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(National Research University)
Polytechnic Institute
Faculty of Power Engineering
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Substation monitoring, protection and control using SCADA-REDI
(A case study on VOSTOCHNAYA Substation 110/10 kV)

GRADUATE QUALIFICATION WORK
SUSU – 13.04.02.2018 GQW

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«____» _____ 2018

TASK
Of the Master Graduate Qualification Work
For the student of the group P-282

Sarmad Najeeb H. Alabbad

1. **The topic:** Substation monitoring, protection and control using SCADA-REDI approved by the order of the University from the 04.04.2018 № 580. Direction 13.04.02 – « Electric Power Industry and Electric Engineering ».

2. The deadline for the completion of the work: 10th Jun.2018

3. The source data for the work

– Specialized and scientific literature and reference;

– National standards;

– Standard of the organization;

– Guidelines;

– Methodological instructions;

– Catalogues of manufacturers of relay protection, automation, and electrical equipment.

4. The content of the settlement and explanatory note (the list of the questions, which are subject to development):

I. Power Plants and Substations

1. Main schemes of electrical substation 110 kV

2. Substation – Protection (Relaying) and Automation

3. Choice of protection time

4. Current Cut-offs

5. Three-stage current protection

6. Differential line protection

7. Protection of Transformers and autotransformers

8. The difference between the differential protection of a transformer and generator

10. Remote protection of lines

II. Features of Digital Substation

1. Benefits of digital substations

2. (IEC-61850) Requirements and standards

3. Optical digital measuring transformers of current and voltage

4. Fiber-optic communication line

5. The use of industrial IP/Ethernet network

6. Microprocessor relay protection and automation

7. Automated system of control and accounting of electric

8. Automated process control system SCADA-REDI

9. How do experts assess the prospects for the introduction of this technology in Russia?

III. Digital substation design model

1. Model Sub-station 110/10kV in LabVIEW

2. Model Station 110 kV in LabVIEW

3. Network stream between the main station 110kV and substation 10kV

5. Presentation on the materials of the work

6. Consultants

| Part | Consultant | Date and sign. | |
		Task (issued)	Task (got)
III. Digital substation design model	K.E. Gorshkov		

7. Issuance date of the task: 10.06.2018

Supervisor _____/ Y. V. Korovin /

The task is taken to perform _____/S.N. Alabbad/

CALENDAR PLAN

The name of the stages final qualifying work (project)	Term of performance of work stages (project)	Marks by Supervisor
The calculation of the new design of the substation 110/10 kV	01.05.2018	
Study of peculiarities of digital substations	20.05.2018	
The result of the final qualifying work	01.06.2018	
Preparation of the presentation	10.06.2018	

Head of the department _____/ I. M. Kirpichnikova /

Supervisor of the work _____/ Y. V. Korovin /

Student _____/ S.N. Alabbad /

ABSTRACT

Alabbad S. N., Substation monitoring, protection and control using SCADA-REDI (A case study on VOSTOCHNAYA substation 110/10 KV). – SUSU, Department of Power plants, networks and systems of power supply. – 102 p. – 70 Fig. – 31 Ref.

In recent years, reliability evaluation of substation protection and automation systems has received a significant attention from the research community. With the advent of the concept of smart grid, there is a growing trend to integrate more computation and communication technology into power systems.

This thesis focuses on the reliability evaluation of modern substation protection and automation systems. Such systems include both physical devices (current carrying) such as lines, circuit breakers, and transformers, as well as cyber devices (Ethernet switches, intelligent electronic devices, and cables) and belong to a broader class of cyber-physical systems and controlling it with SCADA-REDI systems. We assume that the digital substation utilizes IEC 61850 standard, which is a dominant standard for substation protection and automation.

Focusing on IEC 61850 standard, the thesis studied the principles of data transmission at the digital substation developed models and interfacing it in the LabVIEW program, data transmission between two levels: digital substation 110/10 kV and remote station 10 kV, consisting of similar substations, studying the possibility of controlling and automating with SCADA-REDI and streaming it with Web SCADA.

ABBREVIATIONS

AC	Alternative Current.
ATS	Automatic Transfer Switch.
API	Application Program Interface.
CB	Circuit Breaker.
CT	Current Transformer.
CO	Current Cut-off.
DA	Data Access.
DAS	Data Acquisition System.
DC	Direct Current.
EM	Entire Mobile in CB construction.
ES	Ethernet Switch.
FO	Fiber-optic.
GIS	Gas Insulated Switchgear.
GOOSE	Generic Object-Oriented Substation Event.
GOST	Russian Government Standard.
HMI	Human Machine Interface.
HV	High Voltage.
IST	Isolators Semi-Transparent.
ISO	International Organization for Standardization.
LED	Intelligent Electronic Device.
LV	Low Voltage.
MMS	Manufacturing Message Specification.
MU	Merging Unit.
OC	Over Current.
OCP	Over Current Protection.
OLE	Object Linking and Embedding.
OPC	Open Platform Communication.
OSI	Open System Interconnect.
PS	Power Substation.
PT	Potential Transformer.
RDBMS	Relation Data Base Management System.
REDI	Rapid Electronic Device Integration.
SAS	Substation Automation System.
SCADA	Supervisory Control and Data Acquisition.
SMV	Sampled Measured Values.
SS	Substation.
TCP	Transmission Control Protocol.
UCA	Utility Communication Architecture.
UHL1	Climate design; 1- accommodation category.
VLAN	Virtual LAN.

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INTRODUCTION

The scope is to study the advancements in digital substation protection and control technology and studying the possibility to improve the reliability of protection and control systems and the power grid at an affordable cost with enhanced applications capability and maintainability for both hardware replacement and software upgrade.

Cyber physical systems have been rapidly gaining attention in the past few years. The modern power systems with more and more integration of computation and communication technology are becoming complex cyber physical systems. Traditional electric substation systems are facing a challenge on integrating the physical parts like the conventional Circuit Breakers (CB) with the new digital relays and Ethernet Switch (ES) networks. Utilities and manufacturers have been using different protocols and devices in the electric substation design and operation, which often create some unnecessary technical difficulties and extra cost on coordination (C. Singh et al. 2010).

LabVIEW software for National Instruments has been used as interfacing software. This makes the modelling process and analysis easier because LabVIEW has many features and functions that can be used together with data acquisition card from National Instruments. LabVIEW is a graphical programming language that uses icons instead of lines of text to create applications. In contrast to the text-based programming languages, where instructions determine program execution, LabVIEW uses data flow programming, where the flow of data determines execution.

The goal of this thesis is to explain the building process of LabVIEW model for digital substation. Inside the modelling, relay protection, controlling, for this relay, the developed model can be included in one block set only by creating the subsystem for the developed model.

This study is divided into three main sections:

-**SECTION ONE:** presents an overview of Power Plants and Substations.

-**SECTION TWO:** deals with Features of Digital Substation.

-**SECTION THREE:** illustrates the digital substation design model in LabVIEW and tools required for the proposed protecting and controlling.

-SECTION FOUR: Conclusion.

SECTION ONE: Power plants and Substations

1. Introduction:

This chapter presents an overview of power plants and substations, in modern conditions, to ensure the reliability and economy of electricity supply to consumers, it is necessary to work together many power plants, substations and various electrical networks connecting them. However, in this case, the electrical diagrams of the stations and substations must ensure the connection of their individual elements simply, reliably and conveniently. In the conditions of substation operation, there is a need to change the scheme when the equipment taken out, for repair, accident elimination (Andersson et al. 2001). To be able to make these changes in electrical circuits, their elements - transformers, buses of switchgears (CB), air and cable lines - are connected to each other by switching devices that will be discuss later in this section.

The main circuit of electrical connections or the scheme of primary switching is the scheme of electrical connections of the main electrical equipment, which includes power and measuring transformers, reactors, switching devices and connecting conductors. For the main substation schemes, the determining factors are the location of the substation in the power system and its purpose, the power processed into the substation and passing through it in transit, the number and power of the transformers and outgoing lines, the levels of their voltages, and finally, the categories of consumers that feed on these lines. This section includes also the main schemes of electrical substation 110/10 kV and their contents, and the protection and automation of the substation and the proper choice of protection then to the three stages of current cuts off protection to the differential line protection and their aspects to the protection of transformers and autotransformers and comparing between the differential protection of the transformer and generator and finally to the remote protection of lines.

2. Main schemes of electrical substation 110/10 kV

The main scheme of electrical connections of a power plant (substation) is a set of basic electrical equipment (generators, transformers, and lines), bus bars, switching and other primary equipment with all connections made in-kind. The choice of the main circuit is decisive in the design of the electrical part of the power plant (substation), since it determines the complete composition of the elements and the connections between them. The selected main circuit is the initial one when the circuit diagrams of electrical connections, auxiliary circuits, secondary connection schemes, and wiring diagrams, etc. are drawing up.
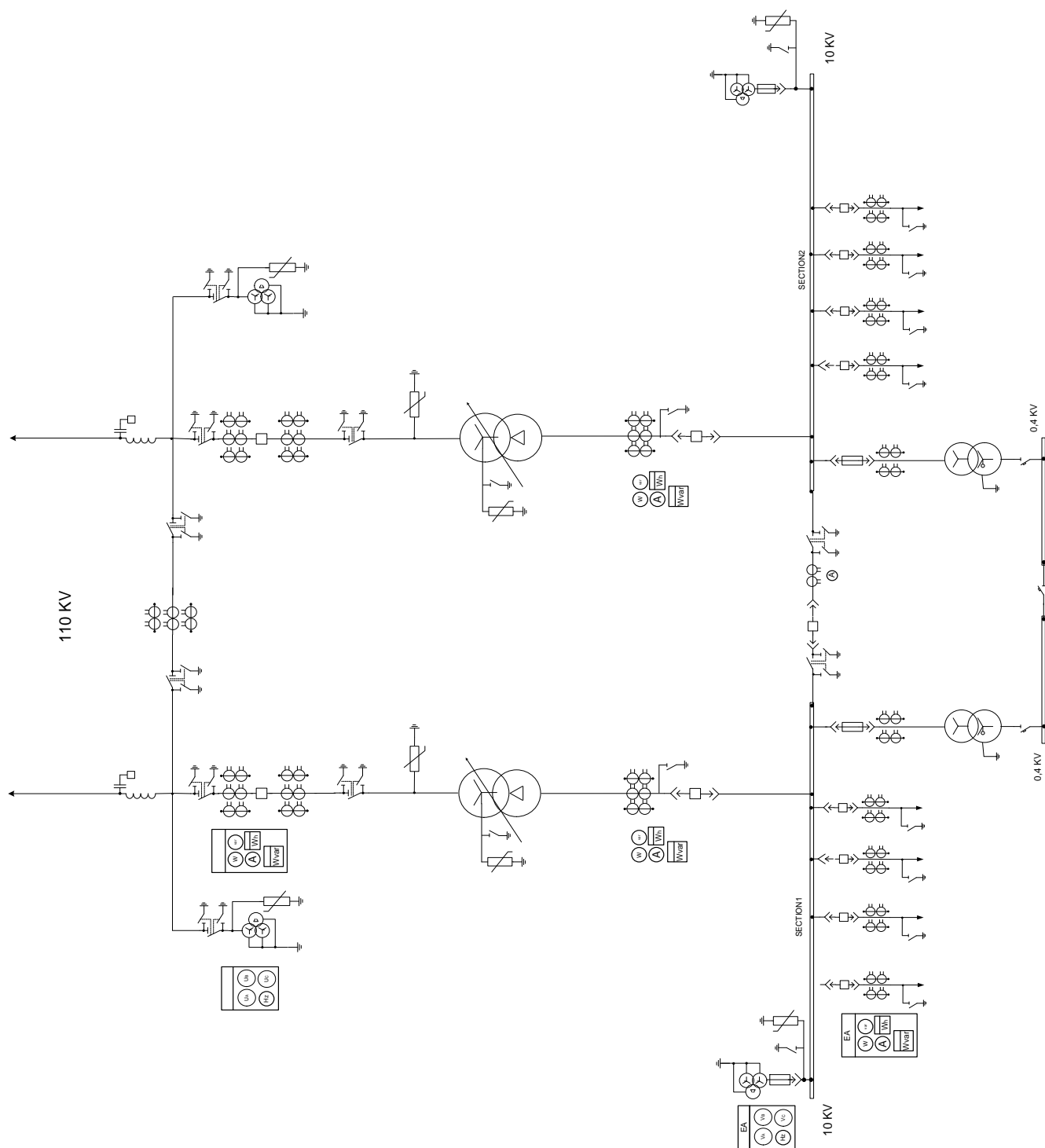
Fig.1 Main schemes of Electrical substation 110/10 kV

2.1 Two of Power Transformers

This transformer, which already has large dimensions, and operates with capacities up to 10 megawatts, is in an open, enclosed area, which clearly delineated in two ways:

• HV 110 kV;

• LV 10 kV.

The 110kV side of the overhead power line connected to another substation, which has even larger dimensions and converts huge energy flows.

The dimensions of only the input support of a single air transmission line make it possible visually assess the significance of the energy flows passing through it.

2.2 Two of the air power lines

Transportation of electric energy to medium and long distances mostly often done through power lines located in the open air. Their design must always meet two basic requirements:

- Reliability of high power transmission;

- Ensuring safety for people, animals and equipment.

When operating under the influence of various natural phenomena associated with hurricane gusts of wind, ice, frost, the transmission lines periodically subjected to increased mechanical stress.

2.3 Repairing bypass on the side between the lines

In the "Bypass" scheme, a switch interconnects lines or transformers on two and three-transformer substations. This scheme used on the HV sides of the 35-220 kV substations if it is necessary to section the circuit breaker or transformers with a capacity of up to 63 MVA inclusive. At voltages of 110 and 220 KV, the bridge circuit is usually applied with a repair bridge, which, if properly substantiated, may not be envisaged (Алексеев Б.М. 2010).
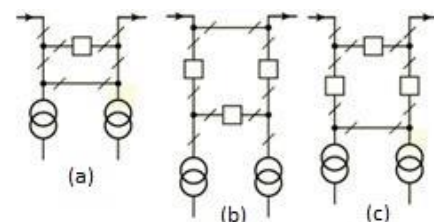
Fig.2 (Bypass) schemes

1. The scheme "bridge with a switch in the jumper and separators in the transformer circuits" used in the same cases as block circuits with separators.

2. The scheme "bridge with switches in the circuits of lines and a repair jumper from the side of the lines" can be applied to the dead-end, branching and passing substations with a voltage of 35-220 kV. At the dead-end and branching substations, the repair jumper and the jumper with the switch are normally open. At the feedthrough substations, the jumper with the switch is normally closed; power transit carried out through it.

3. The scheme "bridge with switches in transformer circuits and a repair jumper on the part of transformers" used in the same cases as the previous scheme. The peculiarity of this scheme is that in case of an accident in the line, the faulty line and the transformer are automatically disconnected. In case of an accident on the transformer, after the automatic switching in operation, two lines and two power supplies remain. Since emergency shutdown occurs relatively rarely, the previous scheme is preferable.

2.4 Gas-Insulated circuit breakers 110 kV (GIS)

High-voltage switches using SF6 as an insulating and arc extinguishing media are becoming more and more widespread, as they have high indicators of switching and mechanical resources, breaking capacity, compactness and reliability in comparison with air, oil and low-oil high-voltage switches.

Successes in the development of SF6 circuit breakers directly has a significant impact on the commissioning of compact switchgear, in gas-insulated circuit breakers,

Switchgear 110 kV Kurpsyaskya HPP administered by JSC "Electric stations"

various methods of arc extinction used, depending on the rated voltage, the rated breaking current and the characteristics of the power system (or a separate electrical installation).

In gas-arc interrupters, unlike air arc extinguishing devices, the arc extinguished, the outflow of gas through the nozzle does not take place in the atmosphere, but in a closed chamber volume filled with SF6 gas at a relatively small overpressure (Андреев К.Е. 2013).

The following gas-insulated circuit breakers distinguished by the method of extinguishing the arc:

1. An auto compressive SF6 circuit breaker, where the necessary mass flow of SF6 gas through the nozzles of the compression arc interrupter is created during the movable circuit breaker system (an auto-compression switch with one pressure stage).

2. An SF6 circuit breaker with electromagnetic blasting, in which arc extinction in the arcing device is provided by rotating it over the ring contacts under the action of the magnetic field created by the tripping current.

3. An SF6 circuit breaker with high and low-pressure chambers, in which the principle of providing gas blasting through the nozzles in the arcing device is analogous to air interrupters (an SF6 switch with two pressure stages).

4. Auto generating SF6 circuit breaker, where the necessary mass flow of SF6 gas through the nozzles of the arc-extinguishing device created by heating and increasing the SF6 gas pressure in a special chamber (self-generating SF6 circuit breaker with one pressure stage).

Let us consider some typical designs of SF6 circuit breakers at 110 kV and above:

Gas-insulated circuit breakers of 110 kV and higher for one break of different firms have the following nominal parameters: $V_{nom.}$ = 110-330 kV, $I_{nom.}$ = 1-8 kA, $I_{o.nom.}$ = 25-63 kA, pressure SF6 = 0.45-0.7 MPa, tripping time 2-3 short-circuit current periods. Intensive research and testing of domestic and foreign firms allowed developing and putting into operation an SF6 circuit breaker with one break at $V_{nom.}$ = 330-550 kV at $I_{o.nom.}$ = 40-50 kA and the time of current disconnection one period of short-circuit current.
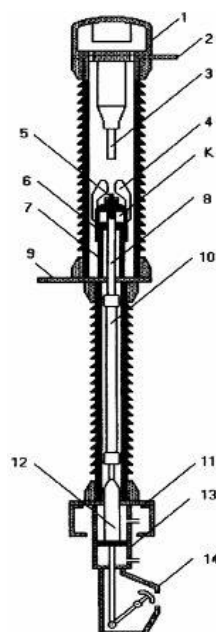
Fig.3 Typical design of an auto compressive SF6 circuit breaker

A typical design of an auto compressive SF6 circuit breaker shown in Fig. 3

The device is in the disconnected position and contacts (5) and (3) are open.

The current lead to the stationary contact (3) carried out through the flange (2), and to the movable contact (5) through the flange (9). In the upper cover (1), a chamber with an adsorbent is mounted. The insulating structure of the SF6 circuit breaker fixed to the footrest (11). When the switch turned on, the pneumatic actuator (13) operates, the rod (12) of which connected through the insulating rod (10) and the steel rod (8) with the movable contact (5). The latter rigidly connected to the Fluoro-plastic nozzle (4) and the movable cylinder (6). The Entire Mobile EM system (elements 12-10-8-6-5) moves upward relative to the fixed piston (7), and the cavity (K) of the arcing system of the switch increases.

When the circuit breaker is disconnected, the drive shaft (12) pulls the moving system downward and an increased pressure created in the cavity (K) in comparison with the pressure in the switch chamber. This self-compression of the SF6 gas ensures the outflow of gas medium through the nozzle, intensive cooling of the electric arc that arises between contacts (3) and (5) upon disconnection. The position indicator (14) makes it possible to check the starting position of the contact system of the switch visually. In several designs of auto compressive gas-insulated circuit breakers, spring, hydraulic power drive mechanisms are used, and the expiration of SF6 gas through the nozzles in the arc chute based on the principle of two-sided blasting.
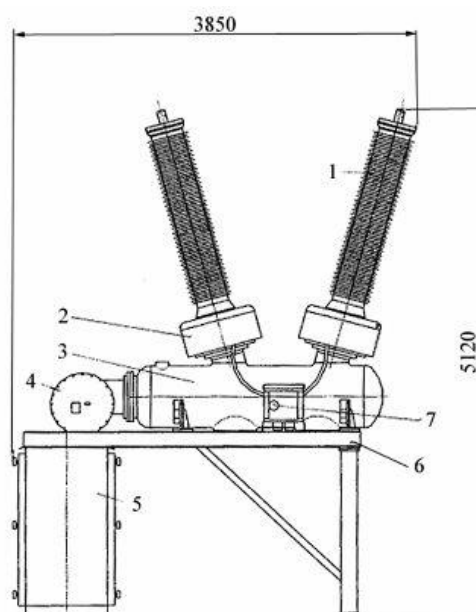
Fig.4 Gas-Insulated Switchgear (GIS) of 220 kV type, (Scale mm.)

Fig. 4 shows a gas-insulated switchgear (GIS) of the 220kV type ($I_{nom.}$ = 2500 A, $I_{o.nom.}$ = 40 kA of scientific and research institute of high-voltage apparatus (NIIVA) with an autonomous hydraulic drive (5) and built-in current transformers. (2) The EV has a three-phase control (one drive in three phases) and is equipped with porcelain (polymeric) tires of (1) air-gas-insulated inputs.

In the gas-filled tank (3), there is an arcing device, which connected to the hydraulic drive (5) through a transfer mechanism located in the gas-filled chamber (4). The design of the gas-insulated circuit breaker fixed to the metal frame (6). To fill the SF6 gas circuit breaker, a connector is used, (7) when installing the switch in the switchgear is equal to 1atm. (abs.) and further it is necessary to provide p = p$_{nom.}$

The advantages of the tank of gas-insulated circuit breakers with integral current transformers before sets "coring sulfur hexafluoride switch plus detached current transformer" are: increased earthquake resistance, a smaller area of disposal site substation, smaller volume required foundation work at construction substations, increased safety substation personnel (extinguishing device disposed in grounded metal tanks),besides the possibility of using SF6 heating for use in areas with a cold climate.

In the tank structures of the circuit breakers of 220 kV and above for outdoor switchgear, it is necessary to increase the nominal gas pressure ($p_{nom.} > 4.5$ atm(abs.)), and so the injected heated gas environment with the aim of preventing liquefaction of Sulphur hexafluoride at low values of the ambient temperature or a mixture of sulfur hexafluoride and nitrogen or tetra Fluoro methane.

As practice shows, a rated voltage 330-500 kV tank-breaker with one break for nominal current 40-63 kA is the most promising type of switching equipment for outdoor switchgear and CB.
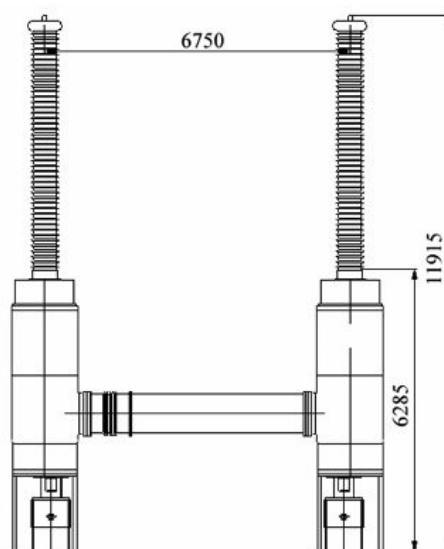
Fig.5 Switch GIS-750-50 / 4000У1 development of "NIIVA", (Scale mm.)

Switch GIS-750-50 / 4000У1 development of "NIIVA" (Fig. 5) with two-break auto-compression arc-quenching device, built-in current transformers, bushings polymer "air-sulfur hexafluoride" is provided with two hydraulic drives per pole, which allows for full-off time of not more than duration of two periods of the current of the industrial frequency.
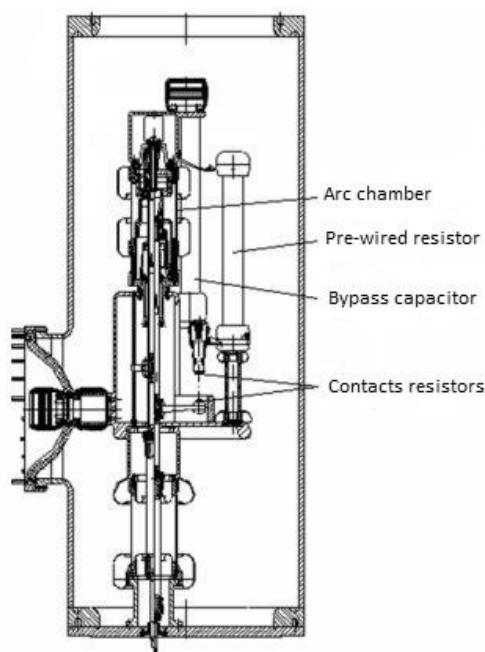
Fig.6 Section through one arc device semi pole GIS-750-50 / 4000У1 with closing resistors, (Scale mm.)

Fig. 6 shows a section through one arc device semi pole GIS-750-50 / 4000У1 with closing resistors (for limiting switching surges). The movable contact of these resistors is mechanically connected to the movable system of the switch. The distribution received by SF6 circuit breakers with one break at a nominal voltage of 110-220 kV with a rated breaking current of 40-50 kA.
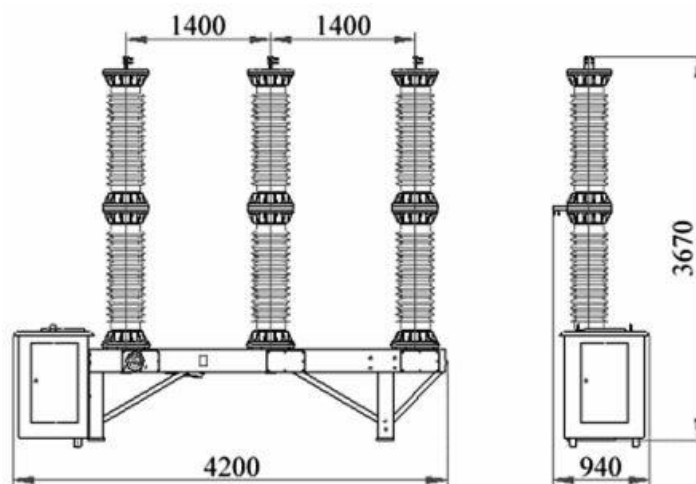
Fig.7 Typical design of a gas-insulated circuit breaker of the GIS type 110 kV, (Scale mm.)

A typical design of a gas-insulated circuit breaker of the GIS type 110 kV ($I_{nom.}$ = 2500 A, $I_{o.nom.}$ = 40 kA) with a spring drive of "Electro apparat" is shown in Fig.7

2.5 Isolators with earth switches 110kV

Isolators are designed to switch on and off the de-energized sections of the electrical circuit under voltage and ground the disconnected sections with ground loops. Isolators are made in the form of separate poles. The pole of the disconnector is a device with a folding knife in a vertical plane, which is mounted on one of the two supporting insulators. A fixed contact of the isolator is mounted on the second insulator. The movement from the drive to the contact blade is transmitted through the rotary insulator by a system of links and levers. Isolators, depending on the order, are manufactured with one or two earthing switches. Between the contact knife and earthing switches, mechanical, electrical and electromagnetic interlocks are provided. Control of the contact knife and earthing switches is carried out by electric drives of PD-11 UHL1 type with remote control. The drives are equipped with commutating devices and a modernized electromagnetic interlock.

Isolators of semi-transparent type (IST) have the following design features:

1. The overall dimensions of the disconnectors are narrowed at the level of the live parts, which allows to reduce the distance between the poles and the areas occupied by them at substations by 20%;

2. The lamellae of the detachable contacts of the main knife and earthing switches are made of the alloy of beryllium bronze and, due to their elasticity, they create a contact pressing, which does not require adjustment in operation during the entire service life;

3. Fixed contact of the swivel type creates a small bursting force acting on the insulators, when turned on;

4. There are sliding contacts in the hinge of the folding contact knife, the contact surfaces of which are covered with silver;

5. Flexible connections of earthing switches are made of braided copper wire covered with tin;

6. Earthing devices are reliably fixed from the garbage forces at short-circuit currents;

7. Full protection of the plug contacts of the contact blade from icing;

8. Support and rotary insulators are made of high-strength porcelain.

2.6 Vacuum circuit breakers 10 kV

The requirements for CBs are as follows:

1. Reliability in work and safety for others;

2. Speed - possibly a short shutdown time;

3. Easy maintenance;

4. Simplicity of installation;

5. Quiet operation;

6. Relatively low cost.

Fig.8 Resource switches of different types

Current switches are meeting the above requirements to a greater or lesser extent. However, the designers of the CBs tend to more fully match the characteristics of the switches with the requirements set forth above.

The electrical strength of the vacuum is much higher than the strength of other media used in circuit breakers. This is explained by an increase in the mean free path of electrons, atoms, ions, and molecules as the pressure decreases. In vacuum, the mean free path of particles exceeds the dimensions of the vacuum chamber.

The restoring electrical strength of the gap is 1/4 "long after the current is cut off at 1600 A in vacuum and various gases at atmospheric pressure. Under these conditions, the impacts of particles on the wall of the chamber occur much more often than collisions between particles. The dependence of the breakdown voltage of vacuum and air on the distance between electrodes of 3/8 "diameter made of tungsten is shown in Figure 8. With such high electrical strength, the distance between the contacts can be very small (2 to 2.5 cm), so the chamber dimensions can also be relatively small.

The process of restoring the electrical strength of the gap between contacts when the current is disconnected is much faster in vacuum than in gases. The vacuum level (residual pressure of gases) in modern industrial arc chutes is usually Pa. In accordance with the theory of the electrical strength of gases, the necessary insulating qualities of the vacuum gap are also attained at lower vacuum levels (of the order of Pa). However, for the present level of vacuum technologies, the creation and maintenance of a Pa level vacuum chamber during the lifetime of a vacuum chamber is not a problem. This provides vacuum chambers with electrostatic storage for the entire lifetime (20-30 years). A typical design of a vacuum arc chute is shown in Fig.9
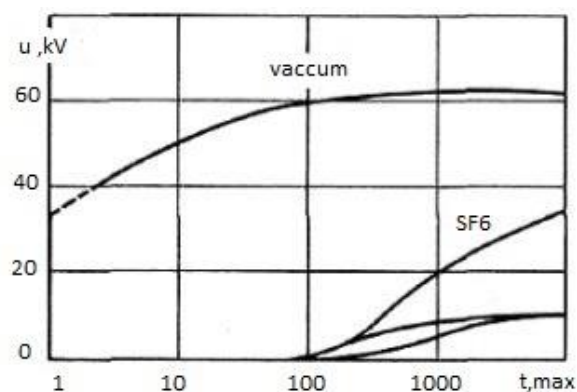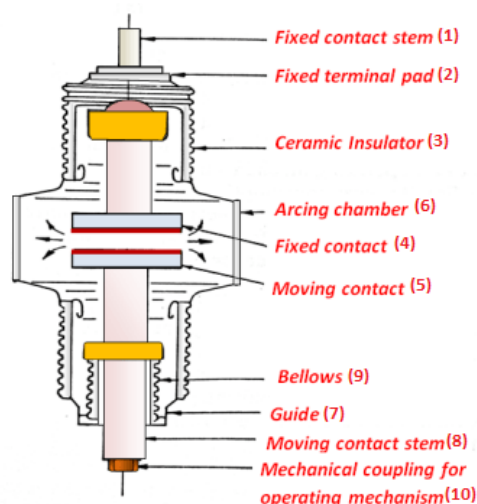
Fig.9 The design of the vacuum arc chute chamber

The design of the vacuum chamber consists of a pair of contacts (4; 5), one of which is movable (5), enclosed in a vacuum-tight shell, welded from ceramic or glass insulators (3; 7), upper and lower metal caps (2; 8) and metal screen (6). Moving of the movable contact relative to the fixed contact. Provided by using a bellows (9). The camera leads (1; 10) serve to connect it to the main current carrying circuit of the switch.

It should be noted that for the manufacture of the shell of the vacuum chamber only special vacuum-cleaned metals, copper and special alloys, as well as special ceramics, which are purified from dissolved gases are used. Contacts of the vacuum chamber are made of a metal-ceramic composition (usually copper-chromium in a ratio of 50% -50% or 70% -30%), which provides high breaking capacity, wear resistance and prevents the emergence of welding points on the contact surface. Cylindrical ceramic insulators, in conjunction with the vacuum gap with diluted contacts, provide insulation between the chamber terminals when the switch is turned off.

TAVRIDA-ELECTRIC has released a new design of a vacuum switch with a magnetic latch. The basis of its design is the principle of coaxially of the drive electromagnet and the vacuum arc chute at each pole of the switch. Switching on is carried out in the following sequence (Локус 2016).

In the initial state, the contacts of the vacuum arc chute are opened due to the action of the opening spring (7) through the pulling insulator (5). When applying a positive polarity voltage to the magnet coil (9), a magnetic flux builds up in the gap of the magnetic system.

At the moment when the armature traction force generated by the magnetic flux exceeds the force of the opening spring (7), the electromagnet armature (11) together with the traction insulator (5) and the moving contact (3) of the vacuum chamber starts to move upward, compressing the opening spring. In this case, the motor counter appears in the coil, which prevents further increase of the current, and even slightly reduces it.

During the movement, the anchor gathers a speed of about 1 m / s, which avoids pre-breakdowns when turning on and eliminates the bounce of the contacts. When the contacts of the vacuum chamber close, in the magnetic system there is a gap of additional compression of (2 mm). The movement speed of the armature drops sharply, since it also must overcome the spring force of the additional contact jaw (6). However, under the influence of the force generated by the magnetic flux and inertia, the armature (11) continues to move upward, compressing the release spring (7) and the spring (6) of the additional contact jaw.

Now, closure of the magnetic system, the armature contacts the upper cover of the actuator 8 and stops. After the switching-on process is completed, the coil current of the drive is switched off. The switch remains in the on position due to the residual induction generated by the annular permanent magnet 10 which keeps the armature 11 in the position drawn to the top cover 8 without additional current feeding.

To disconnect the circuit breaker, a negative polarity voltage must be applied to the coil terminals.

At present, vacuum switches have become the dominant devices for electrical networks with a voltage of 6-36 kV. Thus, the share of vacuum switches in the total number of manufactured devices in Europe and the US reaches 70%, in Japan - 100%. In Russia in recent years, this share has a constant tendency to increase, and in 1997 exceeded 50%. The main advantages of explosives (in comparison with oil and gas switches) that determine the growth of their market share are:

- higher reliability;
- Lower maintenance costs.

2.7 Single Bus section 10 kV of the both sides

The single busbar arrangement is simple to operate, places minimum reliance on signaling for satisfactory operation of protection and facilitates the economical addition of future feeder bays. Figure 10 illustrates a single busbar scheme with fourteen feeder circuits and one bus section circuit breaker.

Fig.10 Single Bus scheme with Bus Section Breaker

Characteristics:

1. Each circuit is protected by its own circuit breaker and hence a fault on a feeder/transformer does not necessarily result in loss of supply to other feeders.

2. A fault on a feeder or transformer circuit breaker causes loss of the transformer and feeders circuits. They may be restored after isolating the faulty circuit breaker.

3. A fault on a bus section circuit breaker causes complete shutdown of the substation. All circuits may be restored after isolating the faulty circuit breaker and the substation will be 'split' under these conditions.

4. A busbar fault causes loss of one transformer and all feeders on that bus section. Maintenance of one busbar section will cause the temporary outage of all circuits. Can be used only where loads can be interrupted.

5. Bus cannot be extended without de-energizing of half of the substation

6. Difficult to do any maintenance, maintenance of a feeder or transformer circuit breaker involves loss of that circuit.

7. Lowest cost

8. The introduction of bypass isolators between the busbar and circuit isolator (Fig.11) allows circuit breaker maintenance facilities without loss of the circuit. Under these conditions, full circuit protection is not available.

9. Bypass facilities may also be obtained by using a disconnect switch on the out-going ways between two adjacent switchgear bays (Figure 12). The circuits paralleled onto one circuit breaker during maintenance of the other. It is possible to maintain protection (although some adjustment to settings may be necessary) during maintenance but if a fault occurs then both circuits are lost. With the high reliability and short maintenance, times involved with modern circuit breakers of such bypasses are not nowadays so common.
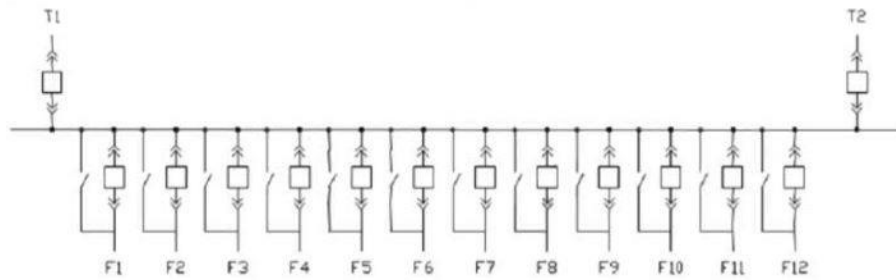
Fig.11 Single Bus scheme with Bypass Isolator
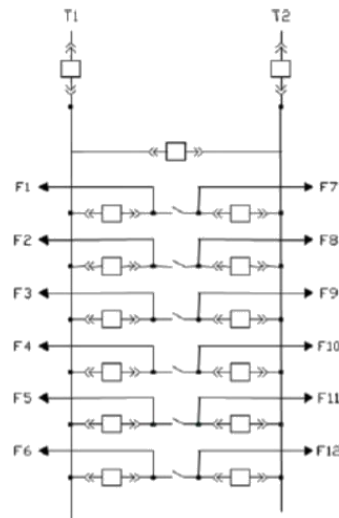
Fig.12 Single Bus scheme with Bypass Switch between Two adjacent Bays

2.8 Auxiliary Transformer

At the substations of power lines, there are many units of maintenance equipment. For such consumers, an auxiliary transformer (AT) is used. The unit stabilizes the operation of such installations in different categories of objects. This type of transformer reduces the voltage for the correct functioning of consumers.

Auxiliary Transformer (AT)

- Application area:

Transformers, of their own needs, are characterized by a special area of purpose. The list includes several power plant devices. Current consumers of a certain power can be:

- Electric motors of cooling systems.

- Heating devices for oil equipment switches, switchgear cabinets, including associated instruments and installations.

- Insulation monitoring device.

- Lighting devices inside and outside, heating and other systems.

- Regulators of power equipment under load.

- Charging units, capacitive batteries.

- Bearing lubrication systems of the category.

- Own hydrogen installation.

- Pumping equipment of fire extinguishing systems, water supply.

- Automation and compression of air systems.

- Mechanisms of ventilation, boilers.

The most important devices that are powered by electricity from transformers of their own needs are control equipment, relay protection, security equipment, alarms, tele-mechanics and automatic devices. The full operation of the plants depends on them. If they are interrupted for a short time, a partial or complete cut-off of the electric power supply along the lines is possible.
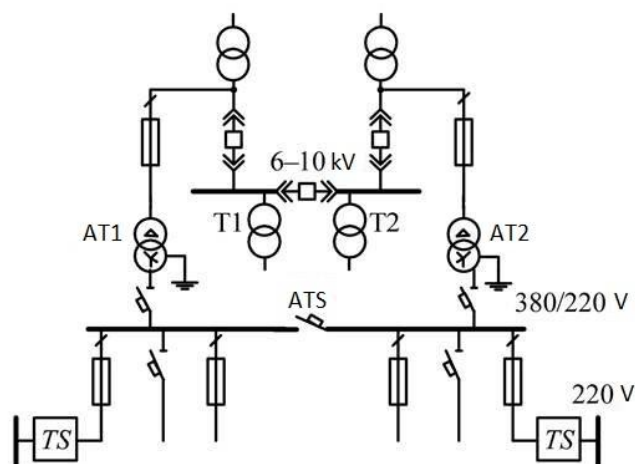
Fig.13 Schemes of the Auxiliary Transformer

There are power schemes, consumers in which do not affect the operation of the substation. The operation of this equipment is secondary. These are irrelevant devices. There is no need to feed them with transformers of own needs all the time.

The principles of organizing the supply of electricity at substations are similar. However, the categories of consumers can be different depending on the variety of the object. At conventional substations, aggregates with a capacity of 6 (10) kV are used. Traction substations powered by

equipment with a nominal value of 27.5 kV. If a constant voltage transmitted along the substation lines, the equipment buses have a power of 35 kV.

- Features:

The sum of the capacities of the service equipment of the substation is not high. Therefore, such units are connected from the low side to the step-down transformer. The amount of equipment presented depends on the features of the substation. If two main transformers are installed here, two AT will be required in such conditions. In the case of the need for the required quantity, power is determined in accordance with the load of the substation, including possible overloads. If there are many units of critical devices at such a substation, 3 ATs are installed at once. Each transformer in the aggregate provides stable operation of the object. More often for such operating conditions, 10 / 0.4 kV equipment is used. Their limiting capacity can be up to 1600 kVA.

- Power calculation

The power of AT, which will be used at the substation, can be calculated by a certain formula. This considers the type of service of the object. In the first situation, the calculation is made for the substation, where staff are not constantly on duty. If one AT is used, the power of the transformer should be as follows:

$$M_{Transformer} \geq M_{Calculated}$$

When installing two ATs on the site with a 24-hour, the value (MPEO - the maximum permissible emergency overload factor) is added to the divider. Usually it is 1.4. The formula with such a divisor will have the form:

$$M_{Transformer} \geq M_{Calculated} / MPEO$$

More than two ATs can be used at the substation. In this case the divider will be the magnitude of the emergency (emergency load – E). the calculation will be:

$$M_{Transformer} \geq M_{Calculated} / E$$

With this action, it becomes possible to establish the required capacity of the units. The above divisors make it possible to calculate the need for an object in transformer installations. The power of each of the AT should not exceed 630 kVA.

- Connection diagrams

When putting into operation, connecting equipment, strict standards and requirements are applied. This approach increases the reliability of equipment, prevents the insulation of transformers due to overheating.

A network with a voltage of 6-10 kV requires the use of a neutral. It can be covered with insulation or grounded through a coil that extinguishes the arc. The power lines are long, characterized by high capacitive characteristics. The cable acts as a capacitor. When a single-phase fault occurs in the fault location, the current to the ground is determined in the number of hundreds of amperes. The insulation here is quickly destroyed. This results in a two- and three-phase fault. Therefore, networks with a capacitive cable in the event of an emergency completely stop the supply of electricity to consumers.

To prevent such an adverse event, a grounding inductor installed in the network at the zero point. This part compensates for the capacitive earth fault current. Having considered the peculiarities of the operation and selection of the auxiliary transformers, it is possible to determine the need of the substation devices and systems in the presented equipment.

2.9 Transmission lines T.L.

Cable line (C.L.), - a line for power transmission, comprising one or more parallel cables, made in any way gasket (Fig.14). Cable lines pave where the construction of impossible due to constrained areas is unacceptable in terms of safety, it is inappropriate for economic, architectural and planning ratios and other requirements.
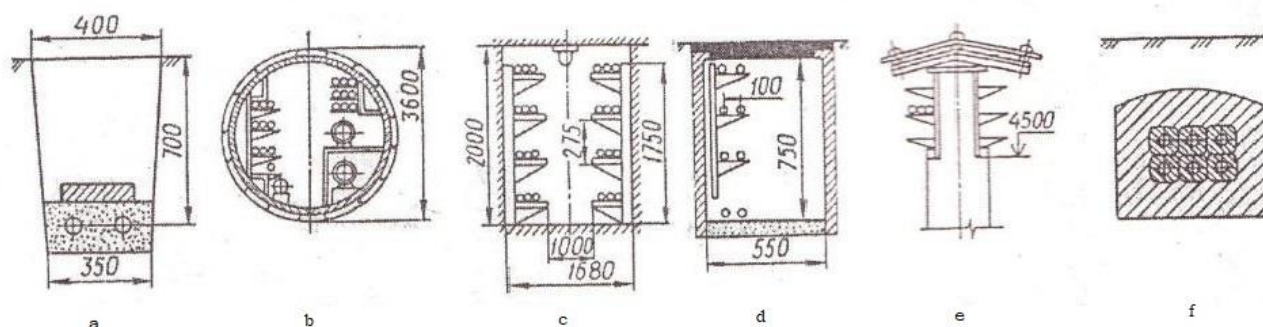
Fig.14 Methods of laying cables and cable structures
a. earthy; b. collector; c. tunnel; d. the channel; e. flyover; f. block.
(Scale mm.)

The greatest use of T.L found in the transmission and distribution electricity at industrial enterprises and in cities (internal power supply systems) in the transmission of electrical energy through large water areas, etc. Advantages and disadvantages of cable lines in comparison with air: non-exposure to atmospheric influences, stealth and inaccessibility for unauthorized persons, less damage, compactness of the line and the possibility of broad development of electricity supply to consumers in urban and industrial areas. However, C.L is significantly more expensive than airs of the same voltage (an average of 2-3 times for 6-35 kV lines and 5-6 times for 110 kV and higher lines), is more difficult to construct and operate.

The structure of C.L includes cable, connecting and end clutches, building structures, fastening elements, etc.

The cable is a finished factory product, consisting of isolated conductor cores enclosed in a protective hermetic shell and armor, protecting them from moisture, acids and mechanical damage. Power cables have from one to four aluminum or copper veins with a cross section of 1.5-2000 mm^2. The veins cross-section up to 16mm^2 are single-wire, more than a lot of wire. The veins are round, segmented or sectoral in shape.

Cables with voltage up to 1 kV made, as a rule, four-core, 6-35 kV voltage - three-core, and 110-220 kV single-core voltage.

Protective covers are made of lead, aluminum, rubber and PVC. In 35 kV cables, each core additionally enclosed in a lead sheath, which creates a uniform electric field and improves heat removal. The alignment of the electric field in cables with plastic insulation and sheath is achieved by shielding each conductor with semiconducting paper.

In cables for a voltage of 1-35 kV, a layer of waist insulation is laid to increase the electrical strength between insulated conductors and a shell. Cable armor, made of steel tapes or steel galvanized wires, is protected from corrosion by an outer cover made of cable yarn impregnated with bitumen and coated with chalk composition. In cables with a voltage of 110 kV and higher, the electrical strength of paper insulation is increased when they are filled with gas or oil under excess pressure (gas-filled and oil-filled cables).

In the mark, the designation of the cable indicates information about its design, rated voltage, number and cross-section of cores. For four-core cables with a voltage of up to 1 kV, the cross-section of the fourth ("zero") conductor is less than that of the phase conductor. For example: cable VPG-1-3·35 + 1 25 – (a cable with three coppers conductor's cross-section of 35mm^2 and a fourth cross-section 25mm^2). Polyethylene (P) insulation for 1 kV, a shell of PVC (B) unarmored, without an external cover. (D) - for laying indoors, in channels, tunnels, in the absence of mechanical influences on the cable АОСБ-35-3·70 – (cable with three aluminum (A) wires of 70mm^2, with insulation on 35 kV, with separately leaded (O) veins, in lead (C) shell, armored (B) steel tapes, with external protective cover - for laying in the earthen trench).

OSB-35-3·70 - means the same cable, but with copper cores. Some cable designs shown in Fig.15.

In Fig.15, a, b are power cables with voltage up to 10 kV.

A four-core 380 V cable (see Fig.15, a) contains the elements: 1- current-carrying phase conductors; 2 - paper phase and waist insulation; 3 - protective shell; 4 - steel armor; 5 - protective cover; 6 - paper filler; 7 - zero vein.
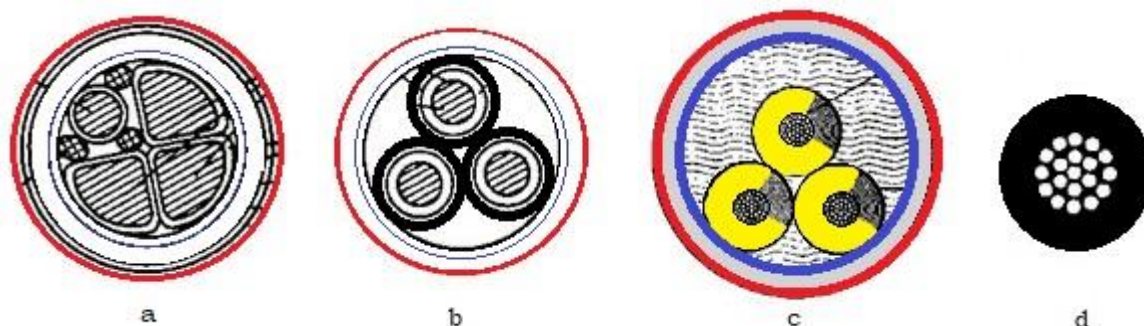
Fig.15 Power transmission lines

a - four residents with a voltage of 380V; b) three-core with a voltage of 35 kV;

c-oil-filled high pressure; d-single-core with plastic insulation

A three-core cable with paper insulation with a voltage of 10 kV (Fig.15, b) contains the elements: 1 - current-carrying veins; 2 - phase insulation; 3 - general waist insulation; 4 - protective shell; 5 - pillow under the armour; 6 - steel armour; 7 - protective cover; 8 - filler.

A three-core 35 kV cable is shown in Fig.15, c. It includes 1- round current-conducting veins; 2 - semiconducting screens; 3 - phase insulation; 4 - lead sheath; 5 - pillow; 6 - aggregate of cable yarn; 7 - steel armour; 8 - protective cover.

(Fig.15, d) shows oil-filled medium and high-pressure cable with a voltage of 110-220 kV. The oil pressure prevents the appearance of air and its ionization, eliminating one of the main causes of insulation breakdown. Three single-phase cables are placed in a steel pipe (4) filled with oil (2) under excess pressure. The current-carrying core (6) consists of copper round wires and covered with paper insulation (1) with viscous impregnation; over the insulation, a screen (3) is placed in the form of a copper perforated tape and bronze wires, which protect the insulation from mechanical damage when pulling the cable in the pipe. Outside, a cover (5) protects the steel pipe. Widely distributed cables in PVC insulation, are produced by three, four and five-core (Fig.15, e) or single-core (Fig.15, d).

Cables are made by lengths of limited length, depending on the voltage and section. When laying, the pieces are joined by means of couplings that seal the joints. At the same time, the ends of the cable strands freed from insulation and sealed in connecting clamps.
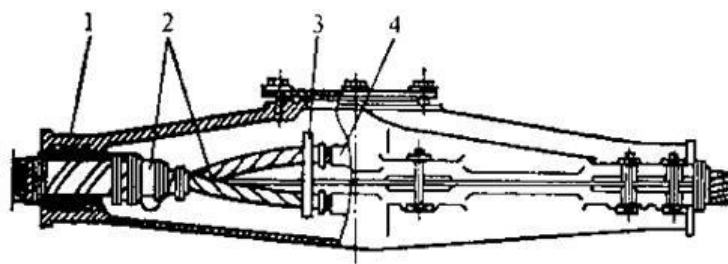
Fig.16 Cast-iron coupling for three-core cables up to 1 kV

When laying cables 0.38-10 kV in the ground to protect against corrosion and mechanical damage, the connection point is in the protective cast-iron split housing. For 35 kV cables, steel or fiberglass casings are also used. In Fig.16, the connection of the three-core low-voltage cable (2) in the cast-iron coupling (1) is Apo graphed. The ends of the cable fixed with a porcelain spacer (3) and connected by a clamp (4). Clutches of cables up to 10 kV with paper insulation filled with bituminous compounds, cables 20-35 kV filled with oil. Applied and other designs of the coupling.

At the ends of the cables, end couplings or end sleeves are used. In (Fig.17), and the mast icon-filled three-phase clutch of the external installation with porcelain insulators for 10 kV cables shown. For three-core cables with plastic insulation, the end clutch shown in (Fig.17, b). It consists of heat-shrinkable glove (1), resistant to the environment, and semiconducting heat-shrinkable tubes (2), through which three single-core cables created at the end of a three-core cable. Isolated heat-shrinkable tubing (3) put on individual wires. They install the required number of heat-shrinkable insulators (4).

For cables of 10 kV and below with plastic insulation in the internal premises, a dry cut is used (Fig.17, c). Finished ends of the cable with insulation (3) wrapped with a sticky polyvinylchloride tape (5) and lacquered. The ends of the cable sealed with a cable mass (7) and insulating glove (1) covering the cable sheath (2), ends of the glove and veins are further sealed and wrapped with polyvinylchloride tape (4), (5), the latter to prevent lagging and unwinding is fixed with cable ties from the twine (6).
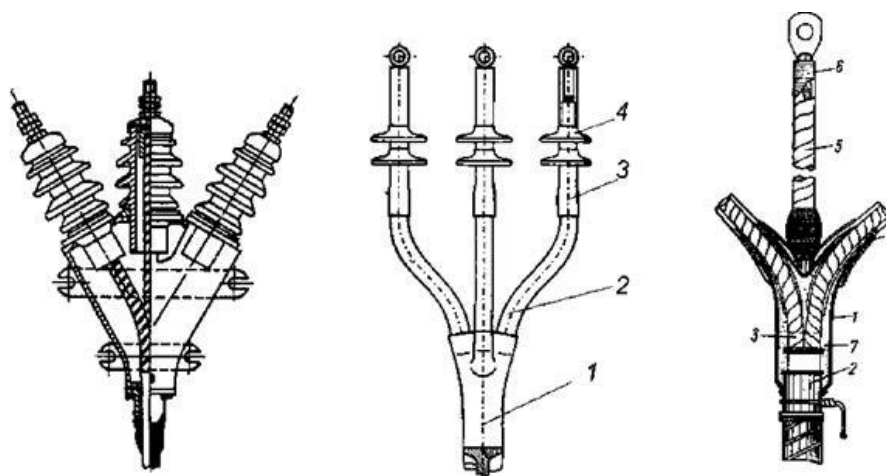
Fig.17 Terminations 3-core cables with a voltage of 10 kV

a- outdoor installation with porcelain insulators; b-outdoor installation with plastic insulation;

c- internal installation with dry cutting.

The way of laying cables is determined by the conditions of the line route. Cables laid in earthen trenches, blocks, tunnels, cable tunnels, collectors, over cable overpasses, also on floors of buildings.

Most often in the cities, industrial enterprises, cables are laid in earth trenches. To prevent damage due to deflections on the bottom of the trench, a soft cushion is created from a layer of sifted earth or sand. When laying several cables up to 10 kV in one trench, the horizontal distance between them must be at least 0.1 m; 0,25 m - between the cables of 20-35 kV.

The mounting of the connector 3 STP-10 (150-240) 3ETA

The cable is covered with a small layer of the same soil and covered with brick or concrete slabs to protect against mechanical damage. After that, the cable trench covered with earth. In the places of crossing the roads and at the entrances to the buildings, the cable is laid in Asbestos-cement or other pipes. This protects the cable from vibrations and provides the possibility of repair without opening the roadway. Laying in trenches is the least expensive way of cable ducting.

In locations where many cables is laid, aggressive soil and wandering currents limit the possibility of their laying in the ground. Therefore, together with other underground utilities use special facilities: collectors, tunnels, canals, blocks and overpasses. The collector serves for the joint placement in it of various underground utilities: cable power lines and communications, water pipes along city highways and on the territory of large enterprises. With many parallel cables, for example, from the building of a powerful power station, a gasket used in the tunnels. At the same time, the operating conditions are improved; the surface area of the earth reduced, which is necessary for laying cables (Вараксин Э.В. et al. 2017). However, the cost of tunnels is very high. The tunnel designed only for laying cable lines.

With a smaller number of cables, cable channels are used that are closed by ground or reaching the ground level. Cable trestles and galleries are used for aboveground cabling. This type of cable facilities is widely used where direct laying of power cables in the ground is dangerous due to landslides, landslides, permafrost etc. In cable ducts, tunnels, collectors and overpasses, cables are laid on cable brackets. In large cities and large enterprises, cables are sometimes laid in blocks that are asbestos-cement pipes, the joints of which are cemented with concrete. However, in them, the cables do not cool well, which reduces their throughput. Therefore, the cables in the blocks should be laid if they cannot have laid in trenches. In buildings, along walls and ceilings, large streams of cables are laid in metal trays and boxes. Single cables can be laid openly on walls and ceilings or hidden: in pipes, in hollow slabs and other building parts of buildings.

3. **Substation – Protection (Relaying) and Automation**

The aim of the protection is to intervene in the electricity grid in case of a fault. To prevent further damage, a part of the grid (containing the faulted component) should be disconnected. This can reduce the availability and thus increase the probability of interruption. It can also influence the load-flow. Sometimes it can reduce a load burden (e.g. by load shedding) but generally it increases the loading of the remaining components, thus increasing the probability of an interruption. To prevent an interruption of the electricity supply as much as possible, the second aim of the protection is to disconnect no more components than necessary, even in case of a failure of the protection. To fulfil both tasks as far as possible the power system divided into "zones": this is the smallest part of the electrical network that can be disconnected from the rest of the system.

In general, the term "zone" used for the part of the network in which a fault is detected by a relay. When assessing the reliability of protection, this "protected region" will be of a stochastic nature. The setting of the relay is not known, nor are the type of fault or the exact network parameters. The term "zone" suggested to use in reliability analysis as the ideal "protected region". Such zones will be separated from each other by circuit breakers.

In case of a fault within a certain zone, the primary protection needs to disconnect this zone. In case a fault influences two or more zones, then it will be considered as separate faults. Each fault then must be disconnected by the protective apparatus of the faulted zone. Such a situation occurs for a fault in a circuit breaker or for a double-circuit fault on a multi-circuit.

Line, in case of a failure of the primary protection the fault needs to be disconnected by a local backup (disconnecting only the faulted zone) or by a remote backup (disconnecting non-faulted zones too). This is again a slight deviation fi-om the standard definition in which a local back-up is situated in the same station as the primary protection and the remote back-up in another station.

For the protection of substation facilities, we use relay protection devices on a microprocessor-based, as the most advanced in comparison with other based devices on a semiconductor and electromechanical element base.

At present, the use of relay protection devices implemented with the use of microprocessor based becomes more and more expedient and promising because they have several significant advantages:

- Visibility of the process for the operator due to many measurements and signalling and presentation of information;

- Remote control of both relay protection terminals and primary substation equipment;

- Continuous diagnosis, which allows for pre-emergency prevention;

- "flexibility" for the engineer when working with devices;

- Reprogramming of programs (in some terminals);

- The ability to register and store all values in pre-emergency and emergency situations for accurate post-accidental computer analysis of the causes of the accident with the built-in surveillance system, etc.

▪ The Proper Choice of Relay Protection

Relay protection devices divided into three types:

- Electromechanical.
- Semiconductor.
- microprocessor-based.

Each of these generations has its advantages and disadvantages. So the <u>advantages</u> of electromechanical relays include:

- Minimum investment.
- High reliability.
- High noise immunity.

<u>The disadvantages include:</u>

- High cost of installation, configuration.
- Difficult to operate.
- Long payback period.

<u>The advantages of solid-state relays are:</u>

- Average investment.
- Functionality almost like microprocessor based.

<u>The disadvantages of solid-state relays are:</u>

- High cost of installation, configuration.
- Average number of failures.
- Very difficult to operate.
- The average payback periods.

<u>The advantages of microprocessor relays include:</u>

- A lower level of selectivity (the difference between the response time of two relay protection and automation) (≈ 0,3s), which allows quick disconnection of short circuits. This entails less equipment wear and less repair costs.
- Low installation and setup costs.
- High functionality.
- Integration with Automated process control system (APCS).
- Short construction time.
- Minimum dimensions.

The disadvantages include:

- Large investments.

- Not enough high reliability (80%).

Thus, microprocessor technology has several advantages. Integration of devices (relay protection and automation) into an automated control system makes it possible to control electrical equipment and relay protection remotely, including their reconfiguration and setting of parameters, monitor system parameters and respond to emergency events. Microprocessor systems have a high speed; have the property of self-diagnosis, warning the staff about the fault in the system.

Main types of relay protection

3.1 Overcurrent protection

▪ The principle of operation of over current protections

In the event of a short circuit, the current in the line increases. This feature used to perform current protection. The overcurrent protection (OCP) comes into operation when the current in the phases of the line exceeds a certain value (Шаббад М. А. 2013).

Current protection sub-divided into overcurrent protection, in which a time delay used to ensure selectivity,

Fig.18 OCP Schemes

and current cut-offs, where selectivity achieved by selecting the pickup current. Thus, the main difference between different types of current protections lies in the method of ensuring selectivity. Fig.18
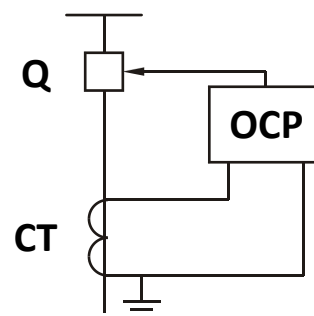
3.1.1 Line protection by means of overcurrent protection with an independent time delay

OCP is the main protection for overhead lines with a single phase. OCP is equipped not only with power lines, but also with power transformers, cable lines, and powerful motors with a voltage of 6 or 10 kV (Андреев А.Н. 2017).
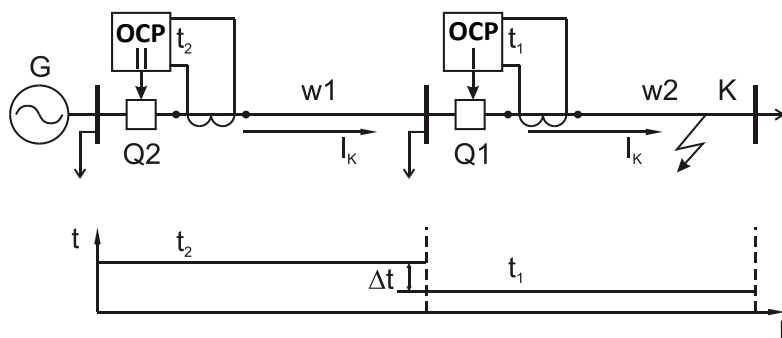
Fig.19 The effect of short-circuit protection at K

Location of protection at the beginning of each line on the supply side.

In Fig.19 shows the effect of short-circuit protection at K. Delay times protections are selected by a stepwise principle, and do not depend on the amount of current flowing through the relay.

3.1.2 3-phase scheme of protection on a constant operational current

The protection scheme shown in Fig.20:

Main relays:

The starting organ is the current relay of the spacecraft.

The time organ is a CT time relay.

Q – CB, switchgear.

Auxiliary relays:

KA – Current Relay (CR).

KL - Intermediate Relay.

KH - Indicating Relay.

KT – time-delay relay.

SQ – trip contact.

YAT – trip coil.
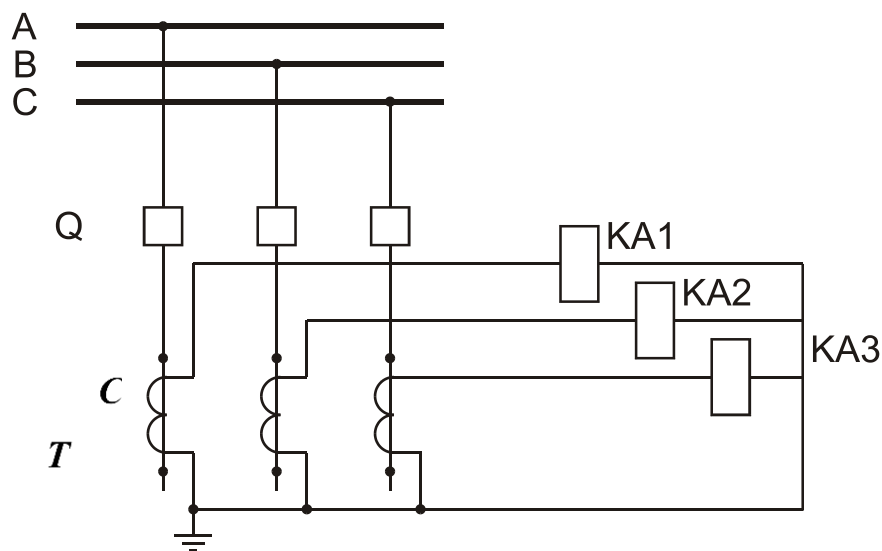
a) Current Circuit
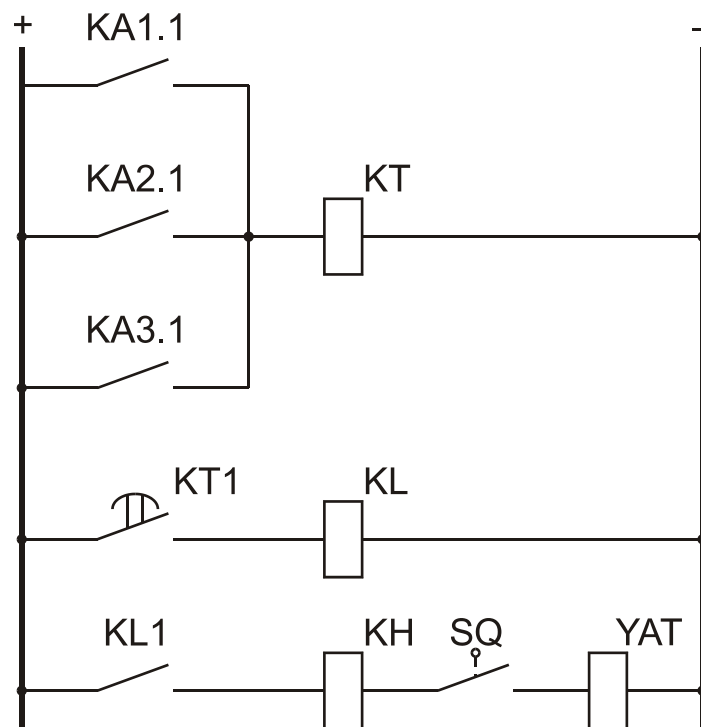
b) Operational current circuits

Fig.20 3-Phase scheme of protection on a constant operational current

Intermediate relay is set when the time switch cannot close the trip coil circuit YAT due to insufficient capacity of the contacts. Block SQ-contact switch is used to divide a current flowing through the trip coil, as intermediate relay contacts are not calculated on opening.

3.1.3 Two-phase scheme of protection on a constant operational current

In cases where the overcurrent protection must only react with phase-to-phase short-circuits, two-phase circuits with two or one relays are used, as they are cheaper.

- Two relay circuits

a) Current circuit

b) Operational current circuits

Fig.21 Two-Phase scheme of protection on a constant operational current

<u>Advantages</u>

1. The circuit reacts to all phase-to-phase faults on the lines.

2. More economical than a three-phase circuit.

<u>Disadvantages</u>

Less sensitivity at 2-phase short-circuits behind the transformer with winding connection Y/Δ-11 gr. (Two times less than that of the three-phase circuit).

4. **Choice of protection time**

For an overcurrent protection with an independent time delay, the protection time delay is calculated using the formula below; the calculation starts from the overcurrent protection set by the electric power consumers (see Fig.22):

$$t_{BB(n)} = t_{BB(n-1)} + \Delta t.$$
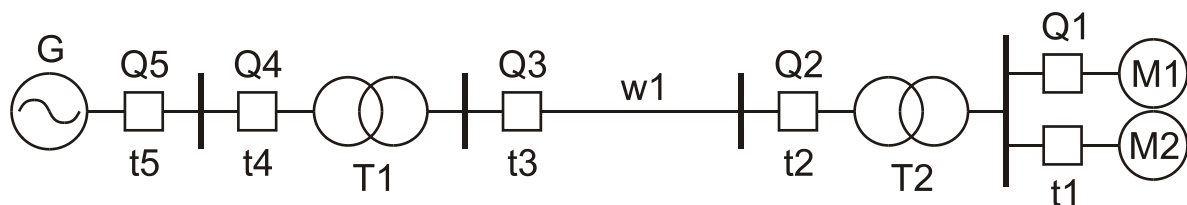
Fig.22 Choice of protection time

t_1=0, t_2=0,5sec. , t_3=1sec., t_4=1,5sec, t_5=2sec.

▪ Application of protection

Over current protection (OCP) is used to protect most 6-10 kV facilities, such as engines, power lines, etc.

5. **Current cut-offs**

▪ Principle of operation

Current cut-off - a type of current protection, which allows quick disconnection of short-circuit.

Current cut-offs (CO) are divided into

- Instantaneous cut-offs.

- Cut-offs with time delay (0.3 ... 0.6 sec.).

The selectivity of current cut-offs achieved by limiting their work area.

The magnitude of the fault current flowing along the line depends on the fault location:

$$I_K = \frac{E_C}{X_C + X_{WK}} = \frac{E_C}{X_C + X_Y L_K},$$

Where; EC is the EMF of the system; X_C – system resistance;

X_{WK} – resistance of the line to the point of short circuit;

X_Y – is the resistivity of the line.

L_K – is the length from the beginning of the line to the point of fault.

I_{PT} – current protection triggered.
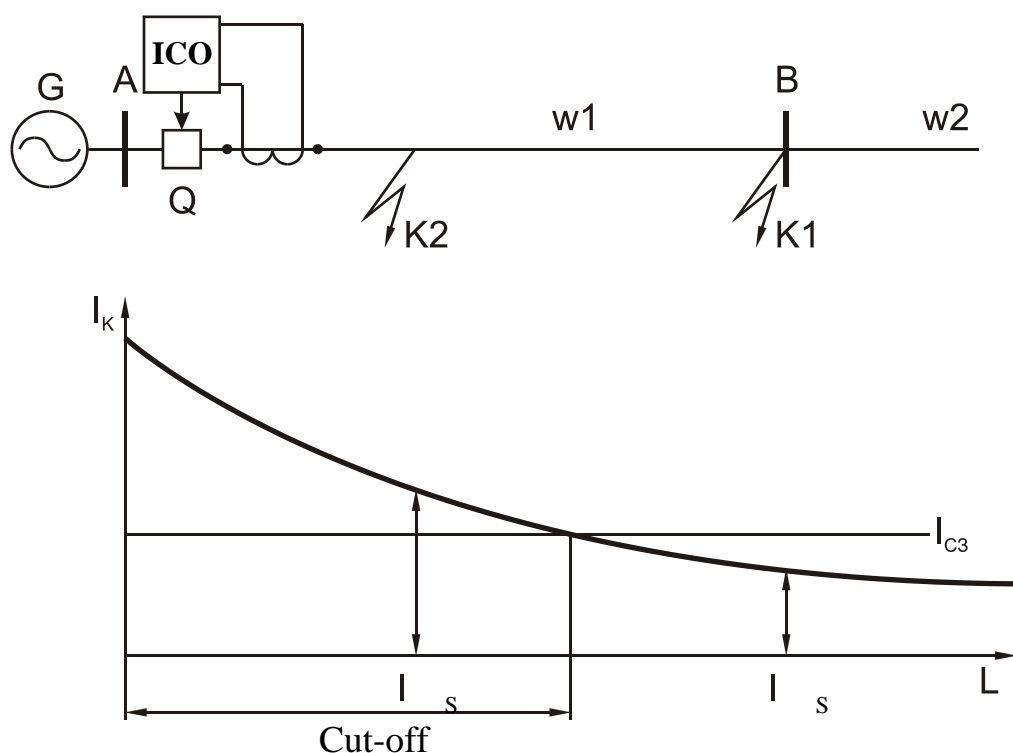
Fig.23 Instantaneous overcurrent trip Zone

To ensure selectivity, the tripping current of protection $I_{PT} > I_{S.C1}$ - short-circuit current on the buses of the opposite substation. Current cut-offs are used both in radial networks with one-sided power supply, and in a network having a two-way power supply.

5.1 Scheme of current cut-off

Diagram of the current cut-off similar pattern to the OCP without time relay.
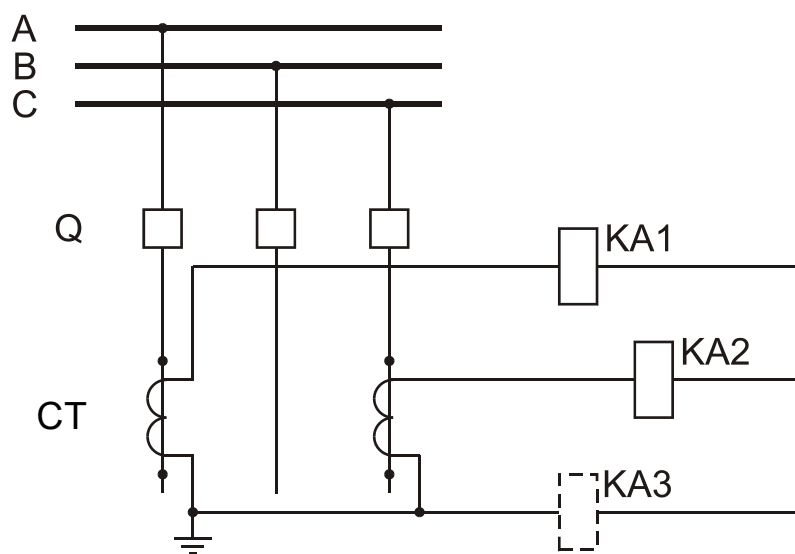
a) Current circuit
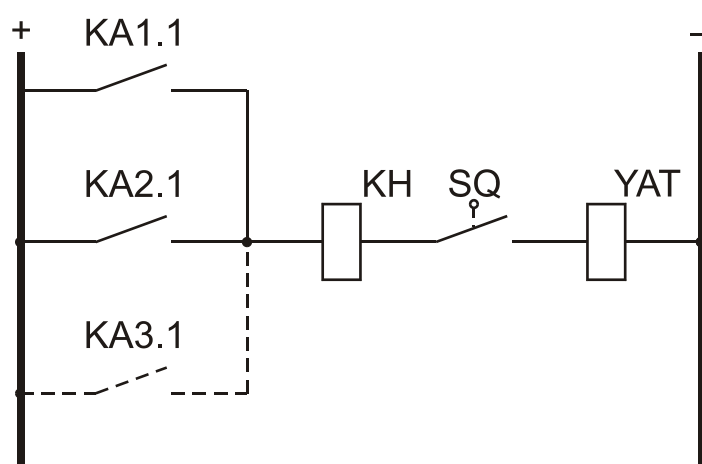
b) Operational current circuits

Fig.24 Schemes of current cut-off

5.2 Applications of current cut-offs

Current cut-offs are mainly used (in low voltage networks) and redundant (high-voltage) protection networks in single-supply lines.

Advantages

1. Constructively one of the simplest protections.

2. High speed of action.

Disadvantages

1. Incomplete coverage by the zone of action of the protected line.

2. The inconsistency of the zone of action under the influence of resistances in the place of damage and changes in the regime of the system.

6. **Three-stage current protection**

Typically, the OCP combined with Instantaneous cut-off (ICO) and time-delayed cut-off (TCO), (Fig.23).
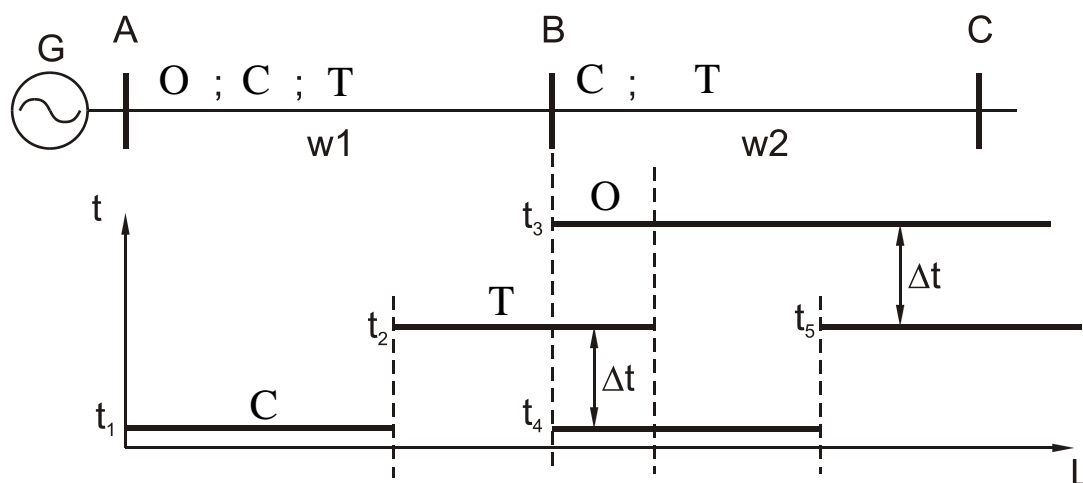
Fig.25 Triggering zone protection stages currents

7. **Differential Line Protection**

For the protection of power lines, devices are used to ensure the disconnection of any kind of damage on the line without time delay. Such devices are differential protection. The principle of operation of differential protection is the comparison of currents at the ends of the transmission line.

7.1 Purpose and types of differential protection

Line current differential protection creates challenges for relay design and application. From a design perspective, the distributed nature of the line current differential system imposes limits on the amount of data that can be exchanged between the system terminals and calls for data alignment schemes to enable the differential protection principle (Hank Miller et al. 2014). From the application perspective, line current differential schemes are concerned with CT saturation, particularly in dual-breaker applications; in-zone reactors and line-charging current; in-line and tapped transformers; sensitivity to high-resistive faults; single-pole tripping; security on channel impairments; application to lines with more than three terminals; and so on.

Differential protection divided into:

- Transverse - to protect only parallel lines.
- Longitudinal - for the protection of both single and parallel lines;

7.2 Transverse differential protection

As one of generator main protections, transverse differential protection is the most simple but sensitive one. It is widely used in huge generators. With system development, it meets with much more challenges. To meet with the practice requirement, for example choosing two elements to fulfil the sensitivity and the credibility respectively. The main criterion is the transverse differential element, which decides whether the protection acts, or not (Li Xiaohua et al. 2003). The negative sequence direction element is the assistant criterion. It just only distinguishes whether faults in internal or external ones. When it judges there is external fault, it may increase the threshold much higher to avoid the disoperation. The sensitivity of the new scheme is determined by that of the transverse differential element, while the credibility is dependent on the negative sequence direction element.

7.3 Longitudinal differential protection

By longitudinal differential protection is meant rapid and selective relay protection for feeders and interconnectors based on a direct comparison of the currents at the ends of the cable. Normally these currents are equal, apart from the capacitance of the cable, but; on the other hand, when fault occurs on the line a certain differential current corresponding to the current at the location of the fault arises. This current actuates the protective system and brings about tripping. As this protection is used especially for cables it's also termed cable differential protection.

7.3.1 Principle of operation of longitudinal differential protection

The principle of longitudinal differential protection is based on comparing the magnitude and phase of the currents at the beginning and end of the protected line when faults outside the protected line currents at the beginning and end of the line are in the same direction and equal in magnitude, (see Fig.26 a) and when faults within the protected line currents are directed in opposite directions and equal in magnitude (typically) (see Fig.26 b).
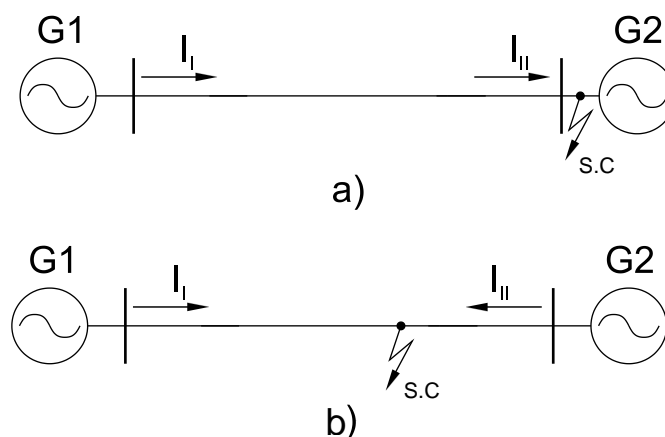
Fig.26 Directions of current flow in the line for internal and external faults

The principle of current comparison shown in (Fig.27) current transformers with the same transformation ratio are installed at the ends of the line. Their secondary windings are connected by cable and connected to a differential relay.

$$I_P = I_1 - I_2 = 0$$
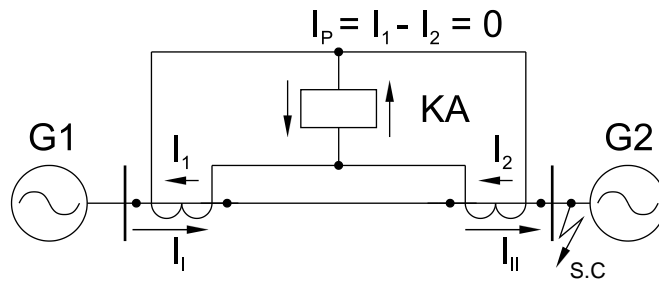
Fig.27 Schemes of line differential protection

There are two schemes for constructing differential protection:

1. with circulating currents;

2. with balanced voltages.

In (Fig.27) a circuit with circulating currents shown. For this scheme, the current flowing through the relays is determined by:

$$I_P = \frac{I_I}{n_{T1}} - \frac{I_{II}}{n_{T2}}$$

$n_{T1}=n_{T2}=n_T$

In the absence of errors $I_1 = I_2$ and $I_P = 0$ relay does not operate. There is no response and swings in the system.

According to the principle of differential protection does not respond to external faults, swing and load currents.

In fact, current transformers operate with an error: $I_1-I_2=I_{NB}$ to avoid false triggering of protection: $I_{C3} > I_{NB.max.}$

Operation of the circuit with circulating currents at the short circuit on the protected line with one-way and two-way power, shown in Fig.28 (a) and (b). Current flowing through relay:

$$I_P = I_1 + I_2 = \frac{I_I}{n} + \frac{I_{II}}{n} = \frac{I_{S.C}}{n}$$

Where: $I_{S.C}$ - full short-circuit current.
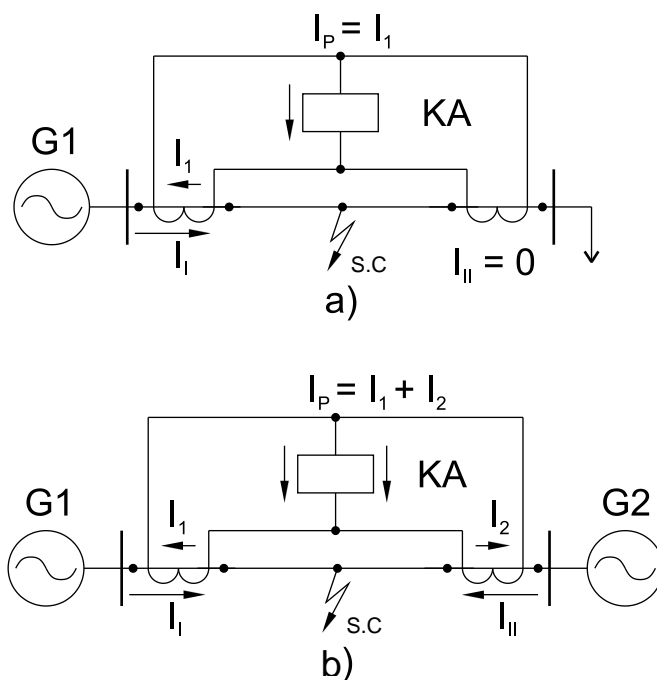
Fig.28 Directions of the currents in the line differential protection schemes

The differential protection reacts to the total $I_{S.C}$ current at the fault location, so in a bi-directional network it is more sensitive than the current protection.

7.3.2 A circuit with balanced voltages.

The operation of differential protection based on a balanced-voltage circuit shown in Fig.29
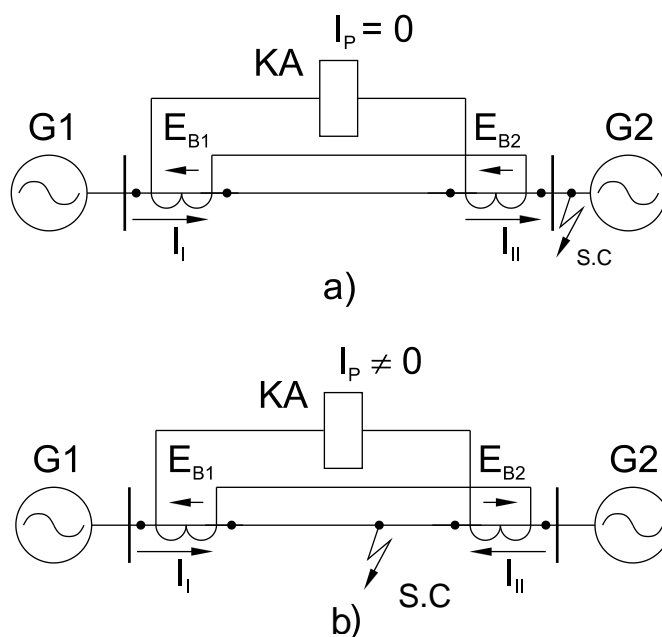
Fig.29 Types of differential line protection

In Russia, as previously, in (USSR) they used differential protection schemes with circulating currents.

7.4 Example of differential protection of the 110kV line

In all the above schemes, the installation of relays in 3-phases is implied. To perform such circuits, we need (6) differential relays and at least four connecting wires.

To reduce the number of relays and connecting wires, the relays switched on via symmetrical component filters or summing transformers (see Fig.30). In the figure, the abbreviation DCF designate current filters, at their output, the current I_{F1} is proportional to the currents of the direct sequence. The direct sequence component is present in the phase currents for all kinds of faults. The circuit provides for the isolation transformers $T_{L3,4}$, by means of which the circuit of the connecting cable A-B separated from the relay circuits. This separation eliminates the appearance of high voltages in the relay circuits that are induced in the conductors of the cable during the passage of short-circuit currents along the protected line. In normal mode and with an external short circuit, a current flow through the connecting wires, proportional to the primary current of the line, and in the short-circuit current in the connecting wires A-B a small current I_1-I_2 passes.
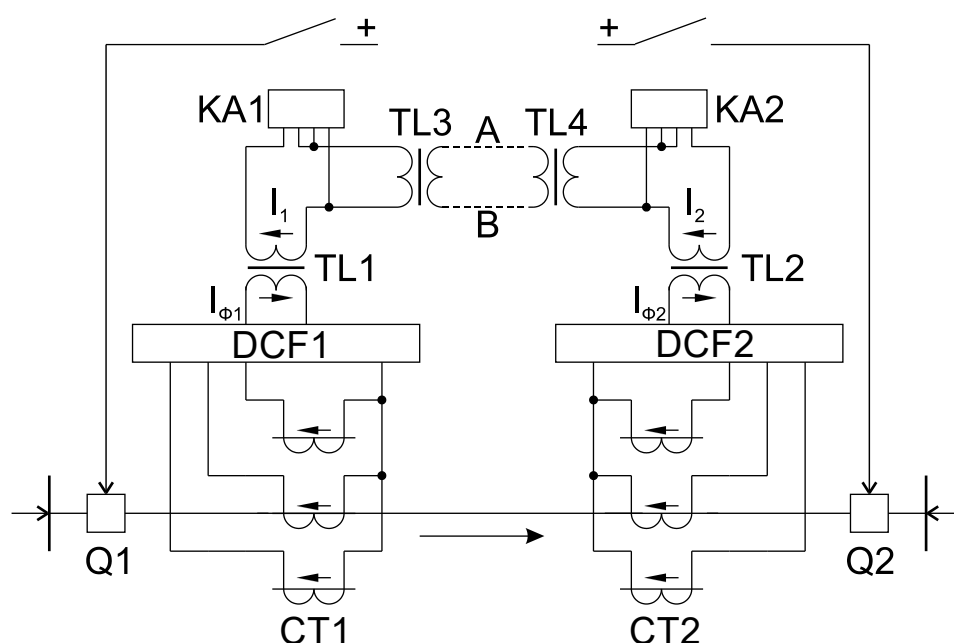
Fig.30 The circuit of differential line protection

8. **Protection of transformers and autotransformers**

Transformers are valuable equipment which make a major contribution to the supply security of the power system. Optimum design of the transformer protection ensures that any faults that may occur are found quickly, so that consequential damage is minimized. A special variant is the so-called autotransformer in which, unlike in the full transformer, the voltage and current transformation is not performed by two independent windings but uses part of the winding from both sides, allowing a much more compact design.

The spectrum of autotransformers ranges from small distribution system transformers (from 1000 kVA) to large transformers of several hundred MVA. Their use becomes more interesting, the less the ratio between the high-voltage (HV) side and low-voltage (LV) side deviates from 1, i.e. the less energy is transmitted via the magnetic coupling which leads to a saving in iron material.

8.1 Types of damage transformers and types of protections

- Damage transformers and protection against them

Types of damage:

1. short circuits between the phases inside the transformer tank and the outer terminals of the windings.
2. short circuits in windings between turns of one phase (coil short circuits).
3. Earth fault windings.
4. Damage to the magnetic three-leg core.

The most common faults are short circuits at the terminals and coil short circuits. Multi-phase short-circuit occurs less often. In three-phase transformers, they are unlikely due to the high strength of the interphase insulation; in transformer groups composed of three single-phase transformers, the closure between phases is practically impossible.

In case of coil short circuits, currents are usually small, so the protection of transformers intended for action in case of coil short circuits, as well as in case of ground short circuits in the winding working on a network with an isolated neutral, must have high sensitivity.

To limit destruction, transformer protection must act quickly. Damage accompanied by a high current must be switched off immediately (protection time not more than 0.05-0.1 sec.).

Types of transformer protection against damage:

1. Differential - instantaneous protection of windings, inputs and transformer buses.
2. Current cut-off protection of bus bars, bushings and part of the winding from the high voltage side.
3. Gas-protection against damage inside the tank, accompanied by the release of gas, as well as when the oil level is lowered.
4. Protection against short circuits on the shell.

8.2 Abnormal modes of transformers and their protection

Abnormal modes of transformers include the appearance in their windings more than currents at external faults, swings and overloads and voltage increase.

8.2.1 External faults

In the case of short-circuits on the bus-bars or the line leaving the bus lines, a fault current is flowing through the transformer, substantially exceeding the current of the normal mode. If the overcurrent is prolonged, the windings of the transformer inadmissibly fired.

To protect the transformer in this case, the maximum current protection is used (conventional, or with a minimum voltage interlock), directional protection, residual current protection. The protection zone should include substation buses (1st protection zone) and all connections from these buses (the 2nd protection zone). These protections reserve the effect of the main busbar and branch line protection; also provide backup protection when the transformer itself damaged.

8.2.2 Overloading

Transformer overloading of the order of 1.5 - 2 from the nominal value can be tolerated within tens of minutes. If the transformer overload is transient short-time, for example, when the 6-10 kV motors are self-starting, then the transformer not required to disconnect. If the overload lasts a long time, for example, when connecting the load from the ATS, in this case the transformer shut down by the automation or personnel for tens of minutes.

Transformer protection from overload should only act on a trip if personnel or automation cannot eliminate the overload. In other cases, the protection acts on the signal.

8.2.3 Boosting Voltage:

In the stations with 500-750 kV, unilaterally disabling long lines with large capacitive conductivity is probably dangerous to increase the voltage transformers. When the voltage increases, the magnetic induction in the magnetic circuit of the transformer increases. The magnetizing current and eddy currents increase, which can cause a fire in the transformer.

8.3 Differential protection of transformers

Transformer differential protection schemes are ubiquitous to almost any power system. While the basic premise of transformer differential protection is straightforward, numerous features employed to compensate for challenges presented by the transformer application.

8.3.1 Purpose and principle of differential protection

Differential protection (DP) is designed to protect against short-circuit between phases, to earth and from winding closures. The principle of the DP is the same as for the longitudinal differential protection of lines - based on a comparison of the values and the direction of the currents before and after the element to be protected. The distribution of the currents for short-circuit in the transformer and outside it is shown in Fig.31

The task in the design of protection is to balance the secondary currents in the protection arms so that the current in the relay is absent and the DP does not work under load and external faults (Fig.31a). At short-circuit in the transformer (Fig.31b), if $^*I_R > I_{RA}$ - The relay will trip and turn off the transformer.

* I_{RA} – Relay Actuating Current, I_R – Relay Current.
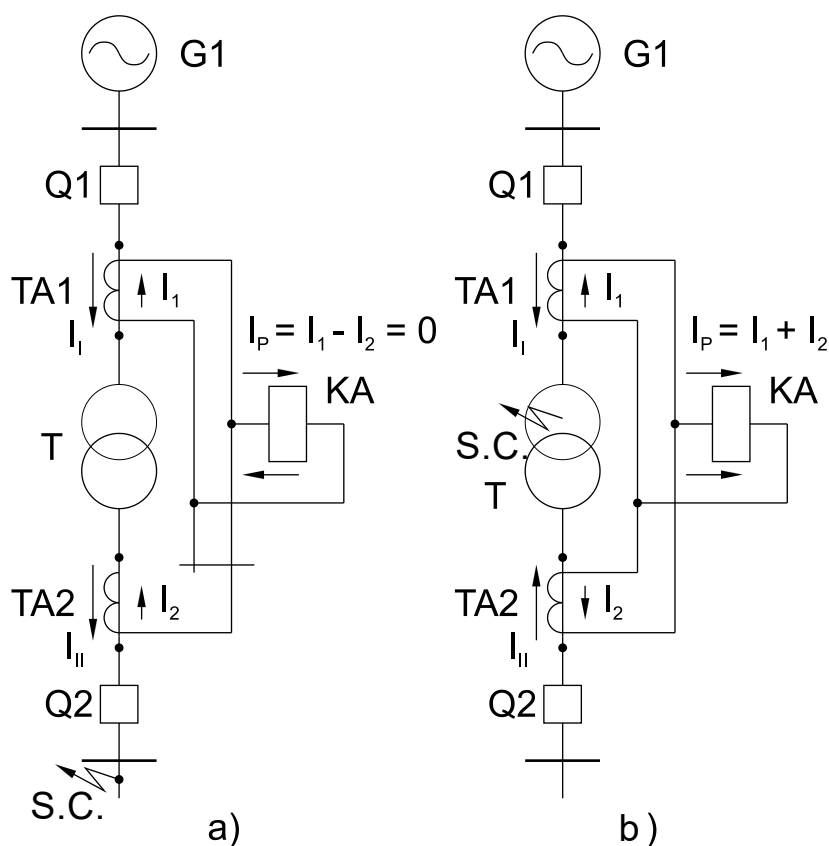
Fig.31 Distribution of the currents for short-circuit in the transformer and outside

9. **The difference between the differential protection of a transformer and a generator**

Generally, Differential protection is provided in the electrical power transformer rated more than 5MVA. The Differential Protection of Transformer has many advantages over other schemes of protection. The faults occur in the transformer inside the insulating oil can be detected by Buchholz relay. But if any fault occurs in the transformer but not in oil then it cannot be detected by Buchholz relay. Any flash over at the bushings are not adequately covered by Buchholz relay. Differential relays can detect such type of faults (J. Scott Cooper 2013). Moreover, Buchholz relay is provided in transformer for detecting any internal fault in the transformer, but Differential Protection scheme detects the same in more faster way.

Differential protection for a generator is mainly employed for the protection of stator windings of generator against earth faults and phase-to-phase faults. The stator winding faults are very dangerous, and it causes considerable damage to the generator. For the protection of stator winding of the generator, the differential protection system is used for clearing the fault in the shortest possible time for minimizing the extent of a damage.

10. **Remote protection of lines**

To protect dead-end cable or overhead lines with one-sided power supply, a maximum current protection or current cut-off is sufficient. However, if these lines connected in series one after another or connect several power supplies among themselves, it is impossible to perform such protection selectively.
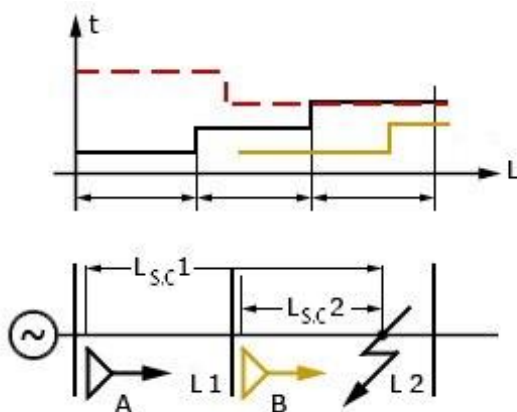
Fig.32 Step protection line

Let us imagine that the line feeding another substation - №2 departs from the buses of the substation №1. In addition, from the bus of this next substation goes another line. When using OCP at substation №1, it must operate in case of short circuit on the first line but give an opportunity to protect the substation №2 with short circuit at the next.

However, at the same time, it must also reserve the protection of the second substation, for which it should also act in case of short-circuit on line №2. In this case, the protection time must be set so that the exposure at the first substation is longer. In addition, it is necessary to divide the logic of the OCP operation into two or more stages, setting for the first of them a pickup current equal to the design short-circuit current at the end of the first line.
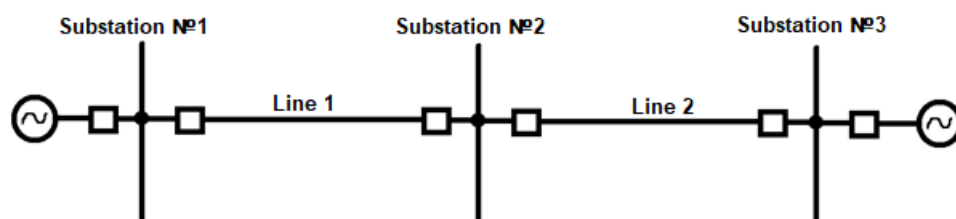
Fig.33 Lines with bi-directional power plants

Now let us assume that from the opposite side the line №2 feeds another source of energy, independent of the first one. Now the task becomes more complicated: short-circuit currents change. In addition, OCP lines need to perform targeted.

There is another type of protection that can help to effectively disable the line with damage - differential protection. However, for a long-distance transmission line it is very difficult to fulfil.

When using the same overcurrent protection and current cut-offs, the protection devices are complicated, and insufficiently effective. An exit from a situation - application of remote protections.

10.1 Principle of operation of remote protection

Remote protection (RP) is defined as that respond to the distance of the short-circuit point. In addition, more precisely: the logic of its operation depends on the location of the point of closure, which determines the protection. It does this with devices called resistance relays. Their task is indirectly to measure the resistance from the location of the protection to the point of short circuit. And for this, according to Ohm's law, it needs not only a current, but also a voltage received from the voltage transformer installed on the buses of the substation.

- The resistance relay operates under the following conditions:

Here Z_{set} - set the resistance of the relay. The measured value is fictitious, since in some modes of operation (for example, during rocking) its physical meaning, like resistance, is lost. The setting of the trip, and, consequently, of the resistance relay in the RP, as a rule, is not less than three. The protected area is divided into areas called _zones_. The response is time for each of its own zones. In addition, the setting of the resistance relay is equal to the resistance to the fault point at the end of the corresponding zone. For an explanation, let us do an example with substations and lines.

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$$Z_R = \frac{V_R}{I_R} < Z_{set}$$

Set: point1 of the zone RP is calculated so that it protects only its outgoing line, but not to the very end, and considering the error in measuring the resistance 0.7-0.85 of its length. When the first zone is activated, the line is disconnected with the minimum possible time delay, since the fault is guaranteed on it.

The second RP zone reserves the protection failure of the next substation. For what it reacts to short-circuiting at the end of line №2, and the first RP zone for the switch of the second line from Substation №2 is exposed to resistance to the same fault point, but from the buses of this substation. However, the time delay for the №2 zones of the RP of Substation №1 is more than №1 RP zone of Substation №2. This ensures the required selectivity: the switch of the second line from substation №2 will be disconnected earlier than the protection time relay at the substation №1.

The third zone of distance protection is designed to be a reserve for the protection of the next line, if it is available. More zones are not provided. The device and operation of the distance is protection kit. However, on one relays of resistance and time relays, such protection cannot be performed. In practice, it includes several functional blocks.

Starting organs, these are current relays or impedance relays. Their task is to determine the presence of a fault in the protected circuit and to start the work of other protection devices (Бунден Д.С. 2014). On the other hand, Remote organs are a set of resistance relays for determining the trigger zone and the distance to the fault location. Remote organs are a device that generates time delays for protection zones. These are conventional time relays.

10.2 Power Direction Relay

In fact, it is rarely used, because the resistance relays have their own directional diagram, which does not allow the protection to be triggered by short-circuit protection. As a result, protection is prevented from closing in the direction opposite to the protected line.

Locking organs, one of which is protection against the disappearance of voltage. In the event of a fault in the circuits, the TH RP is removed from operation. The next lock works when the system swings. When they occur, there is usually a decrease in voltage on the tires and an increase in current in the protected lines. These changes are perceived by remote protection agencies as a reduction in resistance, because of which the false defence work is also possible.

a) the characterization of the remote protection of the metal short circuit

b) the characterization of the short-circuit through the Relay arc.
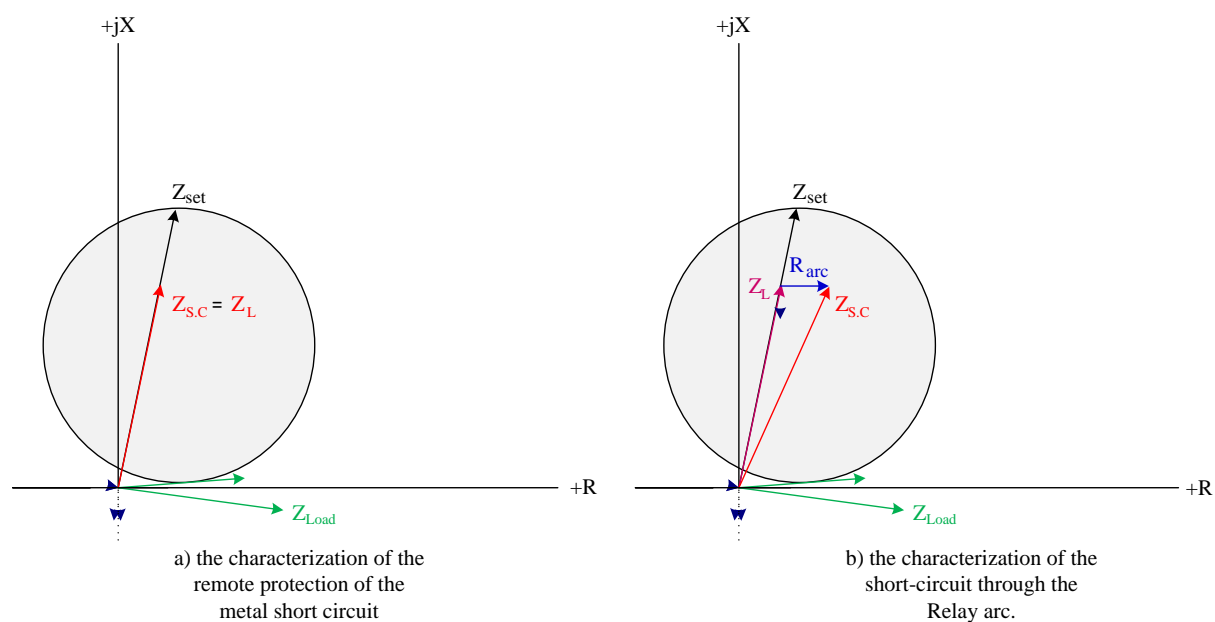
Fig.34 Characteristics of relay resistance

10.3 Application of Remote protection

Remote protection used in networks powered by two or more sources. These are communication lines with a voltage of 110 kV and above, over which electricity transited. Especially effective and indispensable is the RP in the ring schemes of energy supply, the application of which is very often for the unified energy system of the country. For all networks where RP installed, it is the main overhead lines protection (Дамееров А.П. 2015).

The design of the RP on the electromechanical base assumes the presence of many elements conventional relays, transformers. To allocate it, a whole panel selected. Modern versions of microprocessor protectors fit in one terminal, adjacent to other types of them, as well as the possibility of fixing protection trips, blocking operations, recording of oscillograms of emergency processes. By combining several devices in one terminal, not only compactness, but also convenience in the operation of line relay protection provided.

SECTION TWO: Digital Substations

1. Introduction

The digital substation is a substation with a wide introduction of automation and control systems built based on the open standards of IEC-61850. Despite a solid list of advantages and disadvantages of innovative technologies over the traditional model, discussions of supporters and critics of the idea of the digital substation are continuing. For an objective assessment, of course, it takes a long experience of switching to new technologies, as well as the economic performance indicators achieved based on operational results.

Today, the development of solutions for digital substations was promising and fashionable phenomenon, and the presence of the manufacturer of devices that support IEC-61850 - an indicator of forward positions in the market of microprocessor products for electric power. The present section discusses the digitalization and the impact of utilities and how enabling it, the requirements and standards of IEC-61850, the optical digital measuring transformers of current and voltage, fiber-optic communication lines, the use of industrial IP/Ethernet networks, microprocessor relay protection and automation, automated system of control and accounting of Electric systems, automated process control system SCADA-REDI.

2. Benefits of digital substations

Digital substation called the core component of creating an intelligent network - and this topic has recently become more popular. This is a breakthrough, internationally recognized method of automation that solves the problems of efficient management of energy objects. So, the main benefit of digital substations:

- Safety (reducing the risk of electrical shock) by handling of current transformer
Circuits and signalling voltage poses a threat to life and equipment, process bus eliminates the galvanic connection between protection and control panels and the switchyard, eliminates CT and VT circuits in the protection and control panels, replaces conventional 110/220VDC indications with fiber optics.

- Less transport (less material means less transport and CO_2 emissions) by mean more than 30 tons less material to be transported to site for an average sized transmission level substation, the weight of the fiber optic cabling is around 90% less than the copper cables it replaces and if CTs are replaced by optical ones, almost 80% weight reduction on CTs is achieved.

- Less space (up to 60% and more reduced space for protection and control panels) because the IEDs require less space due to absence of conventional IOS, absence of terminals enable integration of more IEDs per panel, integration of protection in GIS LCC enables further space reduction, reduction of switchyard footprint by up to 50%, and by using circuit breakers with integrated disconnecting functionality and optical current transformers.

- Less installation and outage time (40% reduction of installation time for new protection and control systems), that means fewer panels to install, fewer cables to be pulled, connected, tested, reduction of feeder outage time by 40-50% during secondary system upgrades, full system test from process I/O to protection, control and SCADA system off-site, installation of new FO based system while station is in service, and flexible placement of new protection panels, without depending on SS cabling.

- Operational cost reduction (saving in maintenance and future retrofits) by supervision of all exchanged data, reduces the need for periodic maintenance testing, permanent supervision enables fast and precise actions in case of failures fast and save testing, and IEC-61850 testing and simulation features enable fast and save isolation and testing of protection. Therefore, functions standard compliance enables efficient future retrofits of secondary system.

3. (IEC-61850) requirements and standards

The IEC-61850 standard defines the communication between intelligent electronic devices in the substation and the related system requirements. To be able to manage the large number of devices and to enable the various devices to communicate with one another, a new communication model is needed.

The abstract data models laid out in IEC-61850 can be mapped to several protocols, which include MMS, GOOSE, SMV, and soon to Web Services. The protocols can run over TCP/IP networks or substation LANs using high speed switched Ethernet to obtain the necessary response times below four milliseconds for protective relaying.

3.1 Communication System Needs

Communication has always played a critical role in the real-time operation of the power system. In the beginning, the telephone was used to communicate line loadings back to the control centre as well as to dispatch operators to perform switching operations at substations. Telephone switching based remote control units were available as early as the 1930's and were able to provide status and control for a few points. As digital communications became a viable option in the 1960's, DAS were installed to automatically collect measurement data from the substations. Since bandwidth was limited, DAS communication protocols were optimized to operate over low-bandwidth communication channels. The "cost" of this optimization was the time it took to configure, map, and document the location of the various data bits received by the protocol (IEC 61850 2015).

As we move into the digital age, literally thousands of analog and digital data points are available in a single IED and communication bandwidth is no longer a limiting factor. Substation to master communication data paths operating at 64,000 bits per second are becoming commonplace with an obvious migration path to much high rates. With this migration in technology, the "cost" component of

a data acquisition system has now become the configuration and documentation component. Consequently, a key component of a communication system is the ability to describe themselves from both a data and services (communication functions that an IED performs) perspective. Other "key" requirements include:

• High-speed IED to IED communication

• Networkable throughout the utility enterprise

• High-availability

• Guaranteed delivery times

• Standards based

• Multi-vendor interoperability

• Support for Voltage and Current samples data

• Support for File Transfer

• Auto-configurable / configuration support

• Support for security

Given these requirements, work on a "next generation" communication architecture began with the development of the UCA in 1988. The result of this work was a profile of "recommended" protocols for the various layers of the ISO, OSI communication system model. This architecture resulted in the definition of a "profile" of protocols, data models, and abstract service definitions that became known as UCA. The concepts and fundamental work done in UCA became the foundation for the work done in the IEC TC57 Working Groups 10, 11, and 12 which resulted in the International Standard – IEC-61850 – Communication Networks and Systems in Substations.

3.2 IEC Substation Model

Putting the pieces together results in the substation architecture shown in Fig.35
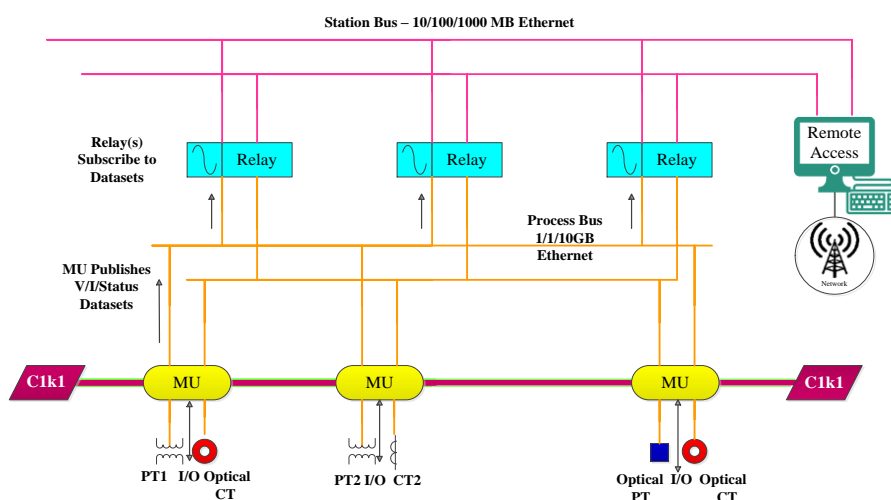
Fig.35 IEC-61850 Substation Model

At the "process" layer, data from Optical/Electronic Voltage and Current sensors as well as status information will be collected and digitized by the Merging Units (MUs). MUs could be physically located either in the field or in the control house. Data from the MUs will be collected through redundant 100MB fiber optic Ethernet connections. The collection points will be redundant Ethernet switches with 1GB internal data buses and 1GB uplinks that support Ethernet priority and Ethernet VLAN. VLAN allows the Ethernet switch to deliver datasets to only those switch ports/IEDs that have subscribed to the data. In migrating to Process Bus implementations, manufacturers will need to provide the ability to integrate data from existing CTs and PTs with the data from the newer Optical/Electronic sensors. A redundant synchronization clock architecture will also have to be addressed. In this architecture, upon detection of failure of Clock1, Clock2 will have to automatically come on line and continue providing sampling synchronization.

At the substation level, a Station Bus will exist. Again, this bus will be based today on 10MB Ethernet with a clear migration path to 100MB Ethernet. The Station Bus will provide primary communications between the various Logical Nodes, which provide the various station protection, control, monitoring, and logging functions (Drew Baigent et al. 2016). Communications will operate on either a connection-oriented basis (e.g. – request of information, configuration, etc.) or a connection-less basis (IEC Generic Object-Oriented Substation Event - GOOSE). Again, a redundant communication architecture recommended as application of IED to IED data transmission puts the communication system on the critical path in case of a failure.

Finally, this architecture supports remote network access for all types of data reads and writes. As all communication is network enabled, multiple remote "clients" will desire access the wide variety of available information. Typical clients would include local HMI, operations, maintenance, engineering, and planning. The remote access point is one logical location to implement security functions such as encryption and authentication. This implementation unburdens the individual IEDs from performing encryption on internal data transfers but still provide security on all external transactions.

3.3 Application Software

Varieties of commercial products supporting IEC-61850 are already available and the future holds promise for many innovations that will greatly benefit users. Of significance are products that support both the IEC-61850 communications standard and OLE for Process Control, OPC, API standard of the OPC Foundation. The combination of a standardized protocol and a standardized API is a powerful tool that allows users to minimize their costs dramatically to build substation automation systems by enabling products from different vendors to plug together into a complete solution.

Fig. 36 Using IEC61850 with OPC

OPC Enables IEC61850 Interface to IT
Figure 37

IEC61850 Data Concentrator Architecture
Figure 38
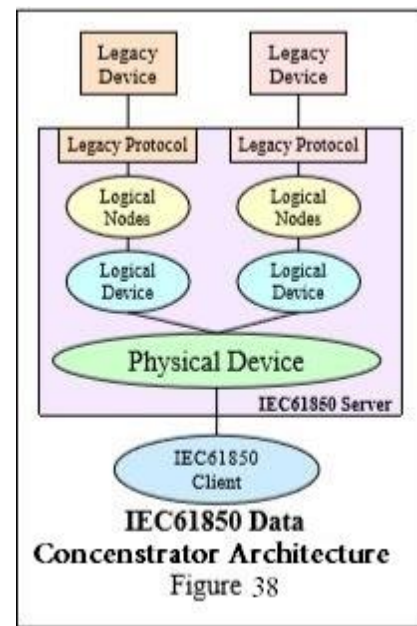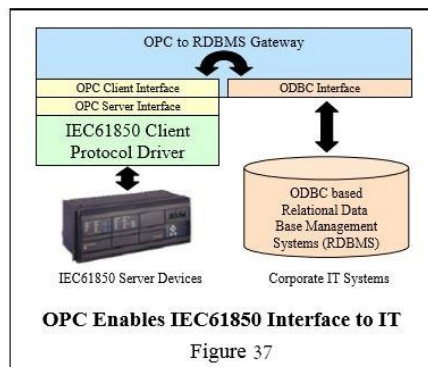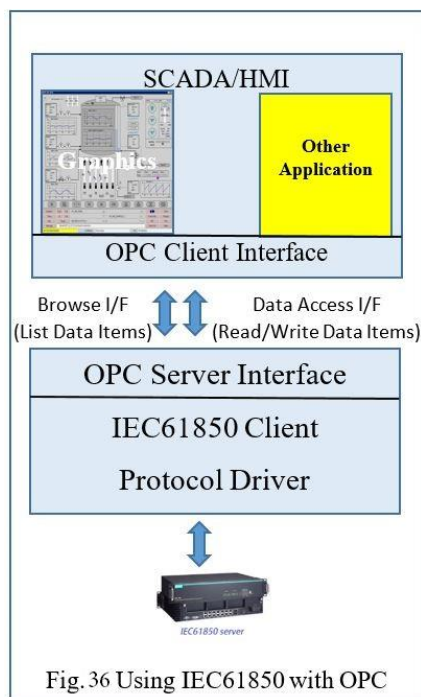
The OPC, DA specification is an API that enables an OPC Client application, such as a SCADA or HMI application, to provide a generic interface to outside data that is independent of any specific protocol (Fig.36). This enables third parties to develop OPC Servers to interface with a wide variety of protocols, including IEC-61850, Modbus, DNP3, and hundreds of other protocols. There is a wide availability of both client and server applications that provide users choice and flexibility. For instance, interfaces to many different applications like RDBMS, spreadsheets, data historians, trending systems, etc. are available that support OPC and provide a large choice of options to implement complex systems at a low cost (see Fig.37). In addition to providing access to data in IEDs, OPC interfaces support an important feature called browsing. The OPC browse interface enables the client to retrieve the list of data items defined in a server instead of having to be pre-configured. This works especially well with IEC61850 devices because of built-in support for object discovery. By combining OPC with IEC-61850 the substation engineer avoids many hours of configuration and can install and commission systems quicker with less effort and fewer errors resulting in lower costs.

Interface with Legacy Protocols Electric power systems are designed to last for many years. For any new technology to be successfully applied into a modern power system, there must be some way to accommodate the use of legacy IEDs and protocols from the past. IEC61850 is no different and there are several methods for accommodating legacy protocols in an IEC-61850 system. IEC-61850 itself is well suited to accommodate legacy protocols with its logical device model. The ability to support multiple logical devices within a single physical device allows IEC-61850 to directly support the modelling of a data concentrator or multi-device gateway inherently without resorting to techniques outside the scope of the standard. Data concentrator devices (Fig.38) supporting the IEC-61850 logical device model is available with new products under development. In addition to the use of separate data concentrators, OPC technology also offers a way to incorporate simple gateway functionality into a substation SCADA system (Fig.39). In this case, the roles of OPC client and server are reversed from the previous example illustrating a substation SCADA

Application by building an OPC client application on top of an IEC-61850 server. The OPC client is then mapped to an OPC server supporting any legacy or proprietary protocol. This enables data from legacy devices to be accessed as IEC-61850 data simplifying the client application development by providing a consistent standardized mechanism for data access across the entire substation.

IEC61850 Data Gateways using OPC
Figure 39

IEC-61850 is now released to the industry. Nine out of ten parts of the standard are now International Standards (part 10 on testing is in the CDV stage). These standard addresses most of the issues that migration to the digital world entails, especially, standardization of data names, creation of a comprehensive set of services, implementation over standard protocols and hardware, and definition of a process bus. Multi-vendor interoperability has been demonstrated and compliance certification processes are being established. Discussions are underway to utilize IEC-61850 as the substation to control centre communication protocol. IEC-61850 will become the protocol of choice as utilities migrate to network solutions for the substations and beyond.
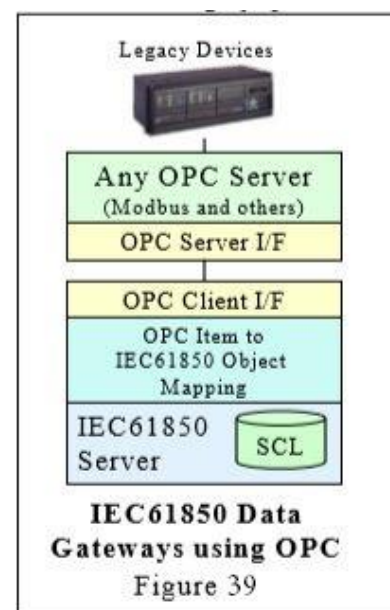
4. **Optical Digital Measuring Transformers of Current and Voltage**

The growing importance of issues related to the commercial accounting of electricity due to the rapid development of the electricity market in Russia. Conventionally used for these measuring, transformers (IT), current (CT) and voltage (PT) (Electromagnetic, capacitive, etc.) have many of disadvantages:

- Large dimensions and heavy weight for measuring current transformer (MCT) and measuring voltage transformer (MVT) for large voltages 110, 220, 330, 500, 750 kV and, consequently, a high cost.

- Possibility of breaking down the insulation due to the presence of metal parts.

- Possibility of insulation damage in case of overvoltage in the station.

- Increased fire and explosion hazard due to the presence of oil, paper.

- Maintenance, inspection and replacement of oil, gas or nitrogen.

- The need for maintenance and verification of it after the emergency mode due to the residual magnetization of the magnetic circuit.

- The lack of a digital interface, the deterioration of the measurement accuracy.

Due to the transmission of the signal over analogue lines, the result is the additional cost of digitizing the signal.

The advantage of traditional current and voltage transformers are time-tested designs, and as a consequence-the predictability of changes in the metrological characteristics of such transformers over time in different modes of the power system.

Most of the transformers in operation released from 30 to 40 years ago, their resource has practically dried up and they are subject to replacement in the coming years. Many of them were checked only when they were released from production or were not checked at all before installation, which could lead to incorrect energy accounting and, consequently, to significant financial losses. The cost of such transformers for large voltage classes (330, 500, 750 kV) can reach up to several million Rubbles depending on the type of transformer, accuracy class and other parameters, so a planned replacement of such transformers can also be a serious financial problem.

In recent years, new optical methods for measuring current and voltage have begun to develop actively, primarily based on the magneto-optical Faraday effect and the electro-optical effect. Devices developed based on these effects, the so-called optical current and voltage transformers, have a number of advantages over traditional means of measuring currents and voltages:

- Light weight, size;

- High electrical strength of insulation, fire and explosion safety;

- Absence of oil, sulphur-hexafluoride, nitrogen, which simplifies equipment operation;

- The absence of a magnetic circuit in the design, which leads to an increase in the stability of metrological characteristics;

- Wide dynamic range of measured currents and voltages (from units to hundreds of kV and from hundreds of amperes to hundreds of kA);

- Wide frequency range of measurements, the possibility of analysing transient processes and measuring the harmonic components of current and voltage for recording power quality indicators;

- Digital interface, easy integration with microprocessor modules of modern digital protection and metering devices, compliance with IEC 61850 standard.

There are several foreign and domestic firms that produce similar optical transformers, for example, ZAO "PROFOTEK".

Fig.40 Combined optical current and voltage transformers for voltage classes of 110-550 kV JSC "PROFOTEK"

Construction current transformers, electronic, optical, with the example of transformers JSC "PROFOTEK"

The effect of the current transformer of the electronic optical (CTEO) is based on the Faraday effect, the magneto-optical effect, which consists in the fact that when the linearly polarized light propagates through an optically inactive substance in a magnetic field, rotation of the plane of polarization of light is observed, depending on the magnitude of this magnetic field («ПРОФОТЕК» 2017).
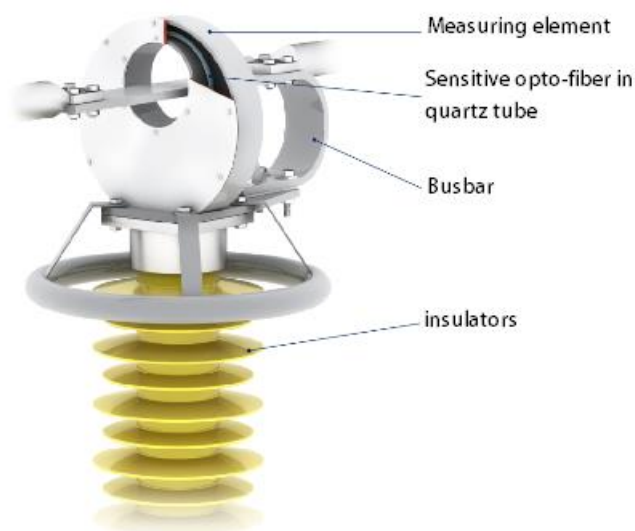
Fig.41 Construction of the universal optical current and voltage transformers JSC "PROFOTEK"

Advantages of application:

• Lack of copper secondary circuits, reducing the cost of materials and installation costs.

• Absence of Ferro-resonances.

• Absence of interference and interference in secondary circuits due to their natural galvanic isolation (signal transmission via optical fiber).

• Ability to connect an unlimited number of consumers of measurement information. Simplicity and flexibility of scaling systems.

• Low costs for current operation, no risk of interruptions in power supply to consumers.

• High accuracy of measurements and ensuring their unity for all devices-recipients of data.

• The ability to measure harmonic components up to 100 harmonics.

• The accuracy class of a measuring complex based on optical converters (via a digital interface) is not achievable on traditional measurement circuits.

• Standardization of the communication interface between the primary and secondary equipment. The possibility of implementing the entire instrument cluster based on unified hardware solutions for a wide range of tasks.

• Improving the safety of personnel when working in secondary circuits.

• The ability to measure DC and AC current.
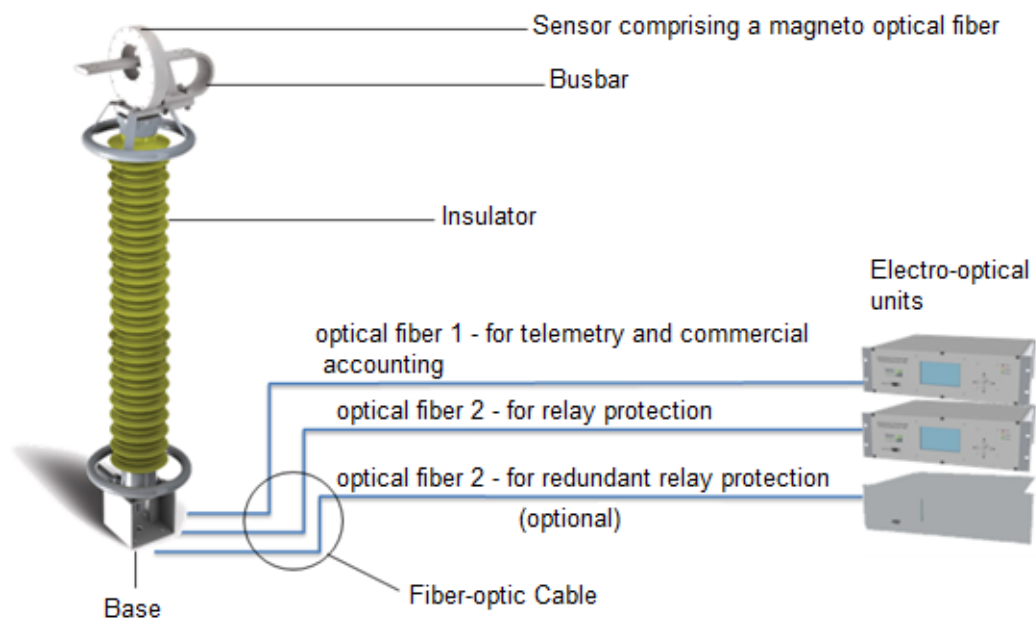
Fig.42 Schemes of connecting the transformer JSC "PROFOTEK"

Specifications:

Parameters	Meanings
Rated voltage, kV	110 – 750
Rated primary current, A	300 - 40 000 (The maximum allowable value is 280 000 kA)
Rated secondary current, A	1 (standard analog output)
Digital output (Available with 1 A analog output, for commercial use)	IEC 61850-9-2 (Duplicated Ethernet100Base-FX with support for PTP and PRP protocols) RS-485 (For DC measurements)
Accuracy class:	
- For measurements	0.2s (digital output)
- For protection	5TPE (digital, up to 65)
Frequency range, Hz	0-9000 (optical sensor), 0-5000 (SV256), 0-2000 (output 9-2LE SV80)

5. Fiber-Optic Communication Lines

Fiber optics is the best transmission medium for medium and low-voltage applications because it is robust and not susceptible to electromagnetic disturbances or capacity constraints. That's why grid operators who choose this technology will be well prepared when their communications need multiply in the future.

Fiber-optic cables laid underground to connect individual substations. This work is associated with heavy civil works, and therefore with great expense. However, when new power cables installed, the cost-benefit analysis paints a clear picture. Fiber-optic cables should generally be the first choice in this case (Nick Massa 2008).

5.1 Application FOCL

Fiber-optic communication lines (FOCL) waves in the optical range (most often in the near infrared) used to transmit the signal. The main component is an optical cable, and the network includes active and reactive components for amplification, filtering, protection and modification of the signal. Today, fiber optic link (FOL) are gradually replacing traditional wire cable, because they offer much better performance greater bandwidth, immunity to environmental influences, lower signal attenuation, etc. (ИЦТЕЛЕКОМ-СЕРВИС 2017).
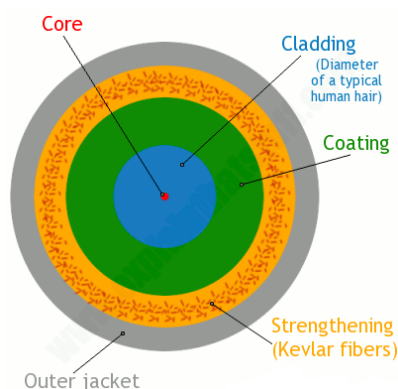
Fig.43 Constriction of Fiber optic cable

The main field of application of fiber optic networks are the transmission of information signals (network, CCTV, telecommunication system, access control, etc.). At the same time, at the level of trunk (up to Intercontinental) signal transmission lines, the fiber optic already occupies a dominant position, whereas in subsystems of internal trunks, the FOCL is used along with a twisted pair ([*]ИЦТЕЛЕКОМ-СЕРВИС 2017).
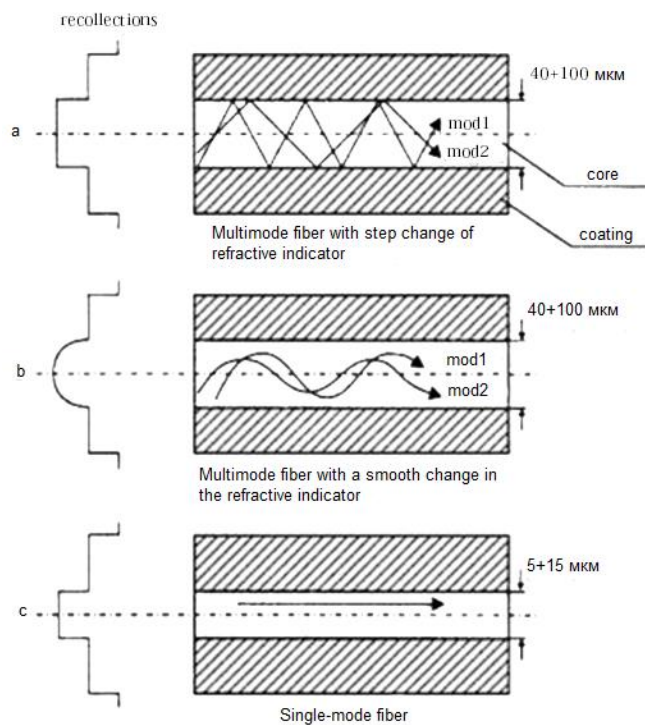
Fig.44 Methods of signal transmission by cable

5.2 The main advantages and disadvantages of fiber optic:

<u>Advantages:</u>

- Low signal attenuation (about 0.15 dB/km in the third transparency window). This makes it possible to transmit information at a significantly greater distance from the traditional wiring without the use of amplifiers. For optical lines, amplifiers usually installed in 40-120 km, which is determined by the class of terminal equipment;

- Light weight and dimensions;

- High level of shielding lines from inter-fiber influences (more than 100 dB). Thus, the radiation of neighbouring lines practically does not interact with each other and has no mutual influence;

- High explosion and fire safety in situations of change of chemical or physical parameters;

- Information security. Through the fiber optic information transmitted from point-to-point, and to intercept or eavesdrop on the signal is only possible with physical intervention in the power line;

- Optical fibres are highly reliable and durable. Fiber optic is not susceptible to oxidation, weak electromagnetic interference and destruction under the effect of moisture;

- High throughput. Other ways of transmission of information lag the optical medium by this indicator.

<u>Disadvantages:</u>

- Low resistance of standard fiber against radiation (there are alloyed fibers, characterized by high radiation resistance);

- High cost of optical terminal equipment in comparison with systems used for traditional lines. Although when compared with the final cost in terms of distance and bandwidth, fiber today shows the best results with respect to competing systems;

- The complexity of restoring the connection in case of line break;

- The complexity of signal conversion (for front-end equipment);

- Complex technology of fiber production, as well as other components of the fiber optic network;

- Fragility of fiber. In case of significant deformations, such as bending, the fibers may break down, be subjected to cracking and turbidity. To avoid damage to the fiber, it is necessary to follow the manufacturer's recommendations, which specify, among other things, the minimum bending radius.

6. **The use of industrial IP/Ethernet networks**

Ethernet network is a widespread standard of data transfer in the field of IT-technologies. The massive use of Ethernet made possible due to the large bandwidth and the support of various physical environments of the media defined in the IEEE 802.3, IEEE 802.11, and its widespread use has made it very affordable to standard network equipment and ushered in a new era in the field of communication technologies, including for industrial use (Roger Moore et al. 2010). Although the use of this technology in industry is associated with certain difficulties, such as working with real-time applications, where the problem of "resolving" conflicts of the network solved by additional hardware or software, just as it is resolved in some industrial busses. Several solutions to this problem have been proposed and successfully implemented in the market of industrial automation for more than 10 years. Thus, industrial Ethernet confidently occupies niches in which the use of traditional industrial busses is impossible or economically justified.

1. Essentially distributed, multilevel systems of data collection and management, which use heterogeneous communication channels, and the number of transmitted and processed data is large (tens and hundreds of thousands of signals). Here it is more about dispatching management of large objects than local I/O bus, and the reaction time in such systems is measured in seconds, so the use of IT-technologies for transferring large amounts of data using TCP/IP – oriented protocols is fully justified.

2. Manage fast processes that require a response time of less than one millisecond. In this niche, the Ether CAT bus has virtually no competitors in performance, any traditional serial industrial bus–about

100 times slower. So far, concentrated hardware systems based on the microcontroller and local I/O channels on the parallel bus have been used in this area.

3. Synchronous acquisition systems for many signals. For example, large test benches that require, for example, about 1,500 distributed analog I/O channels strictly synchronized every 100 microseconds. The traditional industrial busses do not have enough speed to solve such a problem.

4. Conventional control technological processing systems TP, in which the important parameters are the ease of installation, flexible topology of the data collection network, reservation of communication channels with the communication device with objects CDO, cost-effectiveness of solutions. Here, the use of standard network equipment and Ethernet cables can be a decisive factor in choosing the bus.

The use of networks based on Ethernet switches and IP/Ethernet routers for Relay protection and automation channels limited by the difficulties of organizing the main and backup channels in them along static paths with specified stable delays and bandwidth. As previously noted, the nature of the Ethernet Protocol does not imply the presence of closed circuits in the network, thereby prohibiting the construction of redundant channels. The classic approach to resolving this contradiction is to use special protocols that ensure that there is only one active path between devices when there are multiple physical paths. So Rapid Spanning Tree Protocol (RSTP) based on monitoring of communication lines in networks with arbitrary topology, detecting their malfunction and, in case of violation of the active path, switching to one of the available backup paths (Олифер В.Г. et al. 2010). At the same time, switching from one track to another is of the order of one second or more, which is unacceptable for Relay protection and automation. When we use RSTP in a ring topology achieved by the switching time of about 100ms, which is also too much. For ring topologies, Media Foundation Protocol (MFP) was developed (T. von Hoff et al. 2003), which allows for a switching time of 10...200ms depending on the number of switches, but the provision of the required seamless redundancy with zero switching time from the active path to the backup path for it is not achievable.

Higher-level routing protocols is used in IP/Ethernet networks, such as Routing Information Protocol (RIP) or better Open Short Path First (OSPF), have even greater convergence time when a new path is chosen, even compared to RSTP (tens of seconds depending on the topology and network scale) (Олифер В.Г. et al. 2010).

It should be noted that not all the above protocols could provide guaranteed bandwidth channels, which is necessary for the relay protection and automation. At the same time, with the use of PRP and EoS in SDH/PDH networks, it is possible to organize completely isolated from other Ethernet channels for relay protection and automation systems with guaranteed bandwidth and seamless redundancy along static paths.

7. **Microprocessor relay protection and automation**

The equipment of substation switchgears, the outgoing lines, supplying consumers or adjacent substations, must have reliable protection against possible damage. Until the 2000's. As protection equipment at the substations used only relay protection and automation of the electromechanical type, which built on the relay electromechanical principle of operation.

Now, the old electromechanical protection is gradually being replaced by modern devices - microprocessor terminals for protection, control and automation equipment, which are increasingly found in newly constructed or technically re-equipped substations. So, we will examine the functionality and advantages of microprocessor-based protection terminals using the example of using the ABB terminal REF 630 to protect the 35kV line of consumers, we will compare their performance with their predecessors - electromechanical protection.

7.1 Advantages of modern relay protection and automation devices

One of the main advantages of microprocessor terminals over the protections of the old sample is their compactness. For the implementation of protection, automation, control of 35 kV line equipment, it is necessary to mount a complex circuit of a set of electromechanical relays that hardly fit on one relay panel.

In addition, it is necessary for each line to install a switch control switch, switches for selecting operating modes, overlays for switching / withdrawal from the operation of automatic devices, measuring devices for fixing the load current along the line - for the listed elements, another panel must be installed.

The microprocessor protection terminal has small overall dimensions.

Fig.45 External terminal panel ABB REF 630

Due to the small overall size, two protection terminals and corresponding switches for controlling 35kV line breakers can be placed on one relay and automation panel and for switching various modes of operation of relay protection devices .

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In this example, the protection terminal REF 630 provides protection for the outgoing power line. The terminal also has other standard configurations that allow this terminal to be used to protect a power transformer, a sectional or bus coupler.

The main advantage of this device is that the standard configurations can be configured with maximum precision for real conditions, consider all possible nuances, and select the necessary functions. As for measuring instruments, in the case of using microprocessor-based protection terminals, it is not necessary to install them, since the phase-by-phase load of the line, as well as other electrical parameters, is displayed on the monitor of the protective device (Виталей П.Р. 2005).
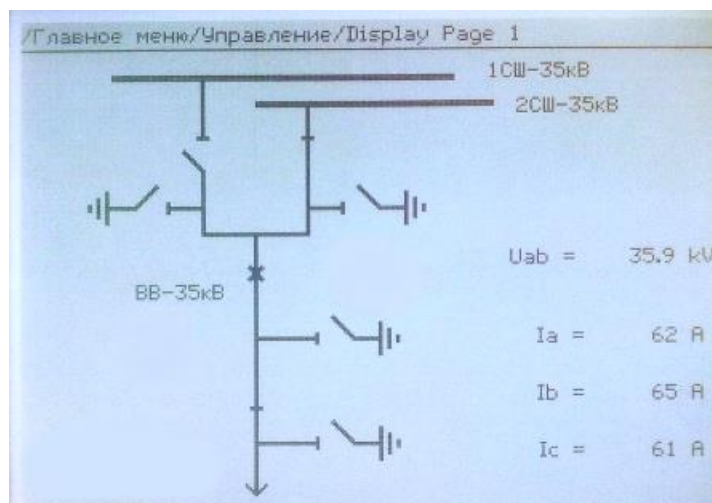
Fig.46 Graphical interface of the ABB REF 630 terminal

As we can see in the Fig1, on the display of the protection terminal, in addition to the load on the line, a mnemonic diagram displayed shows the actual position of the switching devices: bus couplers from 1 and 2 of the 35kV bus system, vacuum circuit breaker, line disconnector, and the position of the stationary earthing devices of bus and linear disconnectors. Also, the display shows the voltage across the bus system from which the line currently feeds.

If necessary, the protection terminal can be configured to display other measured values (phase voltage, active and reactive component of the load, its directivity, frequency of the electric network) and indication of various operating modes (state of the automatic reclosure kit, reclosure, CVV, LZS).

Also, a significant advantage of microprocessor protection is the convenience of control over the operating mode of the equipment, including the elimination of emergent emergencies. On the front panel of the terminal, there are LED indicators indicating their names.

In old-style protections, alarm relays, the so-called "blinkers", were used to indicate the operating modes. In the event of an emergency or deviations from the normal operation of the protective devices, it is necessary to look through each of the indicator relays, which very often had an inconvenient relative position, with each relay to be reset individually "handshake" individually.

At the protection terminal, the LEDs are in one column, so it is convenient to record possible deviations - it is only necessary to look at the corresponding terminal. Another advantage is that one button is enough to "handshake" the LEDs on the terminal.

This advantage is most appreciated in the event of a major accident at the substation, when a set of protective devices is triggered. In this case, it is sufficient to approach each terminal, fix the position of the LEDs and press the button. For electromechanical protections, it is necessary to spend considerably more time to fix the position of each indicator relay and return it to its original position, that is, "handshake".

7.2 Functional features of microprocessor relay protection devices

If microprocessor devices are used to protect the overhead lines, if the circuit breaker is disconnected from the protection or in the case of automatic operation, the device memory records the operating time, the name of the protection or the line automation element, and also the electrical parameters for the pre-emergency, emergency and post-accident periods. With this functionality, you can accurately reconstruct what happened, which is very important in case of large accidents, accidents in the energy sector.
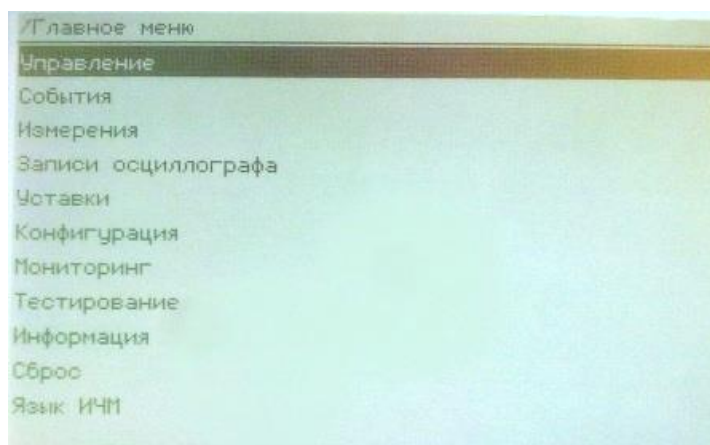

Fig.47 Main menu of ABB REF 630 terminal

Fig.48 Log of event recorder terminal ABB REF 630

Fig.49 Entries embedded oscilloscope ABB REF 630 terminal

In the previous figures, we can see that the fixing of emergencies carried out up to milliseconds. This allows for the analysis of the operation of protective devices, correctly determine the order of their work and draw a conclusion about the correct operation of the protection in accordance with the set values and conditions of their operation.

*The device allows 1000 events to be stored in non-volatile memory.

The protection terminal has the function of self-diagnostics, monitoring of incoming and outgoing circuits, which allows detecting a fault in time. With the use of electromechanical protection, disturbances in the operation of protective devices are not signalled, therefore the violation of their operation is often detected in the event of an incorrect operation of the protection or its complete failure.

Regarding the protection settings, in the microprocessor-based safety device, they are changed in the menu, by selecting the required values. In this case, we can create several groups of settings and quickly switch between them, which is very convenient in the event of the need for a temporary change in the setting values.

Also one of the advantages of microprocessor terminals is the possibility of their connection to the SCADA systems, which allows the substation's service personnel to monitor the state of switching devices, the magnitude of loads and voltages on the buses; as well as to the Automated dispatch control system (ASDU), which allows not only to control, but to control the equipment remotely, from the central control room. Terminal connection diagram shown in Fig.50

Fig.50 Connection scheme for the ABB REF 630 terminal

8. Automated system of control and accounting of Electric systems

The automated system of the commercial accounting of the electric power ASCEM includes the main elements-electronic counters which are converters of the analog signal in pulse frequency which accounting gives the volume of the spent electric energy.

The main advantage of these modern devices is the lack of moving parts, unlike induction meters. They also provide a wide range of input voltage values, make it possible to quickly organize accounting systems with multiple tariffs, allow you to see the amount of energy spent for any past period, measure the power, combined with the equipment of ASCEM and have many other useful functions.

A large list of possibilities is caused by the software shell of the microcontroller, which is part of all modern electronic devices, and energy meters.
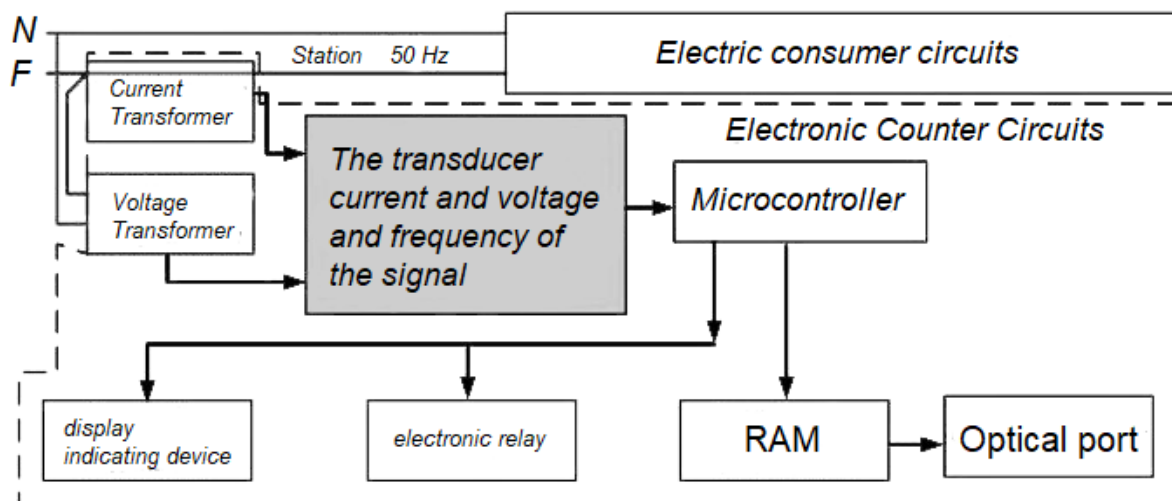
Fig.51 General Structure of ASCEM

The display is a digital indicator, and serves to provide information on operating modes, energy consumption, time and date.

The power supply is intended for supplying the electronic components of the circuit. A supervisor connected to it, which generates a reset signal for the microcontroller when power is applied and turned off.

The clock is used to show the current date and time. In some types of counters, the clock runs from the microcontroller, but to not create an additional load on it, a separate microcircuit is used for the clock (ЭЛЕКТРОСАМ 2018).

The concept and principles of constructing digital ASCEM systems as systems that differ significantly from the number-pulse ASCEM in functional and metrological relationships are formed in the works. The basis of such systems is digital measuring channels (DMC) - "measuring channels, at the output of which the results of measurements are presented in the form of digital results".

According to, the result of measuring a physical quantity is "the value of the value obtained by measuring it," and the value of the physical quantity is "the expression of the size of a physical quantity in the form of a certain number of units accepted for it". The numerical value of a physical quantity is an "abstract number that is included in the value of a quantity" (RMG 29-99 2009).

9. Automated process control system SCADA-REDI

The highest level of any automated system is, of course, a person. However, in the modern technical literature, the upper level understood as a set of hardware and software that serve as a semi-automatic dispatcher node of the automated process control system, the core of which is a PC or a more powerful computer. The human operator enters the system as one of the functional links of the top-level management. This approach has both positive and negative sides. The positive thing is that the operator's responsibilities in this case are predetermined in advance, and no detailed knowledge of the

technological process is required. In other words, not only a skilled technologist can manage the process. The negative sides are the consequence of the fact that the flexibility of management reduced by reducing the influence on the process (C. Purushotham et al. 2015).

In this regard, the developers of the process control system must consider additional requirements. It is necessary to not only consider the hardware component of the process, not only to select modes of equipment operation, but also to develop reliable and correctly operating software. Of course, the best option is the organization of work, when the same team of developers is responsible for both the technological process map, and the selection and debugging of equipment, and for software development. In this case, developers should be equally strong in the technology of a process, and in the use of special equipment, and in writing complex control, service and communication programs. However, it is difficult to choose such a command.

To simplify the development of the software component of the automated process control system, so-called MM-programs (Man-Machine Interface) and SCADA (Supervisory Control and Data Acquisition) now being used. The use of these packages allows for the automated development of software for the automated process control system; real-time monitoring and control of the technological process; receive and process information about the process in a convenient form.

The most exciting and seemingly simple step in the use of SCADA-systems is the simulation of the technological process on the monitor screen. Graphical similar Windows interface of the system is intuitive and simple. For the installation of actuators, electric motors, valves, tanks, pipelines and other equipment used in the technological process, a mouse click is sufficient. Binding hardware parameters to the needs of the process is also simple, performed in a few mouse clicks. Global and "tactical" process parameters entered in forms organized in the form of tables or databases. Standard process controls installed, and survey sensors are organized. Then you can click on the "Start" button and start the work of the technological process. This happens in theory or when demonstrating the capabilities of a SCADA system. However, in practice everything is more complicated (Terrence Smith et al. 2011).

The development of process control systems using SCADA systems, regardless of the process and the specific SCADA package, involves the following main steps:

• Development of the architecture of the system. The process control system built in client-server architecture. The functional purpose of individual automation units and their interaction is determined;

• Creation of an application control system for each automation node (or rather, the algorithm for automated management of this node);

• Analysis and elimination of emergencies;

• Solving interaction issues between the levels of the automated process control system; selection of communication lines, protocols of exchange; the development of algorithms for the logical interaction of different subsystems;

• Solution of possible expansion or modernization of the system;

• Creation of operator interfaces;

• Software and hardware debugging of the system.

All these issues must be solved at the stage of designing and creating exactly the upper level of the automated process control system, otherwise situations may arise where the various functional modules of the technological process will be difficult to link with a single management system in accordance with ideology and technical implementation (Yuri Davidyuk 2010). Using the SCADA system allows us successfully to complete all the above stages of designing and debugging.
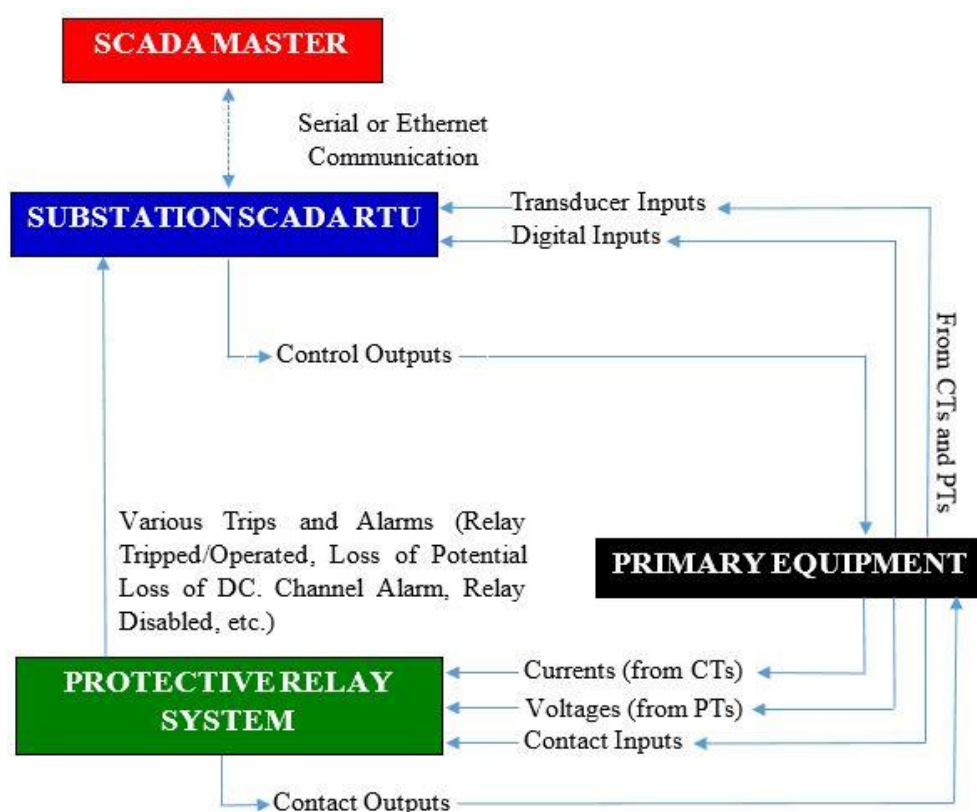

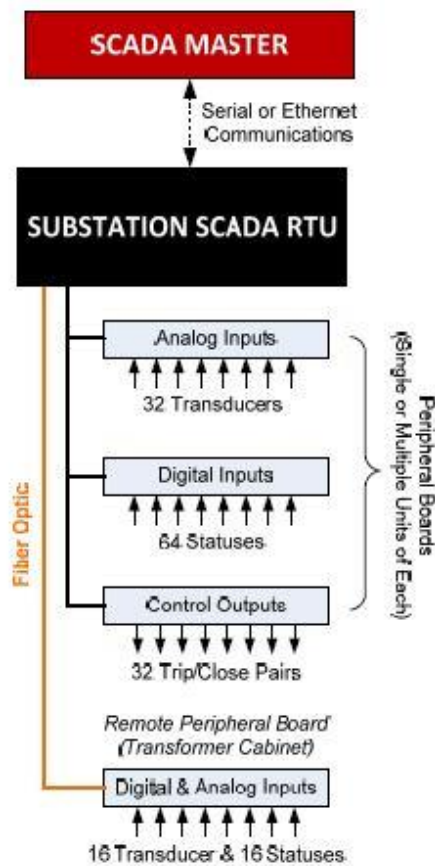Fig.52 Traditional Hardwired Substation SCADA and Protective Relay

Fig.53 Traditional Hardwired SCADA Architecture

9.1 How SCADA systems work

SCADA packages consist of several software blocks: access and control modules, alarms, real-time databases, databases and I/O modules and emergencies.

The main requirement for SCADA-systems is correct operation in real time. And the main priority in the transmission and processing are the signals coming from the process or on it and affecting its flow. They have priority even greater than accessing the disk or the operator's actions to move the mouse or minimize windows. For these purposes, many packages are implemented using real-time OS operating systems, but recently more and more developers are creating their SCADA products on the Microsoft Windows NT platform, integrating RTX (Real Time Extension) subsystems into it. With this approach, we can use Windows NT as a single OS when creating multi-level systems, use the standard functions of the Win32 API and build integrated information systems – ASEM (R. Barillere 1999).
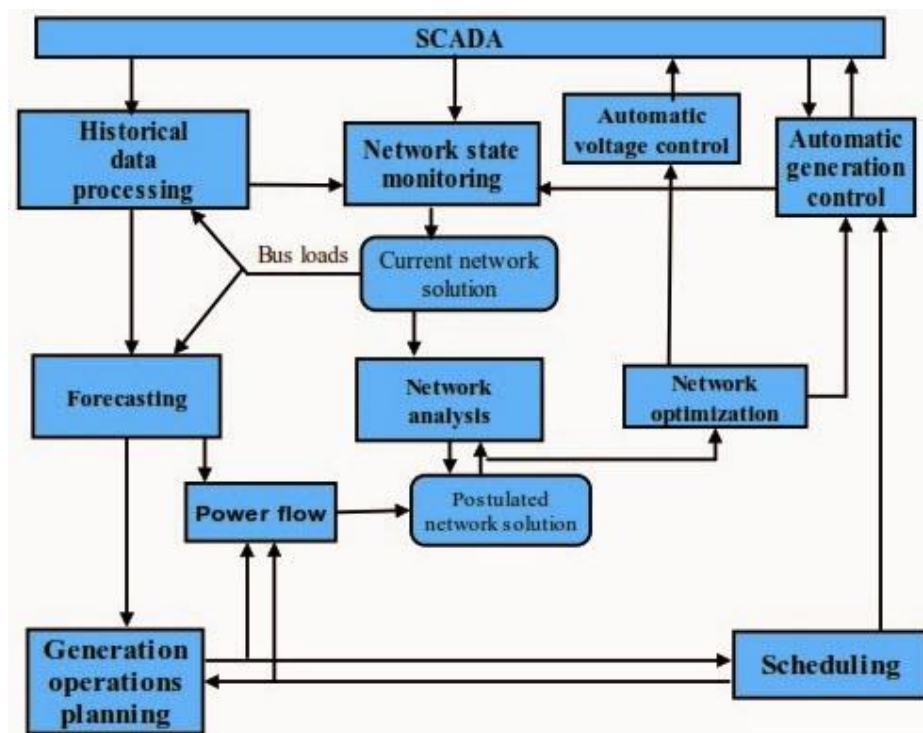
Fig.54 Communication and control lines

Data sources in SCADA systems can be as follows.

• Communication drivers with controllers. The reliability of communication drivers is very important. Drivers must have data protection and recovery facilities in case of failures, automatically notify the operator and system about the loss of communication, if necessary, and give an alarm signal.

• Relational databases. SCADA systems support protocols that are independent of the type of database, so that most popular databases can act as a data source: Access, Oracle, etc. This approach allows you to quickly change the settings of the technological process and analyse its progress outside of real-time systems, various, specially created for this program.

• Applications that include a standard DDE (Dynamic Data Exchange) interface or OLE (Object Linking and Embedding) technology that allows you to include and embed objects. This makes it possible to use even some standard office applications as a data source, for example Microsoft Excel.

The input and output of the transmitted data organized as a system of special function blocks. The current process information is stored in special I/O bases. The input blocks receive information and bring it into a form suitable for further analysis and processing. Processing units implement control and management algorithms, such as PID control, delay, summation, statistical processing, Operations on Boolean algebra can be performed on digital data, etc. Output blocks transfer a control signal from the system to the object. For communication with objects, widely used interfaces are RS-232, RS-422, RS-

485, and Ethernet. To increase the transmission speed, various methods of data caching applied, which eliminates the overload of low-speed networks. In other words, if two different clients simultaneously request the same data from the server, it sends the controller not two requests, but only one, returning the data from the cache to the second client.

Perhaps the most important moment in the creation of the automated process control system is the organization of such a control system that would ensure the reliability and operational development of emergencies both in the control system itself and in the technological process. Alarms and working out of emergencies in the technological process in most SCADA systems allocated to a separate module with the highest priority. The reliability of the control system achieved through hot backup. We can reserve everything: the server, its individual tasks, network connections and separate (or all) communications with the equipment. Redundancy takes place by an intelligent algorithm: in order not to create a double load on the network, the main server interacts with the equipment and periodically sends messages to the backup server that keeps the status of the system in the memory. If the primary server fails, the backup takes control of itself and works until the main server starts working again. Immediately thereafter, the primary server databases updated with backup data and control returned to the primary server.

All SCADA-systems are open for further expansion and improvement and have for this purpose embedded high-level languages, most often Visual Basic, or allow the connection of software codes written by the user himself. In addition, systems can be connected to development of other companies, ActiveX objects, standard Windows DLLs. To implement these technologies, special tools and a specialized interface developed.

SCADA-system can be integrated with various networks: other SCADA-systems, office networks of the enterprise, recording and signalling networks (for example, security and fire alarms), etc. For effective work in this heterogeneous environment, SCADA-systems use the standard protocols NETBIOS and TCP/IP. The mere mention of the TCP/IP protocol already shows that SCADA-systems can work on the Internet, especially as the transmission of operational and static information about the process to Web sites becomes more urgent.

9.2 The principle of SCADA-REDI system

ABB has incorporated a new concept to verify end to end integrity of data between microprocessor-based relay IED devices. The new technique is called SCADA – REDI ® (SCADA Rapid Electronic Device Integration). ABB devices traditionally have "read" only components (reporting the present state of the function or input/output device). ABB microprocessor-based protective relays traditionally have control capabilities in forcing physical devices attached to the relay, but there

was no method to force analog readings, to verify database mapping integrity. The analog readings are stored in the MODBUS protocol in 4X memory and were traditionally "read" only. ABB DPU 2000, DPU 2000R, TPU 2000 and TPU 2000R relays have the capability to allow a read only 4X register to be forced from a personal computer through the relay's communication port. SCADA–REDI ® allows one port (attached to a computer) to force a register with data, while the host device polls the second port and verifies the data forced by the auxiliary computer (W.J. Ackerman et al. 2002).

Figure 55 illustrates the methodology with SCADA REDI enabled and disabled.

Pictorially, a power system installation involving IEDs can be shown as follows:
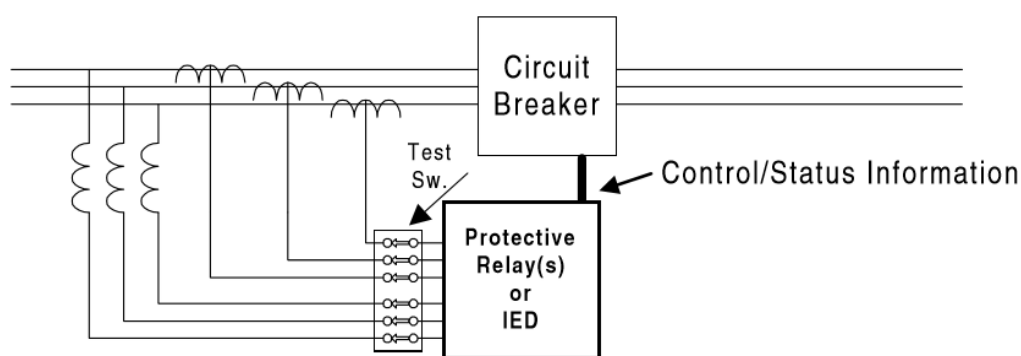

Fig.55 Control scheme for CB

In this diagram, sensing devices (potential transformers and current transformers) are connected to the power system apparatus to produce a directly scaled replica (voltage or current) for input to the IED. The IED processes the inputs and determines if power system conditions are outside specified bounds, and if so, causes the circuit breaker to be opened.

The electric utility cannot, for all practical purposes, alter the primary voltages and currents in the power line to test the proper operation of the IED. Therefore, a method for synthesizing the power line loading signals is required. The connections for doing this are illustrated as follows, wherein the power system simulator is identified as a V,I,f Generator where V,I,f stands for voltage, current and frequency.
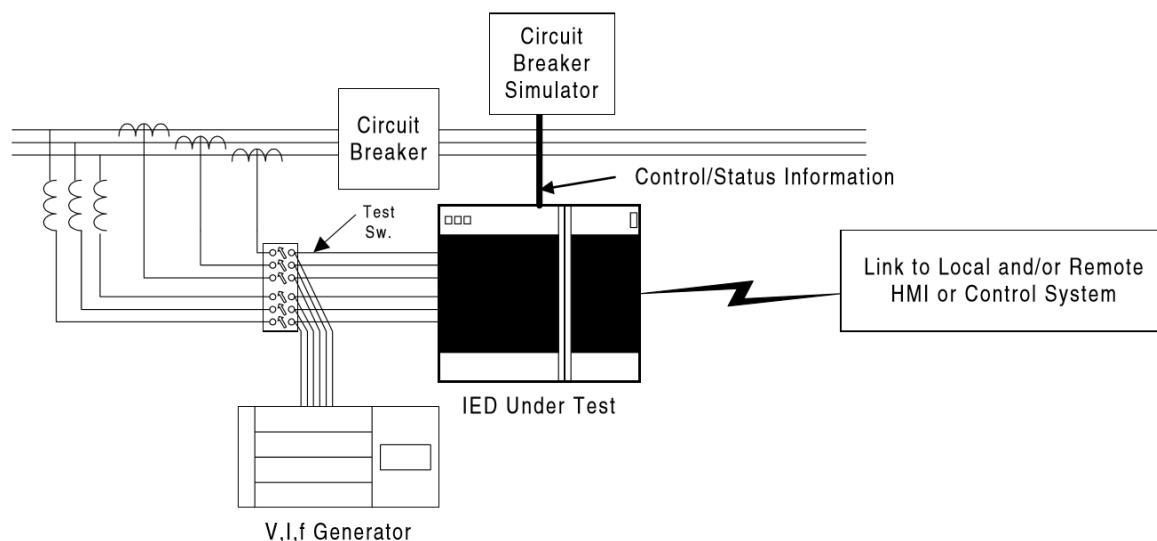
Fig.56 Checking digital signals and communication channels by simulating a shutdown the CB

This diagram shows that to make use of a device such as the simulator, the "test switch" must be opened so that the IED under test is disconnected from the primary inputs from the electric power system. The V,I,f generator is then connected to the IED under test and all required test signals are produced by the generator and the proper operation of the IED can be verified.

Testing the IED in this manner has a significant disadvantage, i.e., the IED is disconnected from the power system and is therefore unable to perform its intended functions while under test. The testing utility is thus forced to accept one of three undesirable alternatives:

a. The power system circuit is disabled (i.e., the circuit breaker is opened) for the duration of the test period.

b. The circuit breaker is by-passed for the duration of the test period, thereby relying on backup protective devices which are generally less selective or accurate.

c. The IED is disconnected from the circuit breaker for the duration of the test period, on the assumption that nothing will happen on the power system during the testing.

Protective relay IEDs as currently used in electric power systems typically are multi-function devices. Two specific functions of concern here are those relating to protecting the electric power system from abnormal conditions and serving as a measuring and control device for interfacing to a SCADA or Substation Automation control system. (As used herein, SCADA will include automation systems, user displays, etc.)

When an electric utility tests the IED for correct performance of protective functions, a power system simulator (test generator) is essential. The test technician causes the generation of many input

signals designed to verify that the IED settings are correct and that the IED response is what is desired. Without a test generator, IED protective setting testing would be unacceptably prolonged, causing a tendency to use short cuts and assumptions. In any case, the electric utility applies one of the alternatives described above for testing the protective functions of the IED. There is great emphasis on minimizing the duration of such testing, which in turn creates the possibility of inadequate testing and future mis-operations.

When testing the IED for correct performance of SCADA functions, the situation is quite different. It is assumed that the protective functions have been tested and verified, thus establishing the correct operation of the measurement and calculation functions of the IED. Therefore, the remaining testing is to verify that the data generated by the protective functions is correctly communicated to the SCADA system. In this case, knowledge of the exact numerical representation of the data being passed over the communications circuit is the important factor. The fact that the numerical value was produced by the measurement circuits of the IED is not important. In fact, the number must be unique, but does not have to be realistic.

The following block diagram illustrates some of the processes that take place inside the IED:
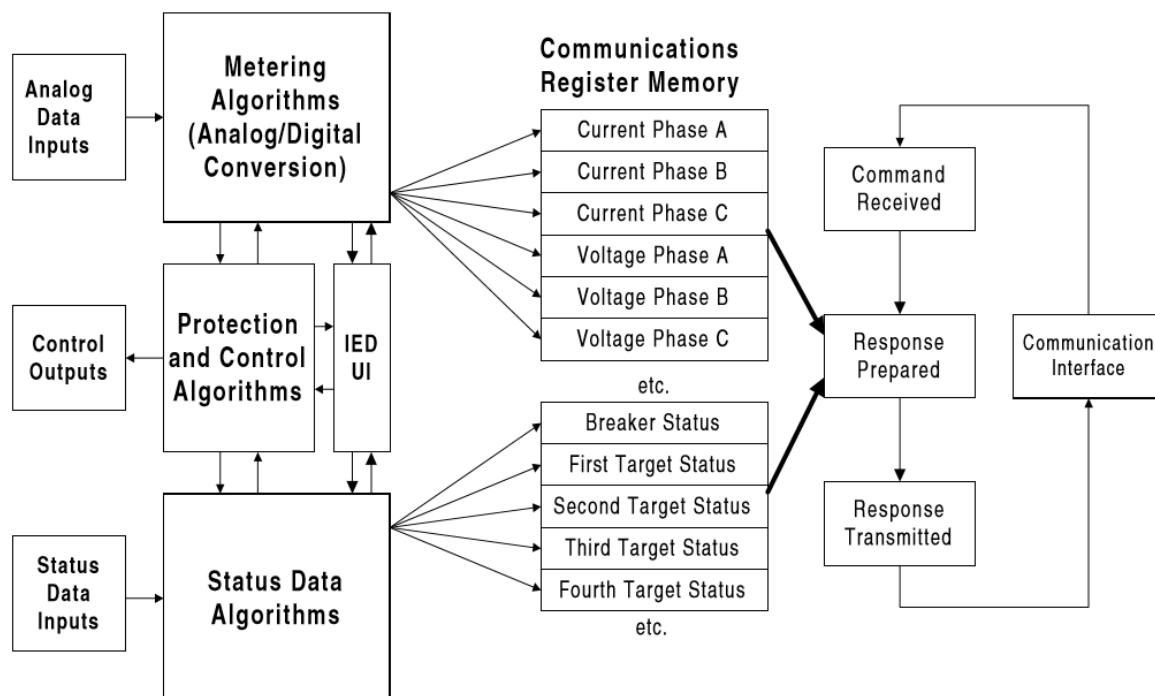
Fig.57 Diagram of the processes that take place inside the IED

The blocks on the left represent the data inputs. These blocks are where the test generator signals are applied to the IED under test. The input signals are processed by the metering or status algorithms

and then passed to the protection and control algorithms. If the IED has a User Interface (UI), the data is also made available to that function.

As a part of the signal processing, digitized representations of the analog inputs and status inputs are placed in a separate set of data registers dedicated to communications. These registers then supply the requested data to the communications process in the IED for transmission to the requesting device (external user interface or SCADA system).

When testing the communications function, the use of a signal generator may be counter-productive. In the performance of a SCADA checkout, the ideal situation is when one specific quantity can be tested at a time. This eliminates any ambiguity in the SCADA system response. When a signal generator approach is used, ambiguity is unavoidable, especially when testing SCADA response when the test range includes values that exceed defined limits.   A single input such as a phase current that exceeds the specified operating limit will cause the transmission of the digitized phase current value, plus an alarm that the trip circuit has been energized, plus one or more targets indicating the exact initiating value and possibly other status signals.

ABB's SCADA-REDI provides a technique that eliminates the need for a signal generator and provides the utility technicians with complete control over the data being transmitted to the SCADA system.

There are two facets of SCADA-REDI the first provides for the local use of an input device, such as a laptop (or other)computer, as illustrated in the following figure:
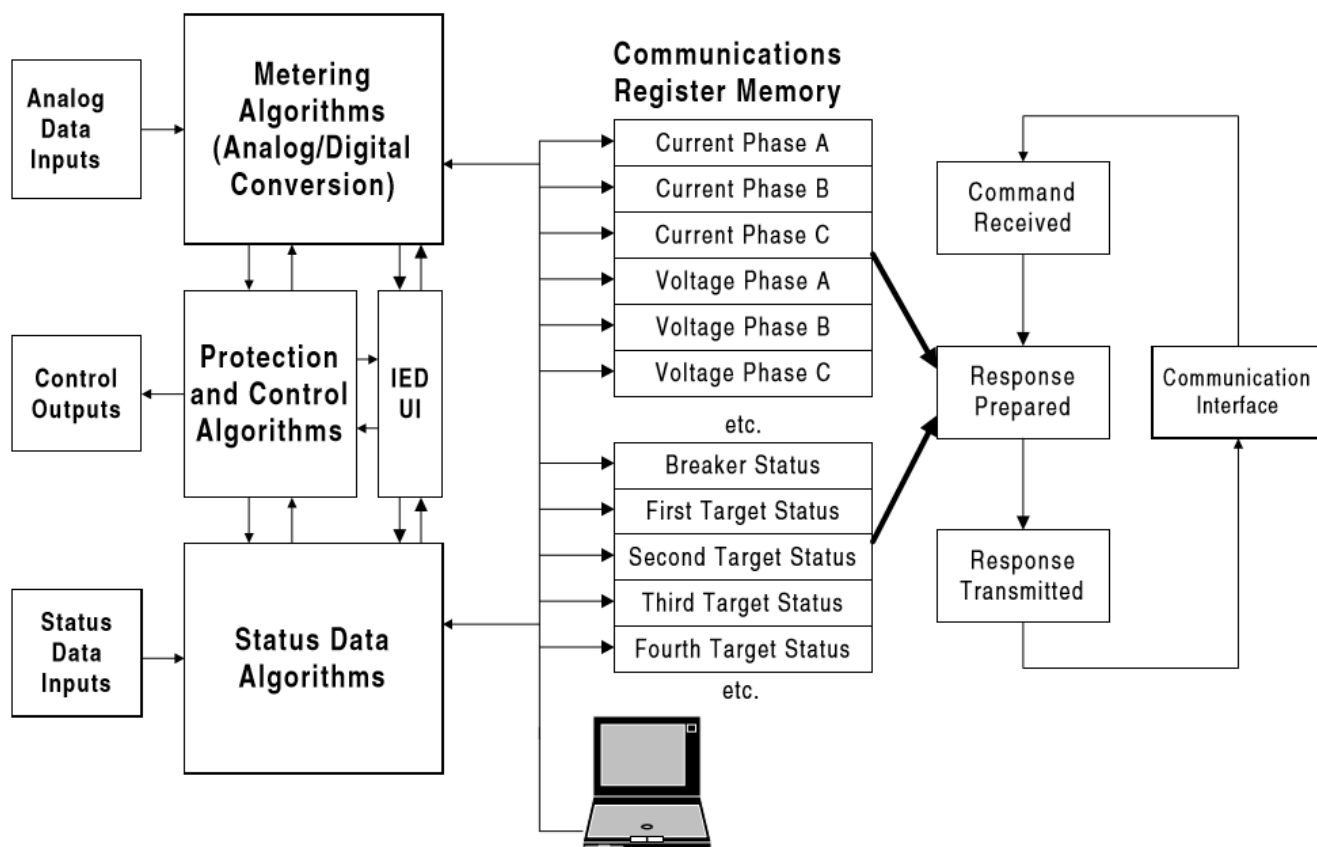
Fig.58 Logic signal communication diagram

In this illustration, the metering and status data algorithms continue to be connected to the analog and status data inputs. However, the function that transfers the digitized data from the protection portion of the IED to the communications portion of the IED is suspended. In its place, a laptop (or other) computer is connected and a program is used to inject arbitrary values into the communications registers. In this way, the test technician located at the IED can communicate to the SCADA test technician the exact numerical values he has injected into the communications registers;

and the SCADA test technician can verify that those same values have been received and processed by the SCADA system.

The implementation of the proposed invention can also allow a complete remote testing process as illustrated below:
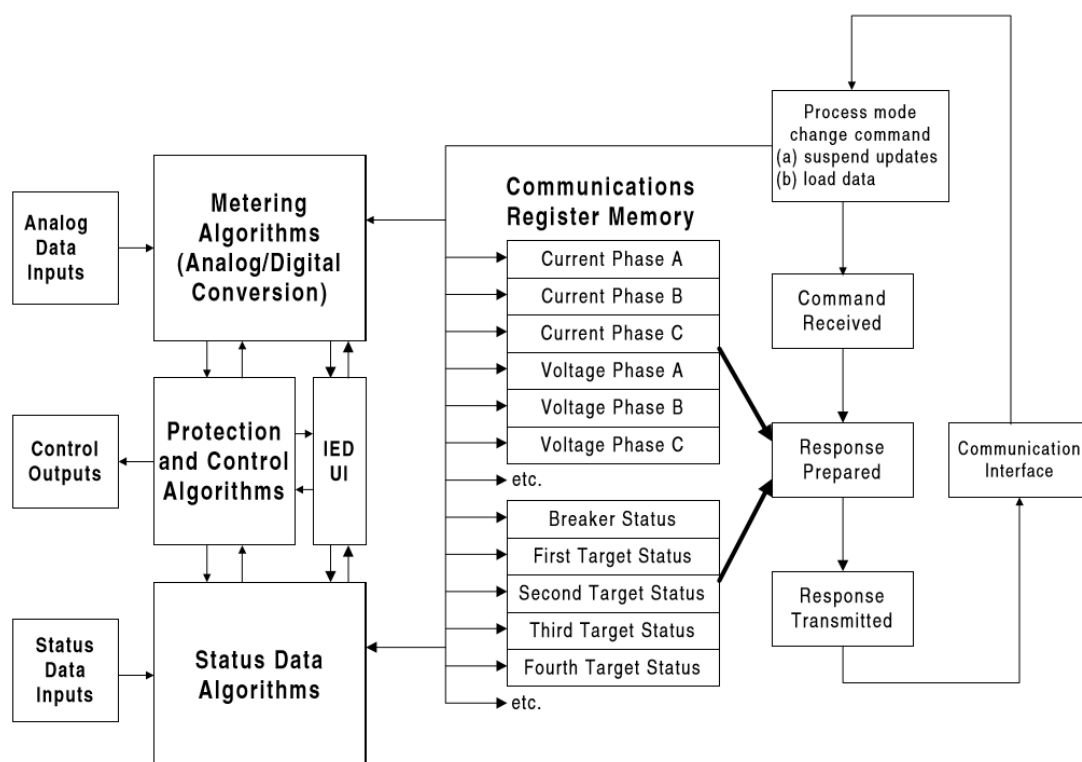
Fig.59 Diagram of communication with logical signals

In this diagram, SCADA-REDI allows the IED to be placed in the test mode by using the communication interface, and then the remote injects any arbitrary number into the communications registers as described above.

A final example may be the use of multiple IEDs in a complex automation scheme. Such schemes require the use of multiple test generators, all coordinated and inter-connected, to generate the appropriate test signals. In addition, the testing of automation schemes requires repeatable test sequences to ensure that any changes or modifications to the overall scheme do not disable the proper operation of the automation scheme or cause an improper operation.

The following diagram illustrates an automation scheme being tested using test generators:
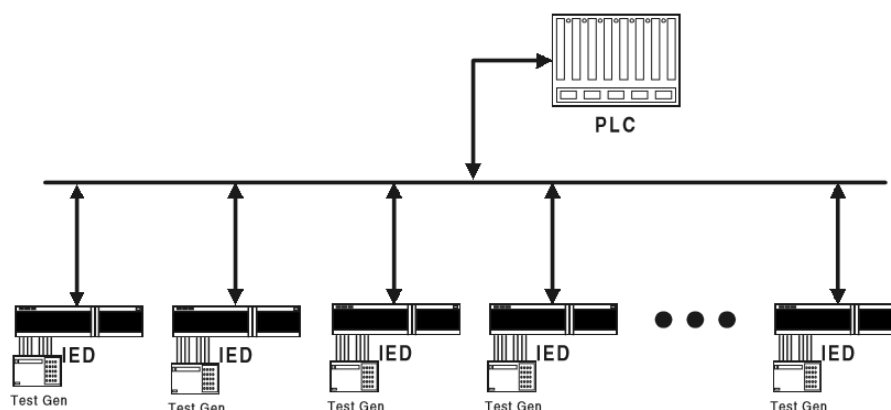

Fig.60 Network structure

Because each IED is an independent entity, a separate test generator must be connected to each IED. Then, each test generator must be programmed and interlocked to insure the correct simulated signals are generated, essentially simultaneously, so the response of the Programmable Logic Controller to the combined inputs can be verified. In addition, the simulated inputs must be varied to cover the possible range of inputs in a real disturbance. A major requirement is that the simulated inputs generated by each test generator arrive at the IED inputs virtually simultaneously, as would happen during an electric power system disturbance. Finally, it must be possible to re-create the exact sequence of tests at any time, so that changes to the PLC logic or automation scheme can be tested to ensure that the automation system still performs as intended. The inability to do this type of comprehensive and intensive testing is a major cause of "false or inappropriate operation" reports.

By contrast, the following diagram illustrates the use of the SCADA-REDI as a system test tool:
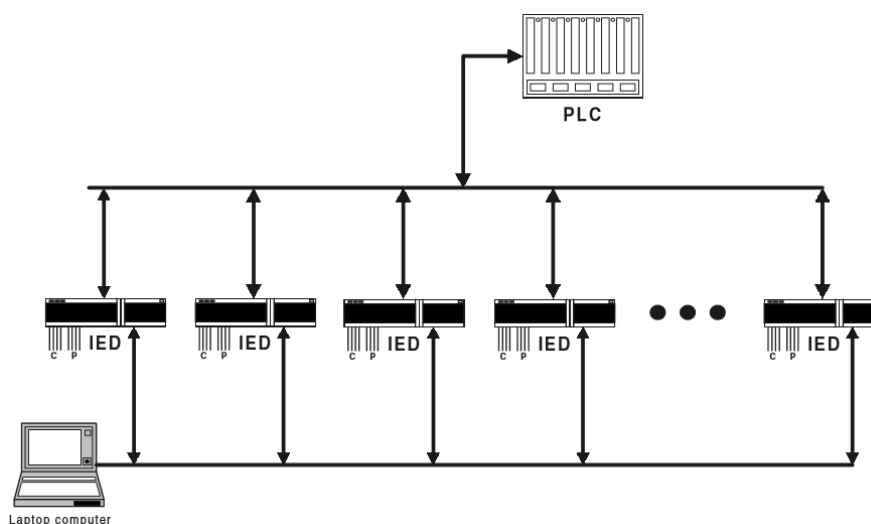

Fig.61 Network structure

This diagram shows that the IEDs under test remain connected to the primary input circuits (C = current transformer connections, P = potential transformer connections). Thus, even while testing the PLC programs and automation system functioning, the IEDs remain connected to the electric power system inputs and continue to perform their intended protective relay function.

Secondly, the use of costly signal generators, transporting them and performing the complex setup tasks is avoided.

Finally, the use of a laptop or other computer allows a comprehensive test program to be written, which can then be archived and re-used after any changes to the automation scheme or PLC logic. This "before and after technique" provides the electric utility with assurance that the automation scheme will continue to function as intended, even after changes.

9.3 Web-SCADA

The term Web-SCADA usually refers to the realization of human-machine interface (HMI) SCADA-systems based on web-technologies.

This allows us to control and manage the SCADA system through a standard browser, acting in this case as a thin client.

The architecture of such systems includes a Web-SCADA server and client terminals - PCs, PDAs or mobile phones with a Web browser. Connecting clients to the Web-SCADA server via Internet. Internet allows us to interact with the automation application task as a simple web or WAP page. However, at this stage of development, Web-SCADA has not yet reached the level of widespread industrial implementation, since there are difficulties with protecting the transmitted information. In addition, the implementation of management functions through unprotected communication channels is contrary to security considerations of any industrial facility. In this regard, in most cases, Web interfaces are used as remote clients for monitoring and data collection.

10. **How do experts assess the prospects for the introduction of this technology in Russia?**

Companies that claim that they have the necessary equipment, have mastered the technology and have the necessary competencies, enough, but practical steps, as usual, less. Another issue is the choice between domestic and foreign proposals. According to the experts of (FSK YeES PAO) company, a compromise is necessary, when "it is possible to take decisions of the brand and - as a backup option - domestic developments offered to the market". Moreover, without the elements of administrative regulation by (FSK YeES PAO) company this process will not be successful.

Yet in Russia, the process of introducing digital substations has gone, as evidenced by the meeting of the management of Alstom and JSC "Russian Networks", dedicated to the discussion of current and prospective projects of digital substations.

As for Alstom, it actively participates in the introduction of intelligent electric system technologies with an actively adaptive network. Currently, the company is participating in the implementation of the project of the first digital substation in Russia based on the 220 kV (Nadezhda) substation, a branch of JSC (FSK YeES PAO) of MES-Ural. Alstom supplies equipment and installs connection controllers with support for IEC 61850-9-2 LE, relay protection and automation systems and process control systems, as well as adjusts them (Антон Канарейкин 2014).

At this moment, several digital substation projects are being implemented in Russia, such as the experimental ground "Digital substation" based on "STC FSK YeES PAO ", the 500kV substation "Nadezhda" based on the Main electric grids of the Urals, and the cluster "Elgaugol".

However, as experts say, while in the issue there is no the most important component - the methodology of designing in full. It is necessary to resolve the issue of automating this process, while the personnel are not yet prepared. Otherwise, it will significantly impede the development of digital substations in Russia, which is highly undesirable.

SECTION THREE: Digital substation design model

1. Introduction

This section will present the interface of the digital substation 110/10kV developed in LabVIEW and how to protect and control it remotely using Web SCADA-REDI system.

2. Model Sub-station 110/10kV in LabVIEW

Initially, the lower-level (second-level) model was developed. It is a model of 110/10 kV substation with a step-down transformer. The model interface is shown in Fig.62.
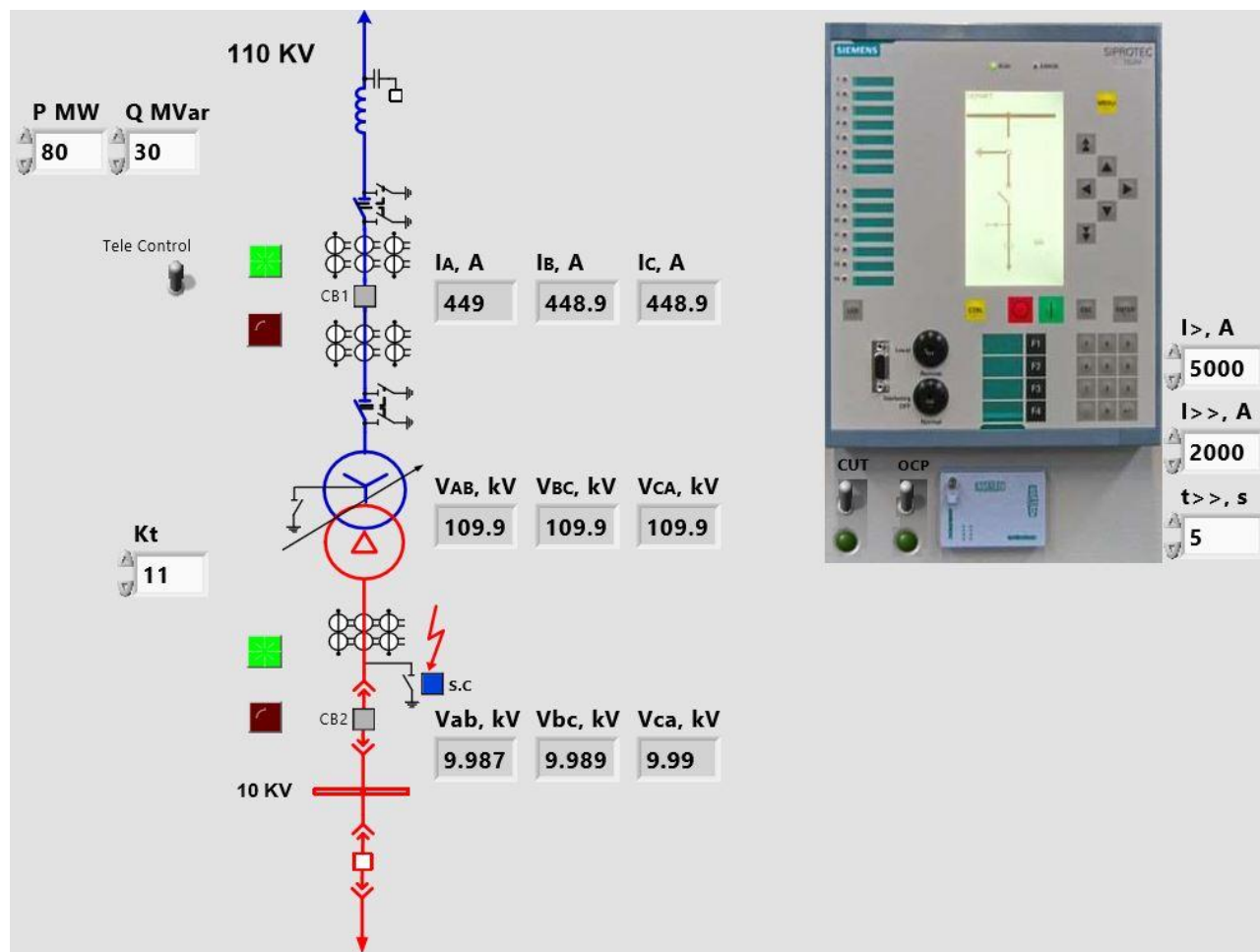

Fig.62 Substation 110/10kV (Lab VIEW mode)

A sub-station 110/10 kV contains:

- Transmission Line 110 kV.
- Transformer 110/10 kV.
- Busbar 10 kV.
- Feeder 110 kV.
- 2 of separators 110 kV.
- 1 Circuit-Breaker 110 kV.
- 2 circuit-Breakers 10 kV.
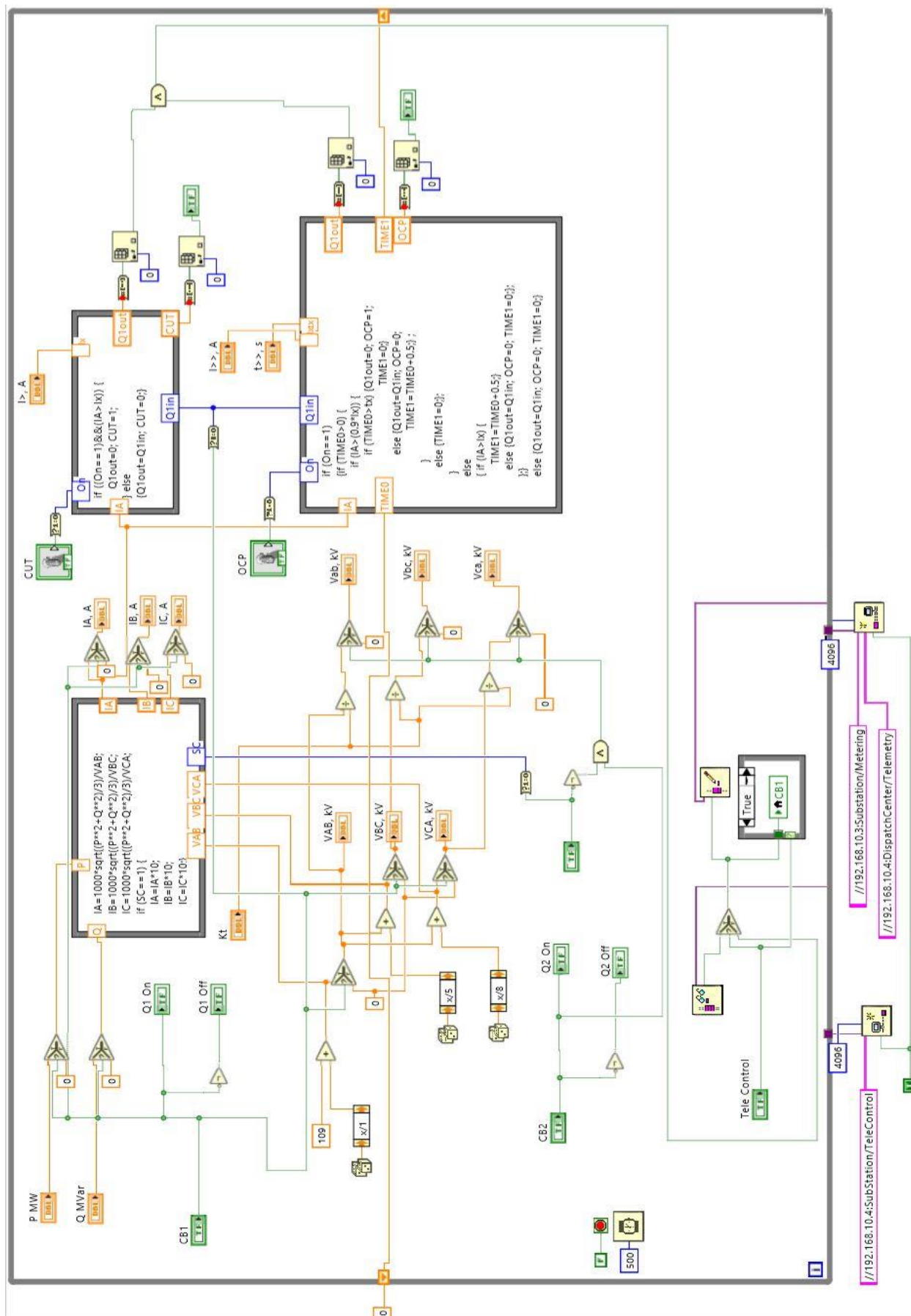- Short circuiter 10 kV.
- Current transformer at 110 and 10 kV.

Fig.63 Block diagram of substation 110/10kV

The model is implemented to control the state of the circuit-breakers 110 kV and 10 kV. Getting each of the CBs can be changed by click, and its status is shown by two indicators: green indicator, lights when the CB is closed, red-when it is open.

The mode parameters at the substation are controlled by the values of currents and voltages, which are displayed besides each unit:

- I_A, I_B, I_C.
- V_{AB}, V_{AC}, V_{CA}.
- V_{ab}, V_{ac}, V_{ca}.

To interface the operating modes of the substation can be set to load P and Q on the sides of 110 kV, as well as the transformation coefficient of the power transformer.

Relay protection is in the model of terminals, the CB in itself:

- Current cutoff (CO).
- Over Current Protection (OCP).

The panel provides protection status switches, input for setting the current cut-off CO (I >) and input for setting the over current protection OCP (I >>, t >>), for visual determination of the triggering of the protections provided for the indicators.

The current cut-off algorithm implemented in the model is shown in Fig.64 The protection controls the current in phase "A" and comparing it with the setpoint "I_x". When the current exceeds the set point, a command is issued on the switch "Q1".
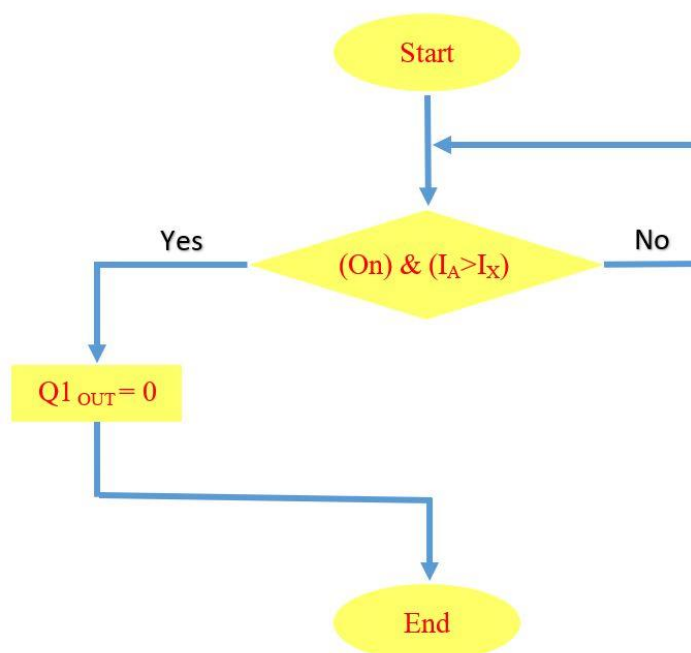

Fig.64 Algorithm of Current cut-off

The logic diagram for maximum current protection is shown in Fig.65 The circuit controls the current in phase "A". Its value is compared by setting "I_x ". If the current exceeds the set point, a cycle is started corresponding to the timer counting down the protection time. If the current in phase "A" is

reduced to 90% of the set point after the protection is started, the timer stops, and the protection returns to its initial state. Otherwise, when the timer reaches the time setting "t_x", a command is issued to turn off the switch "Q1".
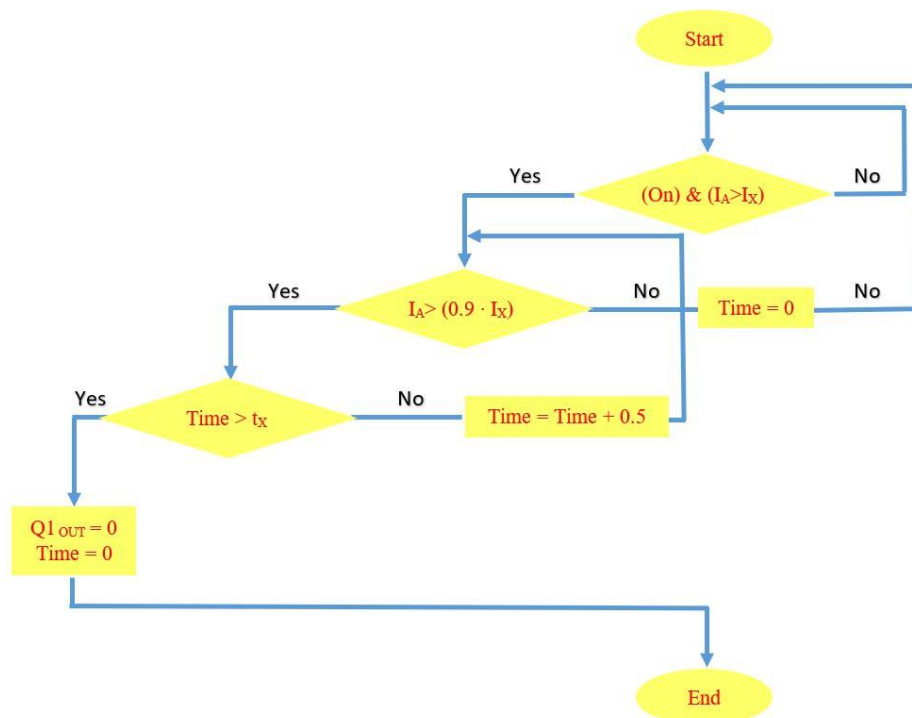
Fig.65 Algorithm of over current protection OCP

The program code is presented below:

```
if (On==1) //checking the switch protection
{if (TIME0>0) {
  if (IA>(0.9*Ix)) {
    if (TIME0>tx) {Q1out=0; OCP=1;
                    TIME1=0;}
    else {Q1out=Q1in; OCP=0;
         TIME1=TIME0+0.5;} ;
    }
  else {TIME1=0;};
 }
else
{ if (IA>Ix) {
   TIME1=TIME0+0.5;}
  else {Q1out=Q1in; OCP=0; TIME1=0;};
};}
else {Q1out=Q1in; OCP=0; TIME1=0;}
```

3. **Model Station 110 kV in LabVIEW**

The top level (first level) model is a 110kV ring station model. The substation considered in item 3.1 part of the station. As shown in Fig.66. the previously diagram, considered substation is located at the right bottom.
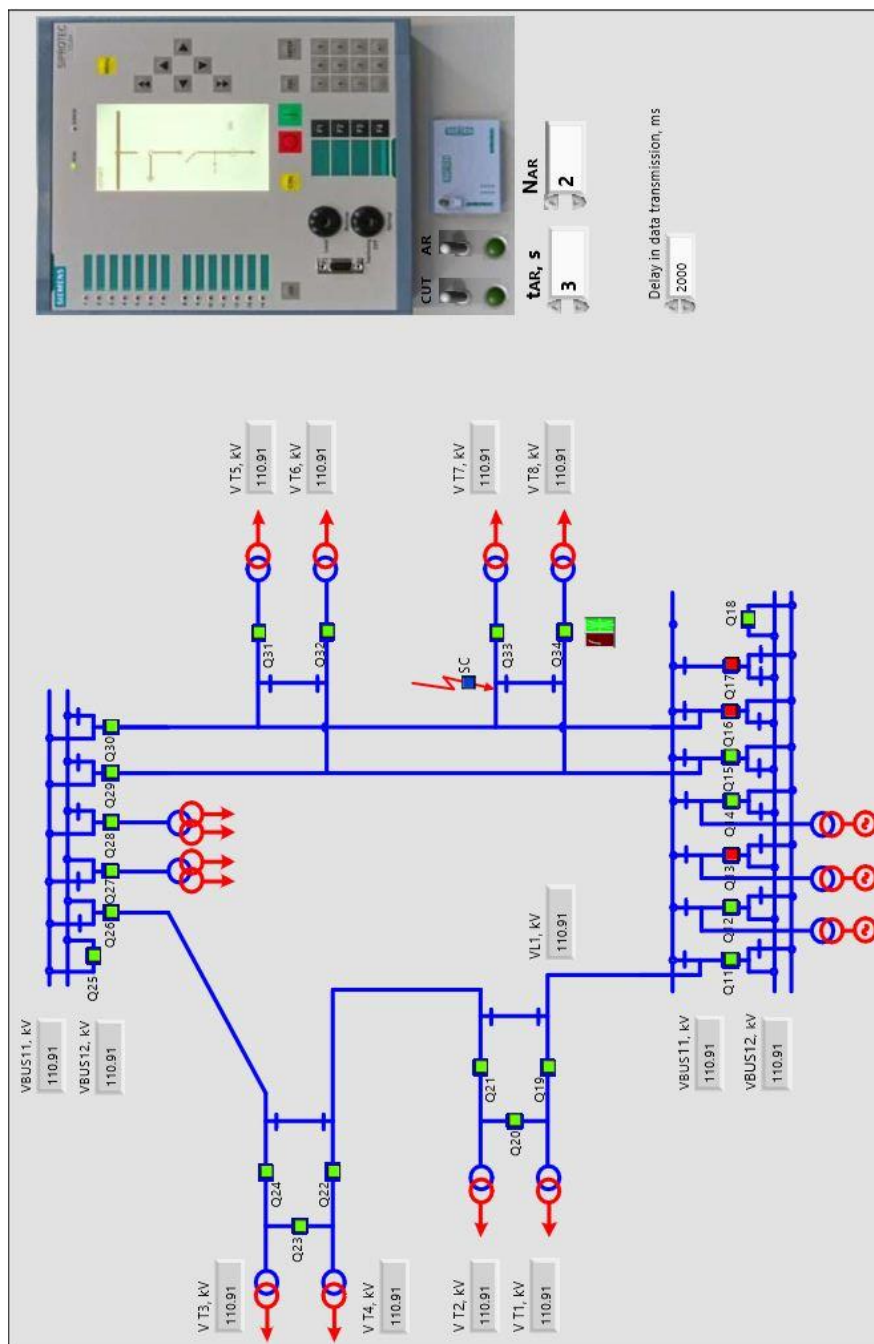

Fig.66 Power station 110 kV (LabVIEW mode)

The model in the station turns off in itself:

- Power plants with 3 generators.
- Nodal substation.
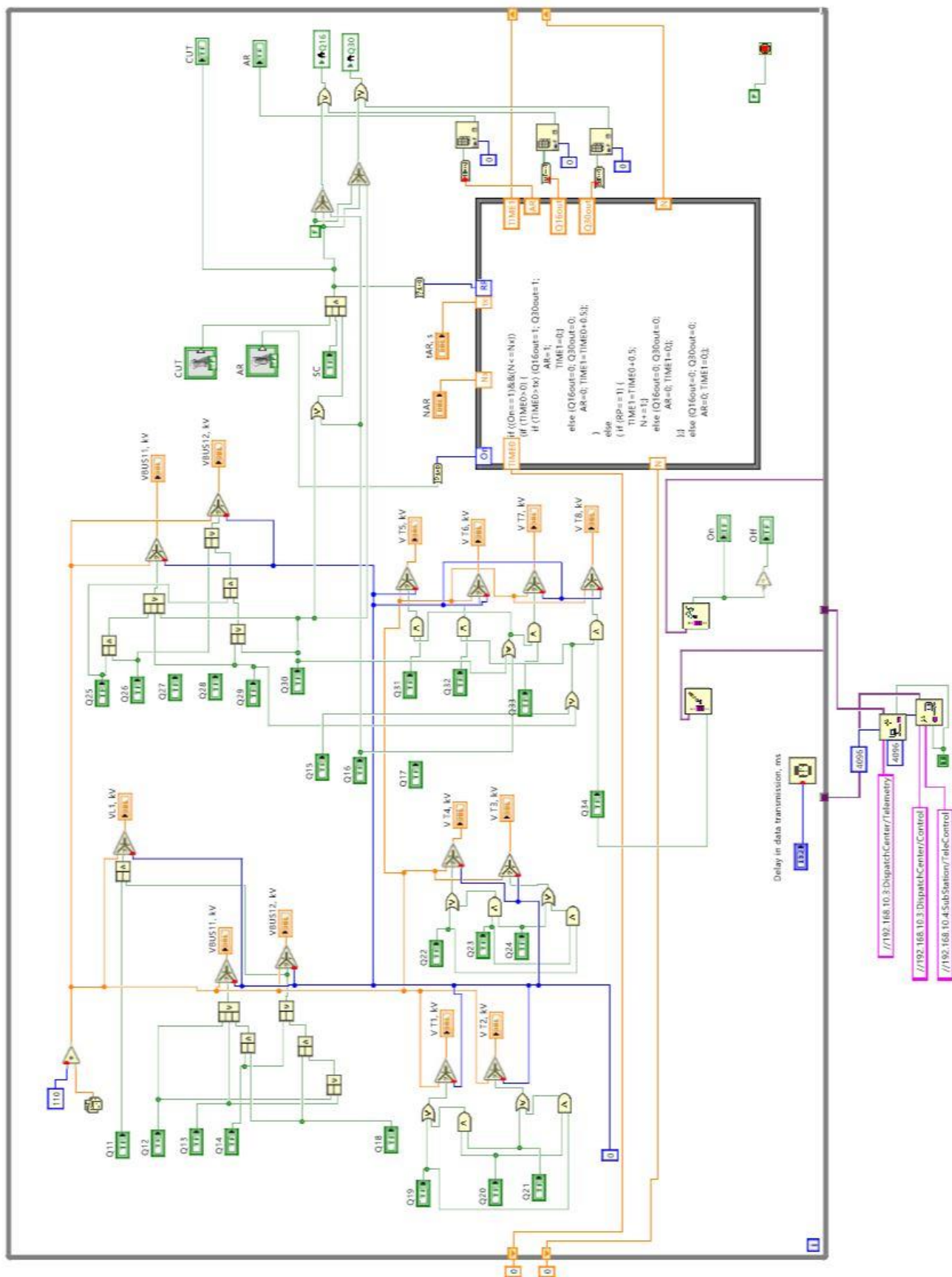- 2 Transit substations.
- 2 tap-off substations.

Fig.67 Block diagram of ring station 110kv

Discussed in substation located on the diagram

the model shows controlling and removing the 110kV switch control of the substation, controlling the voltage on the busbar of the switchgear and in the network nodes. to simulate work .... in this model, the logic of the APV terminal is implemented-Automatic re-shutdown

The code of the program implementing the APV logic is given below:

```
if ((On==1)&&(N<=Nx))
{if (TIME0>0) {
 if (TIME0>tx) {Q16out=1; Q30out=1;
                  AR=1;
                  TIME1=0;}
  else {Q16out=0; Q30out=0;
      AR=0; TIME1=TIME0+0.5;};
 }
else
{ if (RP==1) {
   TIME1=TIME0+0.5;
   N+=1;}
  else {Q16out=0; Q30out=0;
      AR=0; TIME1=0;};
};}
else {Q16out=0; Q30out=0;
    AR=0; TIME1=0;};
```

4. **Network stream between the main station 110kV and substation 10kV**

Network streams are an easy-to-configure, tightly integrated, and dynamic communication method for transferring data from one application to another with throughput and latency characteristics that are comparable with TCP. However, unlike TCP, network streams directly support transmission of arbitrary data types without the need to first flatten and unflatten the data into an intermediate data type. Network streams flatten the data in a backwards compatible manner, which enables applications using different versions of the LabVIEW runtime engine to safely and successfully communicate with each other. Network streams also have enhanced connection management that automatically restores network connectivity if a disconnection occurs due to a network outage or other system failure. Streams use a buffered, lossless communication strategy that ensures data written to the stream is never lost, even in environments that have intermittent network connectivity. In our work we studied the possibility of controlling/streaming data between the main and substation due to the network stream.
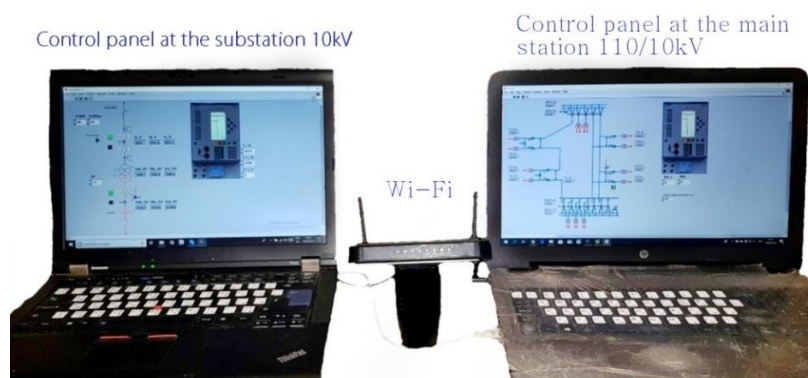
Fig.68 connection status between SS control panel and the main station

3.3.1 Streaming the substation 10kv (the secondary level) with main control centre/station 110/10kV (the first level)

Network streams were designed and optimized for lossless, high throughput data communication. Network streams use a one-way, point-to-point buffered communication model to transmit data between applications. This means that the main station 110/10kV of the endpoints is the writer of data and the substation 10kV is the reader. We accomplished bidirectional communication by using two streams due to localhost, where each computer contains a reader and a writer that is paired to a writer and reader on the opposite computer.

For communication between the substation and the control panel (station), a data transmission algorithm is implemented. Fig.68 shows a stream network diagram in the second level of the project, that interface some SCADA subsystems for a single switch. Information on the switch position at the substation is sent to the control panel through local host, we used due to that a Wi-Fi router with limited area at the IP "`//192.168.10.4:DispatchCenter/Telemetry`".

From the control panel receives information about the control switch, which comes from the local IP address "`//192.168.10.3:SubStation/TeleControl`". When we receive a command to turn off the switch, its position at the substation changes, after which information about the new position is sent to the control panel. The time delay spent switching the switch, receiving and sending data is simulated by a timer. The default value is 0.5 seconds.

To simulate the operation of the relay protection, a short circuit point is added to the model, it's implemented as a button "SC".
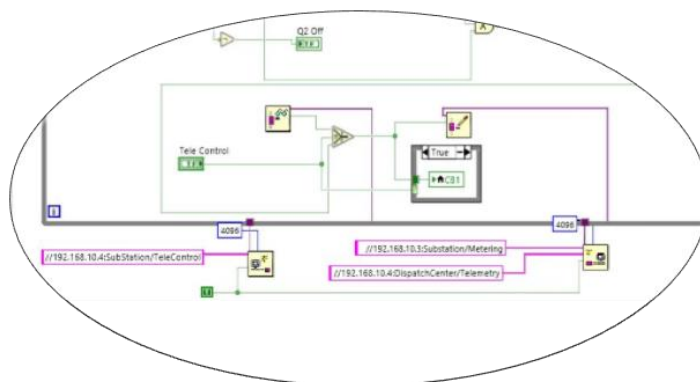
Fig.69 Diagram of data transmission and receipt in the substation (level 2)

Establishing a stream with the remote-control panel/the station by creating network stream writer end point. The end point name is supplied through the writer name input to create the function. LabVIEW uses this name to generate a URL for identifying the end point resource and must be unique.

At the same localhost, by creating new IP address-"//192.168.10.4:DispatchCenter/Telemetry"- to make a communication point with the control centre and the secondary level of the substation, "//192.168.10.3:SubStation/TeleControl".
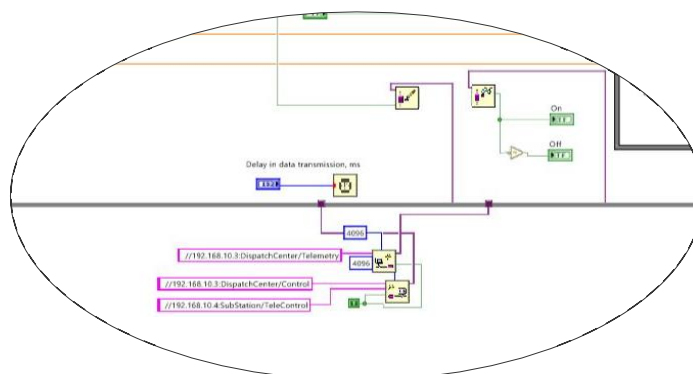

Fig.70 Diagram of data transmission and receipt in the control centre (level 1)

SECTION FOUR: CONCLUSION

Digital substations are a reality now. From petrochemical substations networked by fiber-optic for safer operation, through to utility substations ensuring optimized integration and transit of renewable energy across the grid, the technology is delivering results.

As the world converges, diverse systems are also beginning to converge. In the past, it would seem absurd to mix the telephone and a computer networks, but now it is an idea that is making high ground in the telecommunications sector.

The aim of this project is to gain a better understanding for protection and automation of digital substations used by IEC-61580 and to contribute to a more standardized protection of these.

In this work, the models created to tested 110/10 kV power plant with a five of substations and one power station. A protection and automation the main schemes in this work which based on microprocessor-based relay and SCADA-REDI system has been implemented using LabVIEW. After that the models of the digital substation has been tested. The basic principles of operation of relay protection and automation devices at the digital substation are studied, the main features of substations and the requirements of IEC 61850 standards for them are considered, the principles of operation and construction of SCADA systems of digital substation are analysed, simulating the work of SCADA system at the substation in LabVIEW, allowing to exchange information between digital substations and remote stations and remove the control switch at the digital substation.

The results obtained in the work will be useful in the study of digital substations, their generation and principles of operation.

REFERENCES

(Ackermann et al. 2001) Ackermann, Thomas; Andersson, Göran; Söder, Lennart, "Distributed Generation: A Difinition", Electric power systems Research (Elsevier), Vol.57, 2001, pp.195-204.

(C. Purushotham et al. 2015) C. Purushotham, H. Chandrasekhar, "SCADA Based Advanced Data Monitering System", International Journal of Conceptions on Electrical and Electronics Engineering Vol. 3, Issue. 2, ISSN: 2345 – 9603, August;2015

(C. Singh et al. 2010) C. Singh and A. Sprintson, "Reliability assurance of cyber-physical power systems," in Power and Energy Society General Meeting, 2010 IEEE, pp. 1-6

(Drew Baigent et al. 2016) Drew Baigent, Mark Adamiak, Ralph Mackiewicz, "Протокол МЭК 61850 Коммуникационные сети и системы подстанций Общий обзор для пользователей", pp.5-6

(Hank Miller et al. 2014) Hank Miller, John Burger, "Modern Line Current Differential Protection Solutions", Published in Line Current Differential Protection: A Collection of Technical Papers Representing Modern Solutions, American Electric Power, 2014, pp. 01.

(IEC 61850 2015) IEC 61850 - Communication Networks and Systems in Substations, 2015.
Available at:
http://domino.iec.ch/webstore/webstore.nsf/searchview/?SearchView=&SearchOrder=4&SearchWV=TRUE&SearchMax=1000&Query=61850&submit=OK

(J. Scott Cooper 2013) J. Scott Cooper, Power test conference ,Massachusetts Ave. NE Saint Petersburg, "Understanding Transformer Differential Protection", 2013, pp.1

(Li Xiaohua et al. 2003) Li Xiaohua, Yin Xianggen, Zhang Zhe, Chen Deshu, "A New Novel of transverse differential protection Scheme", International Conference on Power Systems Transients – IPST 2003 in New Orleans, USA, 2003, pp.1

(Nick Massa 2008) Nick Massa, "Fundamentals of Photonics", Springfield Technical Community College, Module 1.8, Springfield, Massachusetts, 2008, pp.319-331.

(R. Barillere 1999) R. Barillere, "Results of the OPC Evaluation done within the JCOP for the Control of the LHC Experiments", Proceedings of the International Conference on Accelerator and Large Experimental Physics Control Systems, Trieste, 1999, pp.511.

(RMG 29-99 2009) RMG 29-99. State system for ensuring the uniformity of measurements. Metrology. Basic terms and definitions, 2009
Available at:
http://www.news.elteh.ru/arh/2009/56/12.php

(Roger Moore et al. 2010)	Roger Moore, Rugged Com, 2010 (Canada) and Maciej Goraj, Rugged Com, (Spain) "Ethernet for IEC 61850", September 2010, pp.2.
(Terrence Smith et al. 2011)	Terrence Smith, Craig Wester, "Fully Monitoring Protection and Control Systems", Texas A&M Protective Relay Conference, 2011.
(T. von Hoff et al. 2003)	T. von Hoff and M. Crevatin, "HTTP digest authentication in embedded automation systems," in Proc. IEEE Int. Conf. Emerging Technologies for Factory Automation (ETFA'03), vol. 1, 24 November 2003, pp. 390–397
(W.J. Ackerman et al. 2002)	W.J. Ackerman, "Proceedings of International Conference on Power System Management and Control", USA, 2002, pp. 445 – 450.
(Yuri Davidyuk 2010)	Yuri Davidyuk, "SCADA-systems at the upper level of the Automated Control System", June 2010, pp 2-3
(Алексеев Б.М. 2010)	Алексеев Б.М., "Ремонтировать перепуск на стороне между линиями" ,2010, Available at : http://locus.ru/energostyle/?reference=energostyle
(Андреев А.Н. 2017)	Андреев А.Н., "Релейная защита: Конспект лекций", 2017. Часть 1, 2017, pp.31
(Андреев К.Е. 2013)	Андреев К.Е., Школа для электрика, 2013. Available at: http://electricalschool.info/main/visokovoltny/1261-jelegazovye-vykljuchateli-110-kv-i-vyshe.html
(Антон Канарейкин 2014)	Антон Канарейкин,"Цифровые подстанции в России: процесс пошел", journal "Энергетика и промышленность России" \№ 10 (246) май 2014. Available at : https://www.eprussia.ru/epr/246/16072.htm
(Бунден Д.С. 2014)	Бунден Д.С., "Дистанционная защита линий", 2014, Available at : http://electricalschool.info/main/elsnabg/1070-distancionnaja-zashhita-linjj.html
(Вараксин Э.В. et al. 2017)	Вараксин Э.В., Щигло Е.В., Окуленко А.Р., "Разновидности и особенности конструкций самонесущих изолированных проводов для воздушных линий электропередач", 2017 Available at : https://studopedia.org/4-95784.html
(Виталей П.Р. 2005)	Виталей П.Р., Релейная защита и автоматика, "Микропроцессорные терминалы защит и автоматики ABB", 2005. Available at :

	http://electricalschool.info/relay/1571-mikroprocessornye-terminaly-zashhit-i.html
(Дамееров А.П. 2015)	Дамееров А.П.,"Дистанционная защита линий", 2015, pp.2 Available at : http://pue8.ru/kabelnye-linii/548-vols-osnovnye-kharakteristiki-i-sfery-primeneniya.html, © AdMe.ru
(ИЦТЕЛЕКОМ-СЕРВИС 2017)	ИЦТЕЛЕКОМ-СЕРВИС (Информационные технологии Искусство интеграции Обратная связь), "волоконно-оптические линии связи", 2017. Available at : https://www.tls-group.ru/services/sistemy-tsod/struktur-kab-sistem/vols/
(*ИЦТЕЛЕКОМ-СЕРВИС 2017)	*ИЦТЕЛЕКОМ-СЕРВИС (Информационные технологии Искусство интеграции Обратная связь), "ВОЛС. Основные характеристики и сферы применения", 2015. Available at : http://pue8.ru/kabelnye-linii/548-vols-osnovnye-kharakteristiki-i-sfery-primeneniya.html
(Локус 2016)	ОАО Локус, электроэнергетическая компания "Вакуумные выключатели 10 кВ", 2016, Available at : http://locus.ru/energostyle/?reference=energostyle
(«ПРОФОТЕК» 2017)	«ПРОФОТЕК» профессиональные волоконно-оптические технологии, "Трансформаторы тока электронные оптические", 2017. Available at : http://www.profotech.ru/products/206/
(Олифер В.Г. et al. 2010)	Олифер В.Г., Олифер Н.А. Компьютерные сети. Принципы, технологии, протоколы: Учебник для вузов. 4-е изд. – СПб.: Питер, 2010.
(Шаббад М. А. 2013)	Шаббад М. А., Расчеты релейной защиты и автоматики распределительных сетей. – Л.: Энергоатомиздат, Москва, 2013, pp.5-7.
(ЭЛЕКТРОСАМ 2018)	ЭЛЕКТРОСАМ, Электрика и электрооборудование, электротехника и электроника, "Система АСКУЭ. Что это и как работает. Электронный счетчик", April,2018. Available at: https://electrosam.ru/glavnaja/jelektrooborudovanie/jelektropitanie/sistema-askue/