspensky M.I. Functional reliability assessment of the phasor measurement unit // Relay protection and automation. 2017, No. 3, pp. 39-44. (In Russian).
3. Uspensky M.I., Smirnov S.O. The Occurrence Reasons and Countermeasures to Power System Blackouts // The International Journal of Energy Engineering, 2014, No. 1, pp. 1- 8.
4. Li W. Risk Assessment of Power Systems: Models, Methods, and Applications. New York: Wiley-IEEE Press, 2005, 325 p.
5. Reliability assessment of the designed FOCL (*fiber optic communication line*). [Electronic resource]. URL: http://www.icete.ru/pegibs-567-1.html. (Application date: 10.03.2019). (In Russian).
6. Tsukanov V.N., Yakovlev M.Ya. Fiber optic technology. Practical Guide. M.: Infra-Engineering, 2014, 304 p. (In Russian).
7. Uspensky M.I., Kyzrodev I.V. Combined Method of a Distribution Network Reconfiguration for Power Supply Restoration // Proceedings of the IEEE PowerTech, St. Petersburg, Russia, 27-30 June, ref. 33, 2005.
8. Real-Time Application of Synchrophasors for Improving Reliability 10/18/2010. [Electronic resource]. URL: http://www. naspi.org. (application date: 09.12.2019).
9. Davydov A.E., Smirnov P.I., Paramonov A.I. Design of telecommunication systems and networks. Calculation of communication network parameters and traffic analysis. St. Petersburg: University of IT-MO, 2016, 47 p. (In Russian).
10. Asanov M.O., Baransky V.A., Rasin V.V. Discrete mathematics: graphs, matroids, algorithms. M. PXD, 2001, 288 p. (In Russian).
11. N.B. Zeliger, O.S. Chugreev, G.G. Yanovsky. Designing networks and systems for transmitting discrete messages. M.: Radio and communications, 1984, 177 p. (In Russian).
12. Gordienko V. N. et al. Optical telecommunication systems. Textbook for high schools/ V. N. Gordienko, V. V. Krukhmalev, A. D. Mochenov, R. M. Sharafutdinov. M: Hotline – Telecom, 2011, 368 p. (In Russian).
13. Morozov Yu.M. Reliability of hardware and software systems. St. Petersburg, 2011, 136 p. (In Russian).
14. Shklyar V.N. Reliability of control systems. Tomsk: Publishing House of Tomsk Polytechnic University, 2009, 126 p. (In Russian).
15. Zhang Y. etc. Cyber Physical Security Analytics for Transactive Energy Systems / Y. Zhang, V. V. G. Krishnan, J. Pi, K. Kaur, A. Srivastava, A. Hahn and S. Suresh // IEEE Trans. on Smart Grid, vol. 11, no. 2, March, 2020, pp. 931-941.

16. Martel E., Kariger R., Graf P.-A. Cyber Resilience in the Electricity Ecosystem: Principles and Guidance for Boards / Center for Cybersecurity and Electricity Industry Community. January, 2019, 29 p. [Electronic resource]. URL: http://www3.weforum.org. (Application date: 03.03.2020).

Received: July 17, 2020
Accepted: September 19, 2020