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Digital Power Industry

A professional training course in English

TOMSK POLYTECHNIC UNIVERSITY

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Recommended for publishing as a study aid
by the Editorial Board of Tomsk Polytechnic University

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Tomsk Polytechnic University Publishing House
2020

МИНИСТЕРСТВО НАУКИ И ВЫСШЕГО ОБРАЗОВАНИЯ РОССИЙСКОЙ ФЕДЕРАЦИИ
Федеральное государственное автономное образовательное учреждение высшего образования
«НАЦИОНАЛЬНЫЙ ИССЛЕДОВАТЕЛЬСКИЙ ТОМСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ»

Цифровая энергетика

Профессиональная подготовка на английском языке

Рекомендовано в качестве учебного пособия Редакционно-издательским советом Томского политехнического университета

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Издательство
Томского политехнического университета
2020

УДК 811.111’243(075.8)
ББК Ш143.21–923
Ц752

Ц752 **Цифровая энергетика. Профессиональная подготовка на английском языке:** учебное пособие /сост. Н.Л. Бацева, И.А. Чеснокова, В.Я. Ушаков, Д.С. Никитин. – Томск: Изд-во Томского политехнического университета, 2020. – 111 с.

В пособии представлены задания, выполняемые индивидуально – работа с поддерживающие тексты, самотестирование и групповые задания – подготовка к решению кейсов, деловых игр. Изложены материалы, способствующие организации научно-исследовательской работы студентов на английском языке для написания докладов на конференции.

Предназначено для аудиторной работы на английском языке магистрантов, обучающихся по образовательной программе «Цифровая энергетика».

УДК 811.111’243(075.8)
ББК Ш143.21–923

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Unit 1. Renewable energy sources and digital power engineering

Introduction

The use of fossil fuels for power production must be reduced to the level of sustainability, which means that alternative sustainable and environmentally responsible methods must be investigated and commercialized. Due to the rapid growth of energy consumption and impossibility of its artificial limitation on the global scale, even in the face of the global threat of “greenhouse effect” and depletion of nonrenewable energy resources, we are forced to solve immediately the problem of unconventional renewable power sources (URPS) utilization.

The term URPS is used for solar, geothermal, wind and tidal sources as well as for small river, biomass, sea wave, and natural temperature gradient sources. (The term “unconventional” means that it does not include powerful hydropower plants built on large rivers). The development of URPS is especially important for Russia and some other countries, which have vast territories and low population density, in order to supply the latter with electric energy [1-4].

Developed countries have embarked on the path not only of the development of URPS, but of the power engineering digitalization. Digitalization is especially relevant for distributed generation based on the use of URPS, since they are characterized by a large temporal variability and regime instability.

This transfer has been approved at the government level. The deadline for completing this work is 2030. Huge investments are required for such a radical modernization of the power engineering, but its positive effects will be equally widespread:

– there will emerge opportunities for the use of new equipment and new approaches that will allow consumers to provide electricity supply services in a more comfortable mode,
– speed, reliability and cost of work will radically change, which will ensure the saving of both labor resources and money.

It is expected that digitalization of power engineering will provide the same high-quality information leap that IT technologies once gave.

The Digital Power Engineering Program, as a part of the Digital Economy, provides for the solution of the following problem: the use of digital technologies in the power engineering based on the principles of economic feasibility and increasing the availability of energy infrastructure and distributed electrical power engineering. Digital power engineering is the result of the digital transformation of the traditional fuel and energy complex, based on the use of new technologies for data collection and processing, with the target of increasing the efficiency of the complex participants.

1.1. Electric power engineering based on unconventional renewable power sources (URPS)

The humanity has made a great progress in utilization of URPS in the last 15–20 years. As a result, due to large capital investments in this branch and legislative and political acts adopted by many countries on the intergovernmental level, the development of systems based on URPS has progressed from research and development to industrial and commercial usage. It must be noted that there are severe geographical, technical, and economic limitations on the application of URPS. Nevertheless, today considerably powerful power plants are developed which use this type energy sources (see Table 1.1).

Table 1.1

The most powerful power plants and individual power units using renewable energy

Type of Power Plant/Power unit	Power, MW	Cost, mln $	Firm-Producer, Country
Land Wind Power Station (comprising 421 individual power units)	735		Horse Hollow Wind Energy Centre, USA.
Offshore Wind Power Station	209	670	Denmark
Tidal Power Station («Rance»)	240	134	France
Tidal Power Unit («Sea Gen»)	1.2	6	Ireland
Solar Power Station (thermodynamic cycle)	392	2200	Ivanpah Solar Electric Generating System, USA
Solar Power Station (photovoltaic)		520	Spain
Geothermal Power Station	100		USA
Biomass Power Station	240(elec.)+160 (therm.)		Finland
Wave Power Station (comprising 3 turbines/units)	2.25	1.3	Aqcadoura Wave Farm, Portugal

Progress in the creation of reliable, technically perfect, and economically efficient electric power units based on utilization of URPS and ensuring simple operation will allow decreasing the cost of a unit of generated power (see Table 1.2).

Table 1.2

Material and labor consumption for building and operation of electric power units of the indicated types

Power plants using various primary energy sources	Material consumption of the power unit, rel. units	Total labor consumption for building and operation of a power unit, rel. units
Natural gas	1.0	1.0
Oil	2.2	1.6
Coal	3.2	2.0
Nuclear power engineering	5.6	2.8
Solar energy: heating photo-conversion	 62.5 109.4	 40.0 140.0
Hydraulic power	62.5	–
Wind energy	250.0	72.0

Exercises

1. Answer the following questions:

1) What are the major aspects of the fast increase of the energy consumption?

2) What is implied by “nontraditional renewable energy resources”?

3) What is the main difference between nonrenewable and renewable energy sources?

4) Why is it necessary to expand the use of renewable energy? What is the current trend?

5) What are the main renewable energy sources?

6) Which countries are the leaders in the use of renewable sources?

7) What impedes the expansion of renewable energy?

2. Watching

1) Watch the video “Germany’s Renewable Energy Revolution” in the e-learning course;

2) Find the main idea of the video;

3) Watch the first 2 minutes of the video and fill in the gaps in the video script:

Germany’s Renewable Energy Revolution

Germany is in _______________. One of the world’s largest economies is pursuing an ambitious goal _____________ to renewable energy. With a complete transformation of its energy infrastructure the German energy market is entering a new age. Intelligent ideas, resolute action and political will have made Germany of front runner. Since the early 1990’s both companies and citizens have been investing in solar, wind and bioenergy

____________________. These investments are supported by an attractive and stable legal framework. Germany's energy revolution is well underway and moving forward with great momentum. More than 1.5 million renewable power plants have been _______________ in Germany over the past 25 years. A world record! Renewables now produce over 27% of the electricity _____________ in Germany. But this is just the beginning. Germany's energy transition is pursuing ambitious goals. It is planned that by 2050 the __________ of greenhouse gas will have been reduced by 80% to 95%. To achieve this _____________ will be reduced by 50% and at least 80% of electricity will come from renewables. Offshore wind, onshore wind and solar are the future pillars of Germany's ____________________. Sun and wind are fluctuating energy sources. Variations in __________________ caused by the weather must ______________. This means integrating renewable energy into the energy infrastructure is the main challenge.

4) Study the presentation in e-learning course.

1.1.1. Harnessing water flow of small rivers and other streams energy

The indisputable advantages of hydraulic power engineering are:

- renewable water-power resources;
- widespread small rivers (unlike large rivers);
- low production cost of electric energy;
- inflation stability;
- environmentally-clean manufacturing.

There are three classes of HPP on small rivers:

- stations with capacities smaller than or equal to 100 kW are called micro HPP;
- from 100 to 1000 kW – mini HPP;
- from 1000 to 10000 kW – small HPP.

Historically, the first HPP were *micro* HPP, and their development was synchronous with successes in industrial production of electric generators. These simplest often half-handicraft systems were widespread, especially in rural regions. The rapid development over the decades of energy *production using fossil fuels (including uranium) and energy of large rivers* significantly reduced interest in small hydropower. Many small HPP were abandoned in the 1950's and 60's when the price of oil and coal was very low, and their environmental impacts unrealized. Due to the achievements in the field of computerized control systems, electric machine building and semiconductor and transformer engineering, increase in the cost of fossil fuels and tightening of requirements for environmental protection, interest in small power engineering has revived.

Exercises

1. Answer the following questions:

1) What are the advantages and disadvantages of micro- and mini- hydropower plants?

2) Briefly describe operating principles, advantages, disadvantages, and the current state of a storage power station (a pumped storage plant).

3) Why were small hydropower plants disregarded in the middle of 20th century?

2. Translate the following English word combinations into Russian:

1) hydroelectric facilities;
2) hydroelectric power plants;
3) high water periods;
4) low head turbines;
5) widespread small rivers;
6) low production cost of electric energy.

3. Watching

1) Watch the video "Hydropower PP (Hydropower or hydroelectricity)" in the e-learning course;

2) Find the main idea of the video;

3) Fill in the gaps in the video script:

Hydropower PP (Hydropower or hydroelectricity)

Hydropower or hydroelectricity refers to the ________________________ from flowing water into electricity. It is considered a renewable energy source because the water cycle is constantly renewed by the Sun. One of the first uses of hydro energy was for mechanical milling, such as ____________________. But today modern hydro plants produce electricity using turbines________________. The mechanical energy created by moving water spins rotor of a turbine. This turbine is connected to an electromagnetic generator, which produces electricity when the ___________spins. There are two main types of hydroelectricity production - _____________. Hydro dams utilize the ____________________ from dammed water to produce __________________. A dam is a large barrier constructed to raise the level of water and control its _______________. The elevation created by the dam creates _______________________________force for turning the turbine when water is released. Some dams also contain an additional reservoir at their base where water is ________________to be pumped to the higher reservoir for release when electricity is in _____________. This is referred to as pumped-storage hydro. The second form of hydroelectricity production is run of river hydro. Runoff river still uses turbines and generators but relies on natural water flow rates of rivers, diverting just a portion of the water through turbines. Because run of river hydro is subject to natural water __________________ it is more intermittent than dammed hydro. There are various sizes of hydro plants that produce electricity. Large hydro greater than 30 megawatts, small hydro 100 kilowatts to 30 megawatts, and micro hydro less than 100 kilowatts. The Hoover Dam in the United States is a whopping 2074 megawatts, which is enough to _____________ 1.3 million people. Of all renewable energy sources hydropower holds the largest share of worldwide electricity production. Hydropower has several _____________. It is a cost competitive form of electricity even though the initial building cost can be high. It is quite _____________ compared to other renewable options and pairs well with other sources as it can be used as base _________________. In some cases, dammed reservoirs can also help with______________ and be a reliable water supply for communities. There are also some concerns with hydropower - especially when it comes to large dams. ________________a river has a major _______________on the local environment changing wildlife habitats, blocking fish passage, and often forcing people in riverside communities to move out of their homes. In addition, dam ___________________can be catastrophic, claiming the lives of those living downstream. Hydro plants are also not completely free of _________________gas emissions. As with most forms of energy ________________ emissions happen during construction particularly due to the large quantities of cement used, and plant matter in the flooded areas makes ______ another greenhouse gas as it decays underwater.

4) Study the presentation in the e-learning course.

1.1.2. Bioenergetics

Bioenergetics can be considered as a branch of solar power engineering based on photosynthesis and subsequent release of chemical energy accumulated in biomass, which is converted into electric or thermal energy. Biomass is the cheapest and largest-scale form of renewable energy accumulation. The term *biomass* involves any material of biological origin, including products of vital activity and organic wastes. Of special importance is *peat* – one of the materials of biological origin. (Sometimes it is called *accumulated biofuel).* Peat is often referred to non-renewable energy resources due to a very low rate of recovery of its reserves. Modern peat deposits were formed 10–12 thousand years ago [5].

In developed countries, to generate heat and electricity by direct combustion of wood, wood waste, straw, and peat mini-CHPPs (combined heat and power plant) are used. In the steam turbine version, the efficiency is 20–25 % and power changes from a few kilowatts (for farmers) to hundreds of kilowatts.

As for the methods of obtaining gaseous and liquid fuels from biomass, three of them should be mentioned.

First, bioconversion is used, that is, decomposition of organic substances of vegetative and animal origin under anaerobic (without access of air) conditions by special bacteria with the production of gaseous fuel (biogas) and/or liquid fuel (ethanol, butanol, etc.).

Second, thermochemical conversion is used (pyrolysis, gasification, fast pyrolysis, and synthesis) of solid organic substances (tree, peat, and coal) into a synthetic gas, methanol, artificial gasoline, and charcoal.

Third, combustion of wastes in special boilers and furnaces is used. Hundreds tons of such wastes are burnt with regeneration of energy all over the world. The calorific values of pressed fuel bricks from paper, cardboard, wood, polymers, sawdust, and garbage are comparable with the calorific value of brown coal.

The use of *secondary resources* – agricultural waste and wood processing, combustible household waste and industrial waste has obvious advantages over the use of primary biological resources (primarily wood, food, and feed crops):

– no threat to the biological balance;
– improvement of the environment;
– no increase of food prices as is the case of a large-scale use of food and feed grains in bioenergetics.

In developed countries, to generate heat and electricity by direct burning of firewood, waste wood, straw, and peat a mini-power plant (mini-TPP) is used. In the embodiment of a steam turbine, their efficiency is 20–25 %, power from a few kilowatts (for farmers) to hundreds of kilowatts.

Increased efficiency and lower operating expenses have automatic boilers that require pre-treatment before combustion of biomass: the manufacture of wood pellets, wood chips, and briquettes.

Pellets are 20–50 mm granules from dried wood waste manufactured under high pressure without chemical fixers. A unit energy cost in this case is approximately 30 % lower than that of diesel fuel or natural gas.

In EU the annual growth in the production of pellets is about 30 %.

Energy chips are 10 to 150 mm long and 10 to 100 mm thick. Often chips are burned with sawdust, which allows recycling waste and improving fuel consumption by about 20 %.

Briquettes are made from timber waste, straw, tops, etc. Their sizes and shapes are different: rectangular, cylindrical; size – from meters to centimeters (depending on the type of boiler and biomass). Their calorific value is close to that of coal.

The reserves of one more energy source – *peat* – are also significant.

World peat reserves are estimated at more than 500 bln tons (by 25 % moisture content, they amount to 225–261 bln tons). The area of peat deposits in the world accounts for 176 mln hectares. Deposits of peat are found on all continents.

Because of low calorific value, peat has not yet found wide application in electric power engineering.

Exercises

1. Answer the following questions:

1) What refers to bio-resources?
2) Name the method of using bio-resources in the energy sector.
3) What limits the use of peat in the energy sector?

1.1.3. Wind power plants

Wind energy has long been used in navigation and for turning round mill wheels. In recent years (from the early 70s), it has been utilized for electric power generation. The potential electric power from wind energy is surprisingly large. The technology under development today will be capable of producing electricity economically from good wind sites in many regions of the world. Detailed wind resource assessments have been proposed or are being considered as part of a plan to increase the use of wind energy in Europe, Asia, Latin America, Australia and other regions.

The first wind power plants (WPP) had a capacity mostly of a few kW. Now the most widely used are wind generators with a capacity of 2 MW, operating mainly as part of power systems. The cost of electric energy generated by WPP is still higher than that generated by TPP on mineral fuel. As the power of a single wind power installation increases, the cost of the energy produced decreases. (Recently, the Holland Company HAIADE-x launched a wind turbine with record-breaking parameters: power – 12 MW, height – 260 m, blade length – 107 m, weight – about 10 thousand tons).

It can be easily shown that the unit output power is proportional to the area of wind rotor blades and to the cube of wind velocity (usually low). In this regard and due to the fact that the density of air is 846 times less than the density of water, the overall dimensions of WPP should be very large compared to hydraulic turbines. The diameter of a wind wheel of powerful wind generators (in megawatt range) is several tens of meters. The most important drawback of WPP that they generate electric power only when the wind blows rather than when required. This drawback of WPP, which is especially relevant for power supply of individual consumers, is mitigated in two ways: 1) with excess electricity it is used for hydrogen production by electrolysis of water or accumulated in batteries, 2) consumers are supplied with electricity from other sources (for example, from diesel generators) or from batteries. At present the annual rate of growth of wind power exceeds 25 %.

Thus, by the present time, the world wind power engineering has turned into the branch of electric power engineering making significant contribution to electric power generation in some countries. Russia is actually taking the first steps towards the development of powerful wind power engineering. The decreasing cost of wind power and the growing interest in renewable energy sources should ensure that wind power will become a viable energy source worldwide.

Exercises

1. *Find in the text synonyms to the following words:*

a) appropriate	d) to appreciate
b) fruitful	e) to suggest
c) limitation	f) unprotect

2. *Match English expressions to their Russian equivalents:*

1) wind energy application	a) энергия ветра
2) wind power	b) оценка ветроэнергетических ресурсов
3) mean wind power density	c) высота гондолы ветроагрегата
4) advanced wind turbine technology	d) средняя плотность энергии ветра
5) turbine hub height	e) передовая технология разработки ветроагрегатов
6) wind resource assessment	f) применение энергии ветра

3. Answer these questions:

1) What are the advantages and disadvantages of wind power plants?
2) What countries lead in the development of wind power plants?
3) What is the maximum power of existing wind turbines?

1.1.4. Solar power engineering

The Sun is the source of all types of energy produced on Earth. People have long considered and consider utilization of solar energy to produce commercially electric energy, hot water, and vapor [6].

At present, solar power plants (SPP) of two different types, distinguished by methods (thermodynamic and photoelectric) of solar energy conversion into electric energy, are built and are in service.

In the first case, solar radiation is converted into heat with rather high potential, then into mechanical energy (in a turbine or other heat machine), and finally into electric energy by a generator). The photoelectric method is based on direct conversion of photon energy into energy of current carriers in irradiated semiconducting photoelectric pickoffs called the photoelectric effect.

Now silicon photocells illuminated by both direct solar rays and scattered light have the best characteristics. The efficiency of silicon photocells increases as temperature decreases, that is, they can successfully operate in both winter and summer. In winter, the decrease of the light flux is compensated by the increase in their efficiency.

Despite the radical difference in the methods of energy conversion, solar thermal (STPP) and solar photovoltanic power plants (SPVPP) have a number of properties and limitations in common caused by the nature of the employed power source. Solar radiation as a power source, in addition to such positive properties as practically unlimited resources, total eco-friendliness, and its accessibility everywhere has also negative properties including *low density (specific power) of solar radiation* (no more than 1 kW/m^2 on the Earth's surface) *and objective (daily and seasonal) and random (caused by weather conditions) time variations.*

Already implemented and only developing ideas can simultaneously reduce the impact of shortcomings in the development of solar power engineering.

It is expected that *the efficiency of the conversion of solar radiation into electric power* will sufficiently increase. Now the efficiency of solar energy conversion by single crystal cells is 11–12 %; 16 % maximum efficiency has been reported. Solar cells (photoelectric converters) can be improved in different ways.

According to the forecasts of the International Energy Agency (IEA), by means of solar energy about 5 thousand TWh of electricity will be produced to 2050, which is approximately 12 % of the needs of all humanity. Undoubtedly, interest in utilization of solar energy – the main energy source – will further increase, and a real of its application will expand.

Solar energy is developing at a moderate pace. In a number of regions favorable for this, solar power plants are being built.

Exercises

1. Answer these questions:

1) What are the main applications of solar energy in the energy sector?
2) What are the advantages and disadvantages of solar energy?
3) What are the principal reasons for power supply of the Earth's regions by means of mirrors or orbital power stations?
4) What could the Sun provide for the humanity nowadays?
5) What are the problems associated with solar progress?

2. Translate the following English word combinations into Russian and explain their meaning:

1) Thermodynamic and photoelectric methods of solar energy conversion into electric energy;
2) The photoelectric effect;
3) The efficiency of silicon photocells;
4) Daily and seasonal variations of solar radiation.

1.1.5. Other unconventional renewable energy sources

Other unconventional renewable energy sources include those that are not yet used or are used on a very limited scale [7]. This is due to several reasons: 1) the high cost of the electricity they produce, 2) availability in a limited number of regions of the world, 3) remoteness from the main energy consumers, 4) low efficiency of the transformation of primary energy into electricity and some others. We attribute to "others" the following unconventional renewable energy sources and, accordingly, PP: tidal power plants; wave power plants; geothermal power plants; ocean and sea currents energy; thermal energy of ocean and sea water; osmotic energy. Power plants using the last two types of renewable energy today can be viewed as exotic and, therefore, are not considered in this Tutorial. (We recommend those wishing to learn about the technologies of using these two types of renewable energy sources in the energy sector watch the video).

1.1.5.1 Tidal power plants (TdPP)

The potential of electric power generation from tidal currents is enormous [8]. There are a huge number of witty projects of tidal equipment. Nowadays, several demonstration projects in tidal power are scheduled to capture the tidal generated coastal currents. The advantage of TdPP over HPP is that their operation is governed by space phenomena and is independent, unlike HPP, of numerous random weather conditions.

However, TdPPs have two significant disadvantages, namely, irregular operation and large volume of investments.

The irregularity of tidal energy within a lunar day and a lunar month that differ from solar ones does not allow TdPP to be used systematically during periods of maximum loading in power systems. The irregularity of TdPP operation can be compensated by their combination with pumped storage power plants (PSPP). When there is an excess output power of tidal power stations, PSPP operate in the pump mode consuming this excess power and pumping water to the upper reservoir. During periods of minimum output power of TdPP, PSPP operate in the generation mode supplying electric power to the system. This project is technically acceptable but expensive, because large installed capability of electric machines is required.

TdPP can also be combined with river HPP having a storage reservoir. When these stations operate together, HPP increase their output power when the output power of TdPP decreases or when they are stopped; when TdPPs generate sufficiently high power, PSPP pump water to the storage reservoir. Thus, both daily and seasonal irregularity of TdPP operation can be compensated.

Work cycle of the simplest (traditional) TdPP includes filling the pool with water during high tide through holes in the dam, the turbine and connected to it the electric generator at low tide when the water pressure becomes sufficient.

Today construction of TdPP is considered cost-effective in areas with tidal fluctuations in the water level of at least 4 m. It is possible to increase efficiency of TdPP through the use of turbines, working during both high tide and low tide. Such TdPPs are able to generate electricity continuously for 4–5 h with intervals of 1–2 h four times per day. To increase the operating time of the turbine, there are more advanced schemes – with two, three and more pools, but the cost of these projects is very high.

TdPPs operate under conditions of fast turbine head change; therefore, their turbines must have high efficiency at variable heads. A rather good compact horizontal double-flow turbine is now in the market. An electric generator and some parts of a turbine are enclosed in a watertight capsule, and a hydraulic unit is immersed in water. Rotating vanes of the turbine provide high efficiency at different heads starting from 0.5 m. The hydraulic unit can operate both in generation and pump modes. When the generator is switched off, the hydraulic unit can pump water directly from the sea to the reservoir and back; in the pump mode, it can pump water from the sea to the reservoir and, thus, increase the head.

Long-term scientific investigations have led to a conclusion that of interest is construction of a few TdPP, rated from several hundred to several thousand MW. Some powerful TdPP operate at present.

Exercises

1. Translate the following English word combinations into Russian:

– sea and ocean tides
– annual output
– a single tidal basin
– tide races
– new tidal generation capacity
– tidal range
– estuary of the river

2. Find the corresponding English sentences in the text:

1) Энергия приливов обладает важными преимуществами по сравнению со многими другими возобновляемыми источниками энергии.

2) Приливные электростанции эффективны только там, где высота прилива не менее определенной высоты.

3) Гидроагрегат приливной электростанции может/должен попеременно работать в режиме турбины или насоса.

4) Существуют режимные мероприятия повышения эффективности работы приливной электростанции.

3. Retell the text.

4. Watching

1) Watch the video "Tidal PP (Tidal power)**"** in the e-learning course;
2) Find the main idea of the video;
3) Fill in the gaps in the video script:

Tidal PP (Tidal power)

Tidal power is a form of ___________________ that converts the energy from the natural rise and fall of the tides into electricity. Tides are caused by the combined effects of _______________ forces exerted by the moon the Sun and the rotation of the earth. Tidal plants can only be installed along _______________. Coastlines often experience two high tides and two low tides on a daily basis. The difference in water levels must be at least five meters high to produce electricity. Tidal electricity can be created from several ______________. The main ones being tidal barrages, tidal fences, and tidal turbines. Tidal barrages are the most efficient tidal energy sources. A tidal barrage is a_________ that utilizes the potential energy generated by the __________ in height between high and low tides. This energy _______________a turbine or compresses air which in turn creates electricity. Tidal fences are turbines that operate like giant turnstiles whereas tidal turbines are similar to __________________only under water. In both cases electricity is generated when the mechanical energy of tidal currents turns turbines connected to a ______________. The generator produces electricity. Ocean currents generate relatively more energy than air currents because ocean water is 832 times more ______________ than air and, therefore applies greater force on the turbines. Tidal power is easy to install and renewable, having no direct ______________emissions and a low ______________ impact. Because the oceans tidal patterns are well understood tidal energy is a very ________________ energy source making it highly ___________ for electrical grid management. This sets it apart from other renewables that can be more unpredictable. However adoption of tidal technologies has been slow and so far the amount of power generated using tidal power plants is very small. This is due largely to the very specific site requirements necessary to produce tidal electricity. Additionally tide ___________ do not always match the daily _______________ patterns of electricity and therefore do not provide ___________capacity to satisfy demand.

4) Study the presentation in the e-learning course.

1.1.5.2. Wave power plants

A promising source of renewable energy is waves of the oceans, seas and large lakes that can develop the greatest specific power, among others renewable energy sources. Energy is stored in waves as both potential energy (in the mass of water displaced from the mean sea level) and kinetic energy (in the motion of the water particles). These waves in the future are able to provide up to 2 TW of electric power, enough to meet the needs of all humanity. With the present level of technology, wave power plants (WavePP) with a total capacity of up to 10 billion kWh can be created. There are over 1000 patents for varied designs of wave energy converters. However, only a few of them are suitable for practical implementation at the current level of technology development.

The trend in the development of WavePP as power plants using other energy renewable resources – a complex of single intermediate power modules (approximately 1 MW). A WavePP module has a size of about 50 m along the wave front. Complexes with hundreds of meters in size and the total capacity of tens of megawatts are often constructed of these modules. Low-power modules (tens of kilowatts) with a sufficiently broad consumer niche have been developed. As in the case of tidal energy, a number of technical solutions currently proposed and partially implemented can be divided into two groups according to the prevalence of kinetic energy or energy rolling surface, which is converted into electrical energy. By design, WavePP can be divided (rather conventionally) on the float – WavePP and chamber – WavePP. The principles of the float – WavePP work are shown in Figure 1.1.

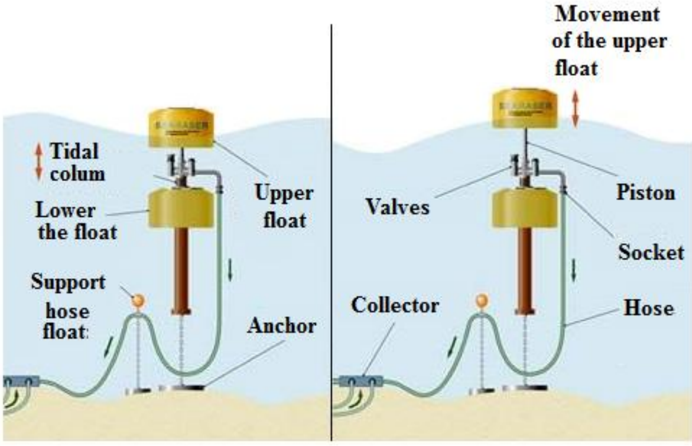

Figure1.1. The operation principle of the float – WavePP

There are two main types of the chamber – Wave PP. In one of them, the kinetic energy of the waves is used. In this embodiment, a receiving pipe of a very large diameter (in the general case, a chamber of a large cross section of any shape) is installed in the path of the waves. The incoming waves rotate the turbine, which drives the generator rotor. In the other type of the chamber – WavePP, tidal waves passing through a special chamber displace the air contained in this chamber. Compressed air under pressure rotates the turbine and rotor of the electric generator. It is expedient to connect such units in series to form a battery thereby creating a reliable and cheap source of high electric power.

Exercises

1. Translate the following English word combinations into Russian:

– relative motion
– shoreline
– in height
– to submerge
– incident wave
– to swing
– mean sea level
– wave power generation
– crest length
– axial-flow turbine

2. Answer the questions using the information from the text and other sources of information

1) How are waves formed and what do their parameters depend on (height, distance between crests, etc.)?

2) How many ideas for converting wave energy into electrical energy are suitable for practical implementation today?
3) What limits the growth rate of the contribution of wave energy to the world energy balance?
4) For which countries, in your opinion, wave energy can be of the greatest interest?

3. Retell the text.

1.1.5.3. Geothermal power plants

One of the largest sources of sustainable and environmentally friendly heat that can be used to generate electricity is geothermal energy. Unlike sustainable energy sources such as wind or solar, geothermal resources provide power stations 24 hours per day, and 365 days per year. It is not unusual to find a geothermal power plant with annual availability factors in excess of 98%, so load factor can be high, the supplied geothermal energy is some 3,5 times greater than for a wind power plant. This firmness in itself can be a considerable asset to the utilities. The eighties of the last century was the golden decade in the history of geothermal energy. During this period, the growth rate of worldwide installed capacity touched 14% per year, and averaged 8,5%.

However, due to the relatively low temperatures of the coolant (steam, hot water), the efficiency of geothermal power plants (GTPP) is only about 15%. It limits the economically acceptable lower limit of geothermal fluids that can be used in the energy sector. However, the projected increase in the cost of mineral fuel resources will shift this boundary down.

According to the methods of the Earth heat extraction, the following classification of geothermal systems is used, Figure 1.2.

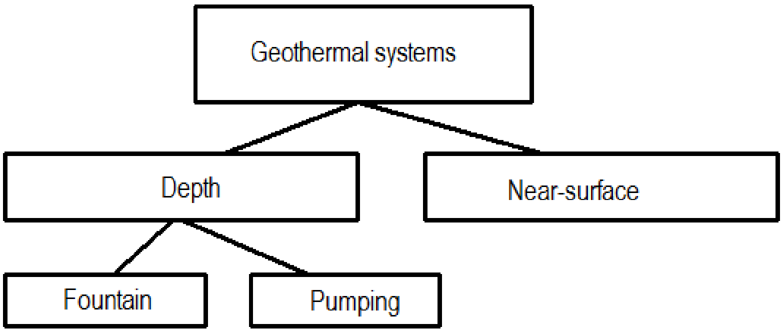

Figure 1.2 Classification of geothermal systems

It is well known that the temperature increases by about 1°C as the Earth's depth increases by 30–40 m. Therefore, water boils at depths of 3–4 km, and the Earth's temperature reaches 1000 – 1200°C at depths of 10–15 km. In some regions of our planet, the temperature of hot natural springs is sufficiently high even near the Earth's surface. These regions are most favorable for the construction of geothermal power plants (GTPP). Thus, GTPP generate 40 % of electric power in New Zealand, 6 % – in Italy.

The scheme of underground heat utilization is simple. Hot underground water produces vapor utilized in GTPP and other technical facilities. Vapor of the Earth's bowels, unlike steam produced by steam generators of TPP, contains impurities of different aggressive gases that destroy the equipment of stations. Therefore, vapor of bowels is either preliminary directed to heat exchangers to obtain pure vapor or special corrosion-resistant equipment is used. In the first case, about 25 % of heat is lost. The second method is considered as the most expedient now.

The base mode of operation is preferable for such GTPP, since wells allow no sharp changes in pressure and discharge.

The examined GTPP are geographically attached to natural springs of hot vapor and water; therefore, regions of their utilization are limited. GTPP on thermal water with the temperature in the range 100–2000°C can become more widespread; these GTPP should have two contours with a working agent of the secondary contour boiling at low temperatures.

The potential reserves of thermal waters with the above-indicated temperatures are concentrated in water stratums at depths of 2.5–5 km and provide the basis for the construction of GTPP with an aggregate capacity of a few million kilowatts (e.g., in the Northern Caucasus). However, whereas GTPP on natural springs of hot vapor and water are commercial facilities, GTPP on thermal water with the above-indicated potential require testing. Similar GTPP can also be combined with vapor hydrothermal GTPP to utilize the heat of separated water. It can increase electric power generation by ~20 %. The wells in fields of thermal water admit the discharge control; therefore, the output power of double-contour GTPP can be controlled without losses of the heat carrier.

In the distant future, high-temperature (up to 1000°C) mantle layers will produce vapor from water pumped to an artificially created volcanic mouth. Of course, the produced energy will be pure and will not influence the biosphere (the huge mantle mass eliminates the effect of heat taken away on the mantle state).

Exercises

1. Match English word combinations to their Russian equivalents:

1) geothermal development	1) устойчивые (стабильные) источники энергии
2) natural hot springs	2) темп роста
3) growth rate	3) развитие геотермальной энергетики
4) sustainable energy sources	4) природные горячие источники

5) load factors	5) влияние на окружающую среду
6) fossil fuel supplies	6) коэффициенты загрузки
7) environmental impact	7) запасы ископаемого топлива

2. Read the text above once again and make up a list of the key words and topic sentences.

3. Watching

1) Watch the video “Geothermal PP” in the e-learning course;

2) Find the main idea of the video;

3) Fill in the gaps in the video script:

Geothermal PP

Geothermal PP refers to producing energy from the _____________of the Earth. It is generated from radioactive decay of minerals and continual heat loss from the Earth's original formation. Geothermal ______________are drilled into the Earth's crust at approximately a depth of 3 to 10 kilometers. The heat is extracted with a variety of methods, but in most cases is drawn from the earth using _____________. Hot water from the Earth may be directly extracted to heat homes and buildings. This is done either by directly _____________the hot water through buildings, or by pumping it through a heat ____________ that transfers the heat to the building. Geothermal heat can also be used to produce electricity in a geothermal power plant. Electricity is generated when geothermal heat produces steam that turns ________________. The major regions of geothermal development are in the most volcanically and tectonic active regions of the world. Though geothermal energy is currently a small player in the world's energy mix, one of its key advantages is its _____________ and ____________ power generation, which means it can provide base load electricity. Concerns with geothermal include the accidental release of CO2, and hydrogen sulfide emissions stored in the Earth's ______________ that is often used to carry geothermal heat to the Earth's surface. Additionally, drawing heat from the Earth's crust can, if done irresponsibly lower the ground temperature below the surface. The upfront costs for geothermal energy ______________ are relatively high. It is expensive to carry out the seismic sensing, test while drilling, confirmation testing, and other necessary ____________investigations to ensure that your new geothermal plant will be _____________ of meeting desired production.

4) Study the presentation in the e-learning course.

1.1.5.4. Ocean and sea currents energy

Global ocean currents, such as Gulf Stream, Curoshio Current, and Florida Stream transport water at rates of 83, 55, and 30 mln·m^3/s, respectively, with velocities of 2.0, 1.8, and 1.0 m/s and possess huge energy. From 1 m^2 of the cross sectional current area, capacity of about 1 kW can be obtained. Currents in Gibraltar, La Manche, and Kuril Straits as well as tidal currents are also of interest for power engineering.

One of the methods of conversion of this energy into electric one is implementation of the idea that combines two technical solutions – a wind-wheel and a tidal power station unit. This allows hybrid HPP operating in free running water to be built whose units have advantages of both wind-wheel and tidal power station:

1) They have much smaller water propeller sizes and hence, reduced material and labor consumption. To receive power of 1 MW, the aqueous two-blade propeller diameter should be about 18 m, and the propeller - about 55 m. The aqueous two-bladed rotor with a diameter of 1 m at a flow rate of 2 m/s can provide power of 7 kW.
2) Compared to TdPP and HPP, the unit of installed capacity for them is by about an order of magnitude cheaper (primarily, due to the absence of a dam).
3) They allow operational characteristics to be estimated much more correctly due to a better predictability of the sea current parameters in comparison with the wind parameters.
4) They do not spoil the landscape and the natural state of the coastal line. The hydro turbine (comprising a water propeller and an electric generator) is mounted on a completely submerged support and is lifted out of water only for repairing or servicing.

The world's first commercial electric PP of this type with a capacity of 1.2 MW has been connected to the National Electric Grids of Northern Ireland. The dual rotor turbine is used. Rotors of the turbine are 16 m in diameter and rotate with an optimal velocity of 14 rpm. The rotor blades are equipped with a control system and can rotate to change the angle of attack. Marine Current Turbine Ltd. that built this PP has already started a new project on building a PP with capacity of 10.5 MW at the coast of Northern Wales.

In the USA, the program Coriolis has been developed which envisages installation of 242 turbines in the Florida Strait; every turbine will be equipped with two driving wheels 12 m in diameter rotating in opposite directions. The whole system with total length of 60 km will be oriented along the main current; its width with turbines installed in 22 rows (11 turbines in every row) will be 30 km. The units will be submerged at a depth of 30 m not to interfere with navigation. The capacity of each turbine will be 400 kW, and the entire complex will generate about 100 MW.

Smaller projects for the use of oceanic and marine deep currents are being developed in several other countries.

Exercises

1. Answer the questions using the information from the text and other sources of information

1) What are the characteristics of the energy parameters of oceanic / sea currents?

2) What is the most efficient method for converting oceanic / sea currents energy into electrical energy?

3) What are the main advantages of oceanic / sea currents energy over other renewable energy sources?

4) What factors are holding back the widespread use of oceanic / marine energy in energy?

1.1.6. Prospective programs for the development of non-traditional renewable energy sources

These programs provide for the solution of a number of specific tasks, in particular:

– Binary geothermal power plants;

– Micro and mini hydroelectric power plants with equipment of unit capacity from 2 kW to 1 MW;

– Silicon-based photovoltaic cells with an efficiency of 14–15%, highly efficient (efficiency> 25%) heterostructural solar cells and power plants with concentrators of solar radiation;

– Solar power plants located in space on solar-synchronous orbits with the subsequent transfer to the Earth of electricity in the microwave range;

– New generation plants using biomass for power generation;

– Orthogonal wind turbines;

– Heating and hot water systems based on efficient fluid and air solar collectors.

1.2. Digital power engineering

1.2.1. The explanation of the concept of "Digitalization"

Leading industry research firm Gartner, defines digitalization in its IT Glossary as “the use of digital technologies to change a business model and provide new revenue and value-producing opportunities; it is the process of moving to a digital business”. This description truly captures the essence of what digitalization is and why it is so important for the power generation industry – and so challenging.

This new information technology completely redefines work processes, processes at the enterprise or park level, or entire business models, as it provides the opportunity to exchange important information in digital format.

Digitalization helps get the right information to users (and workgroups) that need it – at precisely the time they need it – to perform their tasks.

In its most basic sense, digitalization is the evolution from manual and paper-based processes to digital processes, enabled by the integration of information and operational technology (IT/OT) and analytics. This evolution is not a new phenomenon; it began decades ago as plant owners began digitizing piping & instrumentation diagrams, safety procedures and numerous other critical documents to make them easier to store and retrieve.

The digitalization must inherently leverage technology to access the information and distribute it to the people and systems that need it. Furthermore, when analytics are applied to the data, the value grows as actionable insight can be extracted from the data and presented in a format that is easily digestible and can be used to make rapid, informed, and most importantly, accurate decisions. In other words, it helps get the right information to users (and workgroups) that need it – at precisely the time that they need it to perform their tasks. As a result, digitalization can significantly decrease waste and increase wrench time for maintenance, operations and engineering functions. In addition, by enhancing the quality of data and inter-workgroup communications, digitalized operations can increase safety and reliability, reduce unexpected failure, and lead to higher capacity factors and operational excellence.

From the above, it follows that digitalization is an important catalyst for the expansion of the use of unconventional renewable energy sources and increasing the share of distributed generation in the structure of the electric power industry.

1.2.2. The main goals of power engineering digitalization

The development and implementation of the Russian Digital Power Engineering Program will contribute to solving a number of priority tasks:

– Creating conditions for updating production assets in the face of restrictions on tariff growth;
– Creating conditions for the integration of new technologies and the emergence of new business models;
– Improving transparency and simplifying oversight procedures;
– Harmonization of legislation and simplification of legal regulation;
– Development of government support measures for centers of competence;

– Formation of programs for the training and retraining of personnel for the power engineering;

Power engineers will have to introduce technologies and solutions for digital transformation based on a single information space:

– Systems for monitoring and managing the reliability of energy supply;
– Platforms for the collection, processing and use of "big data" (including scientific purposes);
– Forecasting planning (strategic and investment), as well as risk planning;
– Customer services for consumers;

By 2024 it is planned to get the following results:

– A multiple increase in the number of generation facilities and the network complex that exchange data in real time.
– Improving the level of technical condition, automation and network observability.
– Development of smart contracts.
– Introduction of robotic technology.

“Digitalization” is characterized by five features that distinguish it from “automation”, which has been widely used in the energy sector since the mass spread of computer technology.

1. The subject of Digitalization special attention is economic activity, commercial transactions and professional interactions built on new principles using information and communication technologies;

2. One of the main tasks of digital power engineering is to radically reduce the rapidly growing costs of market transactions by displacing machines with inefficient, requiring routine human involvement, operations. Due to these trends, the large costs of integration, coordinated work and commercial interaction of millions of new participants in energy markets can be drastically reduced with the help of digital technologies and platforms;

3. Digitalization involves the creation of a new business model of the interaction of economic entities and the use of digital models that combine the physical and digital worlds. Such a combination is possible when smart machines begin to form and use digital models of the physical world, which ensures independence of decision-making by machines in a close mode to real time;

4. Digitalization is the emergence of a new type of activity with a large share of scientific, technical, artistic, social creativity;

5. Digitalization of energy is a new qualitative leap in the industry, which consists, first, in changing the ways of organizing economic relations, and leading to the effective involvement in the turnover of millions of new entities and the smart machines behind them. Digitalization in the first place will not be subject to technical systems and internal business processes, but

to relations between people, companies and institutions. In this, it is radically different from the automation of production, technological and managerial processes, which is the greatest achievement of the second half of the 20th century. Automated process control systems of power plants, dispatch control systems, automation of active energy devices, accounting and office automation systems – all these are important and relevant directions for the evolutionary development of the industry.

The global data will be more 163 zeta bytes ($1.63.10^{23}$ bytes) by 2025; about 30 billion devices are connected to exchange information by the beginning of 2020.

Unit 2. Smart substations

Introduction

Throughout the developed world, the electric utility sector is beginning a fundamental transformation of its infrastructure to overcome the present challenges faced by the sector. These transformations are aiming to make the grid "smarter" and the resulting outcome is referred to as a "smart grid". The Energy Independence and Security Act of 2007 (EISA 2007, USA) stated that a smart grid is "the modernization of the Nation's electricity transmission and distribution system to maintain a reliable and secure electricity infrastructure that can meet future demand growth".

Current transmission and distribution grids were not designed with a smart grid in mind. They were designed for the cheap, rapid electrification of the country or region. The requirements of a smart grid are quite different and, therefore, reengineering of the current grid is imminent. This engineering work will take many forms including enhancements and extensions to the existing grid, inspection and maintenance activities, preparation for distributed generation and storage, and development and deployment of an extensive two-way communication system.

The "heavy metal" electric delivery system of transmission lines, distribution feeders, switches, breakers, and transformers will remain the core of the utility transmission and distribution infra-structure. Many refer to this as the "dumb" part of the grid. While some changes in the inherent design of these components can be made, the "smarts" in the T&D (Transmission and Distribution) system are related to advances in the monitoring, control, and protection of the "dumb" equipment. Substations, therefore, play an essential role as the operational interface to the T&D equipment in the field. Advances in technology over the years and the introduction of microprocessor-based monitoring, control, protection, and data acquisition devices have made a marked improvement in the operation and maintenance of the transmission and distribution network. However, changes in the way the T&D system is utilized and operated in a smarter grid will create significant challenges. Substations in a smart grid should move beyond basic protection and traditional automation schemes to bring complexity around distributed functional and communication architectures, more advanced local analytics, and data management.

Thus, the development of a "smart grid" plan leads to the concept of smart substation because the construction of a secure and reliable smart substation is critical to the development of a smart grid. A smart or digital substation is defined as an advanced modern substation, which uses advanced, reliable, integrated, low-carbon, environmentally friendly intelligent devices;

where the digitization of the whole station information, networked communication platform and standardization of information sharing are implemented as the basic requirements. A smart substation automatically performs the basic functionalities such as data acquisition, measurement, control, protection, metering and monitoring, etc.; meanwhile it supports advanced functions such as real-time automatic control, intelligent regulation, analytical decision-making online, collaborative interaction. The current chapter is devoted to a smart substation and its principles and components.

2.1. Overview of smart substations

A smart grid includes power generation, transmission, transformation, distribution, consumption, and dispatch, among which the transformation section plays a very important role [9-11]. Digital (or smart) substations are the cornerstone and significant support of strong smart grids, which bring a number of new technologies and promote a new generation of energy revolution. The smart grid development plan in China indicates the following:

«*The equipment information and operation maintenance strategies are fully interactive with the power dispatch, and the complete life-cycle optimization management based on real-time status is realized. The pivotal and central substations should be fully constructed or reconstructed into smart substations to achieve unified collection of the network operation data, realizing real-time information sharing, real- time control and intelligent regulation, which support the safe and stable operation of power grids and various advanced applications*».

With the development of sensing measurement technology, information communication technology (ICT), computer technology, and control technology, traditional substations have been developed into intelligent substations gradually. Plenty of smart substations of 110–750kV voltage levels have been put into commercial operation successively in China. The smart substation realizes online monitoring of the operation status for the primary and secondary equipment in the whole station, which is helpful to enhance the intelligentization and reliability of equipment, improve the efficiency of resource utilization and production management, and make the substation operation more economic, energy efficient, and environment friendly.

The smart grid is a new generation grid that integrates state-of-the-art information and communication technology, computer technology, and existing transmission and distribution infrastructure. It has a number of advantages, such as improving energy efficiency, reducing both the impact on the environment and the power losses of the transmission, and improving the security and reliability of power supply.

The smart (or digital) substation is proposed along with the concept of the smart grid, which plays an important and crucial role in the smart grid. Adopting advanced, reliable, integrated, low-carbon, and environmental-friendly intelligent devices, smart substations are based on the overall station information digitalization, communication platform networking, and information-sharing standardization. Automatically completing the basic functions of information collection, measurement, control, protection, computation, and monitoring, the smart substations also support advanced functions, such as real-time automatic control of power grids, intelligent regulation, online analysis, and decisions so as to interact with adjacent substations and power dispatching. A digital unified application platform for collecting, transmitting, analyzing, and processing all the information of the entire station was established using advanced sensors, information, communication, control, and artificial intelligence in order to realize the substation's informatization, automation, and interaction.

The smart substation has gone through a continuous development. The information in the traditional substation is usually isolated within the subsystems. With the application of IEC 61850, Communication Networks and Systems in Substations, and the development of a new sensor, communication, information, and control technology, the top priorities of a smart substation are to share information resources, to integrate various applications and primary and secondary status information into a unified information platform by means of a unified communication protocol, and to realize the substation's informatization, automation, and interaction. With the implementation of advanced applications of the digitalization and networks in substations, the key research points of smart substations are to achieve intelligent primary equipment, station-level protection and control system, self-diagnosis of equipment, intelligent operation and maintenance systems, and intelligent power dispatching technologies. The development direction is to build a smart substation that is safe and reliable in operation, highly integrated in system, rational in structure and layout, equipped with advanced equipment, economical, energy saving, and environment friendly so as to optimize substation technology and equipment and greatly reduce the floor space and significantly improve the safety, reliability, and economy. At this stage, the smart substation adopts advanced technology and equipment and emphasizes the optimization of the structure and function of the system. In order to improve the ability of the smart grid to perceive panoramic information of advanced applications to achieve the goal of automation and interaction, the smart substation takes technical, economic, and management requirements into account to realize the unified collection and processing of tristate data (steady state data, transient data, and dynamic data).

In the future, with the further development and maturation of advanced technologies, smart substations will focus on promoting a technology revolution and demonstrating innovative concepts, including new types of equipment, new types of materials, and emerging technologies. A new generation smart substation is featured by power electronics technology that can achieve rapid and flexible power control. In terms of the performance of the entire power grid, the new generation smart substation with high-capacity, low-loss, and short-circuit-resistant features is built to increase transmission capacity and reduce network losses and short-circuit currents when a power grid fault occurs.

As an important node of the smart grid, the smart substation has a number of functions, such as transporting energy, transforming voltage, distributing energy, and controlling power flow. At the same time, the information collection and processing of smart substations are wider, deeper, and more complex than those of conventional substations, which make information exchange and integration more convenient and faster and make control methods more flexible and reliable.

According to high-speed network communication, smart substations realize information sharing and interoperation, measurement and monitoring, control and protection, and information management and intelligent condition monitoring through standardized digital information. Smart substations have the important features of intelligent primary equipment, overall station information digitalization, information-sharing standardization, and advanced application interaction, which are discussed as follows:

(1) Information-sharing standardization: The unified standardized information models based on the IEC 61850 standard realize information sharing within and outside the station. The smart substation will unify and simplify the data sources of the substations to form unique and consistent basic information. Through the uniform standard and unified modeling, the smart substation can realize information exchange and sharing in substations, which can make multiple sets of isolated systems in the conventional substation integrate into business applications due to information sharing.

(2) Intelligent primary equipment: With the use of electronic transformers and intelligent breakers based on optical or electronic principles, conventional analog signals and control cables have been gradually replaced by digital signals and optical fibers. The input and output of Multi-parameter-based detections (MPDs) are all digital communication signals. The substation communication network further extends to the field, and the on-site sampling data and switch status information can be shared across the overall station or even a wide area, realizing the true smart substation.

(3) Overall station information digitalization: The smart substation can control primary and secondary equipment flexibly and communicate bidirectionally. It can be managed through the information network to meet the requirement of information collection, transmission, processing, and digital output processes.

(4) Intelligent equipment diagnosis: Besides the reliability of station equipment, the smart substation pays more attention to self-diagnosis and autonomy functions for early prevention and warning of equipment failure and to minimize power losses caused by equipment failures.

(5) Advanced application interaction: All kinds of advanced applications inside and outside a station could interact with each other, and the substation could interconnect and interact with other application requirements.

(6) Commissioning methods: Due to substation configuration description (SCD), the design and system integration of smart substations will be gradually integrated. The SCD contains model information of the whole station, which is designed and provided to equipment manufacturers to download directly. Furthermore, with the digitalization of device interaction information, the commissioning of substations is becoming more and more dependent on software-based tools, which can implement information monitoring and inspection. Therefore, the automation and validity of the commissioning are improved continuously.

Exercises

1. Label the parts of the power grid architecture (Figure 2.1):

a) Businesses.
b) Transmission substation.
c) Transformer.
d) Residential.
e) Distribution substation.
f) Power station.

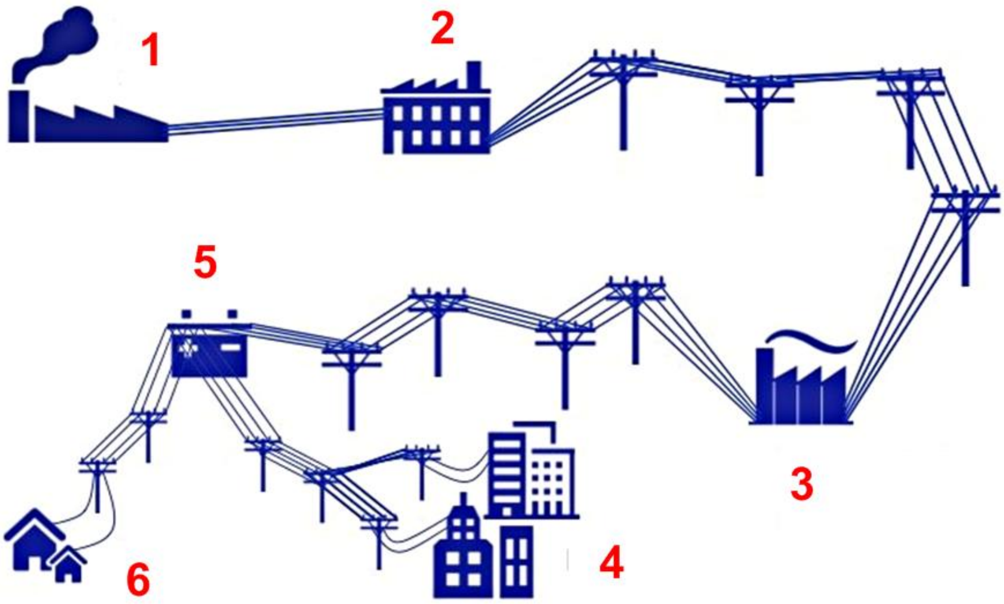

Figure 2.1 Power grid architecture

2. Which of the following is not a smart grid principle, according to EISA 2007?

a) digitalization;
b) use of renewable energy sources;
c) creation of unified international power grids;
d) automated control;
e) cybersecurity.

3. Read the sentences and choose the best answer A, B, C or D:

1. According to the smart grid development plan in China:

a) plenty of substations of 110–750 kV voltage levels have been already reconstructed into smart substations.

b) operation of all transmission substations should be based on the principles of "smart substation".

c) the construction of smart substations is necessary, first of all, for the introduction of renewable energy sources into the power system.

d) the use of sensing measurement technology will allow substations to achieve unified collection of the network operation data and realize real-time information sharing.

2. The information at the smart substation:

a) is usually isolated within the subsystems.
b) is integrated into a unified information platform.
c) occurs only in a digital form.
d) is transmitted by the use of the only protocol.

3. Unlike the traditional substation, the smart substation is able to:

a) transform voltage.

b) control power flow.
c) exchange and integrate information more convenient and faster.
d) transport energy.

4. The important feature of smart substations is:

a) analogue primary equipment.
b) overall primary equipment digitalization.
c) standardization of information sharing .
d) many isolated information systems.

4. Watching

1) Watch the first 4 minutes of the video and fill in the gaps with the words and expressions you hear.

How Do Substations Work

The simple answer to the question where the electricity actually comes from is …(1)…, also known as …(2)…, usually somewhere far away.

Many of challenges associated with the power grid are overcome at facility which, at first glance, often looks like a chaotic and dangerous mess of …(3)… and …(4)…, but which actually serves a number of essential roles in our electrical grid, the substation.

A series of discrete steps on the grid includes distribution, or delivering the electricity to …(5)… .

Critical roles of "substation" in the power grid depend on which parts of the electrical grid are being connected together and the types, number, and …(6)… of the eventual customers downstream.

As a junction point in the grid, a substation often serves as the termination of many …(7)… .

The arrangement of the bus can have a major impact on …(8)… .

Like all equipment, substations occasionally have …(9)… or things that simply require regular maintenance.

At high voltages, if you create a break in a line, electricity can continue flowing in a phenomenon known as …(10)… .

2) Watch the full video. List the main equipment of the substation and define its purpose.

2.2. Primary devices of a smart substation

2.2.1. The structure of a smart substation

The smart substation is defined as an advanced modern substation, which uses advanced, reliable, integrated, low-carbon, environmentally friendly intelligent devices; where the digitization of the whole station information, networked communication platform and standardization of information sharing are implemented as the basic requirements; which automatically performs the basic functionalities such as data acquisition, measurement, control, protection, metering and monitoring, etc.; and supports advanced functions such as real-time automatic control, intelligent regulation, analytical decision-making online, collaborative interaction. It is characterized by the following objectives [9-11]:

- Integrated operation.
- Standardized information.
- Coordinated interaction.
- Industrialization of production and commissioning.

The smart substation includes two main parts – smart high voltage equipment and a unified substation information platform. The smart equipment is defined as high voltage equipment, which is composed of an organic integration of primary high voltage equipment and intelligent components, and characterized by digital measurement, networked control, visualized state, integrated functionalities and interactive information. The smart high voltage equipment mainly includes a smart transformer, smart switching devices and electronic transformers. The intelligent components are made up of a set of IEDs (Intelligent Electronic Devices) – state sensing components and intelligent actuators, including all or part of devices for measurement, control, state monitoring, metering and protection.

It implements the basic functionalities such as measurement, control and monitoring of the host equipment. In certain cases, the intelligent components are also used for metering and protection. The requirements and objectives of smart HV equipments are: 1) enhance the reliability of power grid by making the equipment fault predictable; 2) reduce the lifecycle cost through smart control of a cooling system (energy efficient), integrated design (saving land utilization), and online self-diagnostics (reducing operation and maintenance cost of assets); and 3) optimize the utilization of assets. The first step is to digitize the information of HV equipment. The communication-capable IEDs are embedded into HV equipment (which is not different from traditional HV equipment in theory) to make the state of equipment observable. Figure 2.2 demonstrates the evolution of the substation.

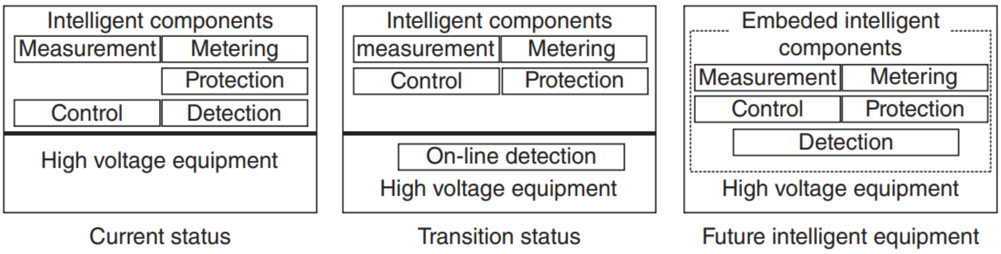

Figure 2.2 Evolution of substation equipment

The major motivation for developing a smart substation is that a traditional substation cannot satisfy the requirement for a smart grid. The problems associated with substation automation system (SAS) at a traditional regular substation can be summarized as follows:

•Inconsistency of data due to various data systems existing in a substation;
•Repeated data acquisition;
•High design complexity difficulty of maintenance due to various devices;
•Poor interoperability among systems and devices;
•Complex communication protocol;
•Lack of conformity test and authorization;
•Nonstandard information, hence difficult to use.

At a traditional substation, there is strict separation between primary high voltage equipment and secondary low voltage (LV) devices. In the future, there will be no clear wall between primary high voltage equipment and secondary low voltage devices. All the measurement, control, protection and detection devices are integrated into primary high voltage equipment. At the current transition periods, on-line detection IEDs are embedded into the primary high voltage equipment. The detected information can be shared through the network by other advanced applications. The introduction of intelligence into HV equipment also leads to the reconsideration of the functionality design of primary HV equipment and secondary LV devices.

Another revolutionary change is the communication network. Figure 2.3 (b) demonstrates the system architecture of a typical smart substation, as compared to that of a traditional substation, as shown in Figure 2.3 (a). At a traditional substation, the remote terminal units (RTU) are hardwired through copper wire to measurement, control and protection IEDs. As opposed to traditional substations with a large number of hardwired RTUs, hardwired switching and limited communications, the advanced substation automation (SA) at a modern substation offers a reliable, hardened and open communication network, advanced data/communication protocols, flexible HMI (human machine interface) and convenient, small, distributed RTUs. Advanced SA can reduce materials and labor cost for the utility while adding additional capability and reliability for a substation.

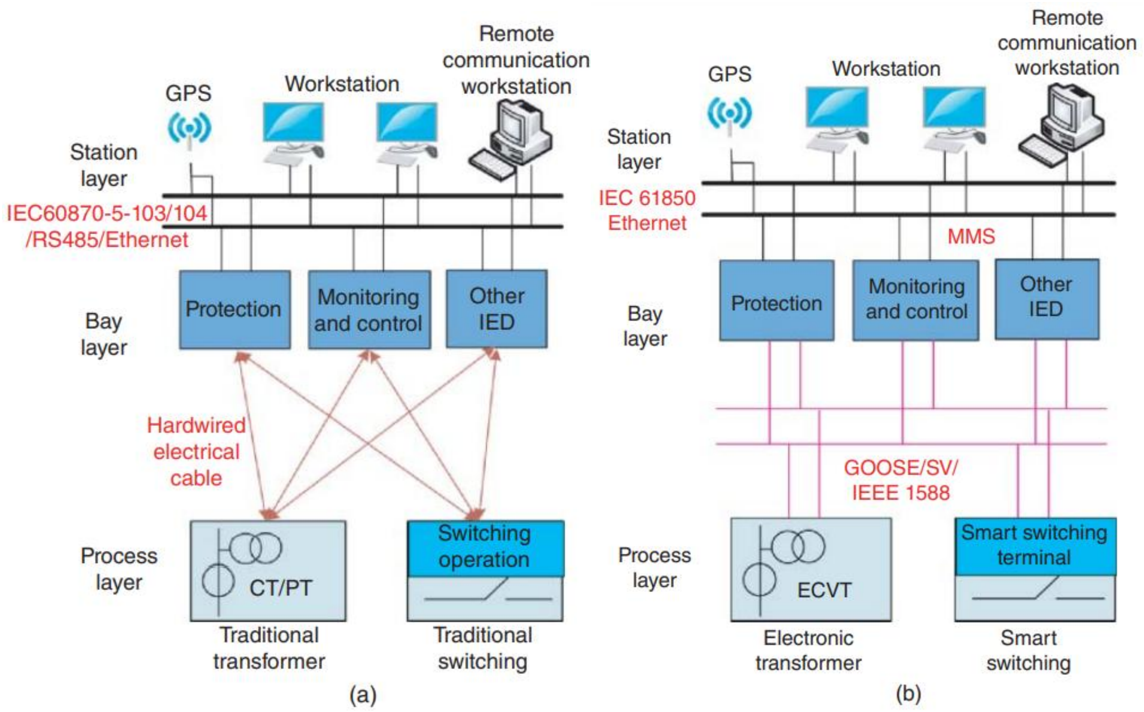

Figure 2.3 System architectures of traditional (a) and smart (b) substation

Although hardwired communication solutions have been extensively utilized throughout the field, a satisfactory supervision of the communication channels has been hard to achieve. The so-called digital substation, based on IEC 61850, offers a significant advantage over those earlier solutions. 1 ☐ GOOSE also enables simplified substation wiring. In practice only one Ethernet cable is required between the IEDs of a substation and an Ethernet switch to enable communication between the protection and control IEDs. This can be compared with a hardwired solution where, for each signal, a copper wire is connected from each IED to all the other IEDs at the substation.

The IEC 61850 is the future standard for a substation, hence is chosen for building a communication platform for a smart substation. The protection relay manufacturers are developing their range of IEC 61850 compliant products. The IEC 61850 technology offers a cost-efficient solution by reducing the need for hardwiring between the switchgear bays. 2 ☐

A smart substation is categorized into three layers: station layer, bay layer and process layer. The most prominent difference between the smart substation and traditional substation includes three aspects: smart primary HV equipment, condition based maintenance and networked secondary devices. 3 ☐

Evolution of substation automation systems went from electromagnetic to numerical relays at first, and was followed by implementation of digital communications at the station level, but still subjected to proprietary protocols. [4] ___ The process bus interconnects the protection and control devices at the bay level, with the instrument transformers and switch-gear equipment at the process level. With it, conventional copper wires will be replaced by fiber optic cables, and the transmission of current and voltage samples, as well as protection and command signals being transmitted over a serial link network, instead of parallel point-to-point connections. The process bus makes it possible to replace conventional electromagnetic instrument transformers by novel optical current/voltage sensors, and to implement assets condition-monitoring systems.

The smart substation is a brand new concept and is still at its initial stage. In China, quite a lot of smart substation demonstration projects aimed at deploying and integrating intelligent solutions to enhance the efficiency and reliability of the electricity network are under construction. [5] ___ In the following three chapters, the test of a secondary system, auxiliary monitoring system and electronic transformer will be discussed in depth.

Exercises

1. What objectives of the smart substation relate to the following characteristics?

• Data sharing and exchange are implemented in the interconnected network.

• A substation is characterized by ease of integration, refurbishment, maintenance and scalability.

• Operations of dispatch, neighbor substation, power sources and customers are coordinated.

• There exists integration of state monitoring of primary equipment, functional integration of secondary devices and organic integration of primary equipment and secondary devices.

2. Using Figure 2.2.describe how substations will develop.

3. Using Figure 2.3 find the differences between the system architecture of a traditional substation and a smart substation.

4. Five sentences have been removed from the first part of the article. Choose from the sentences A-F the one which fits each gap (1-5). There is one extra sentence which you do not need to use.

A. And system flexibility in terms of expandability is a key benefit of the IEC 61850 compliant system.

B. Then the IEC 61850 was introduced, and interoperability between different devices became possible, but the next big step in the evolution of substation automation will come with the implementation of the process bus.

C. It is challenging to transit from a legacy substation to a highly efficient, highly reliable and highly interconnected substation.

D. The smart substation is one of the key parts of the smart grid and the network of process layer is an important foundation for the smart substation which is related to the reliability and real-time of data acquisition and switch control.

E. Using GOOSE (Generic Object Oriented Substation Event) the communication supervision is a natural and integral part of the communication and using GOOSE system enhancements are easier to accomplish than with hardwired solutions.

F. Smart substation uses IEC 61850 protocol, including IEDs in the three layers – process layer, bay layer and station layer, and their network connection.

2.2.2. Intelligent primary devices

Switchgears are the basic equipment of transmission and distribution systems, which are divided into primary equipment and auxiliary equipment. Primary equipment is a high-voltage part of the switchgear, which is used for high-voltage insulation, current-carrying, and opening-closing. Auxiliary equipment is a low-voltage part of the switchgear, which is used for controlling and monitoring of the main components and is installed with the high-voltage part dispersedly.

The primary equipment, such as circuit breakers, disconnectors, and other high-voltage components, is very mature, and the failure rate of primary equipment is lower than that of the corresponding control equipment. In view of the disadvantages of the traditional switchgears and the increasing requirements of reliability and automation, the rapid development of electronic technology has brought the concept of intelligent switchgear. The intelligent switchgear refers to the switchgears and related control equipment with higher performance, equipped with electronic equipment, transmitters, and actuators. It not only has the basic functions of switchgears but also has additional functions, such as monitoring and diagnosis functions. At present, the intelligent primary equipment is still being developed at smart substations. Most of them have no or small changes on the structure of the existing primary equipment (e.g., the installation of sensors). The circuit breaker management (CBM) IED is used as the intelligent interface of the primary equipment to intelligentize it partly. Connected with the primary equipment using cables, the CBM IED uploads the status information of the primary equipment through GOOSE to control it in a real-time way. Meanwhile, connected with the secondary equipment via optical fibers, the CBM IED receives downlink control commands from the secondary equipment.

The intelligent primary equipment has the following forms:

(1) Keeping the actuators (such as spring clamps, hydraulic valves, a disconnector motor, an earthing switch motor, and a spring motor) and their electromechanical control loops unchanged, the CBM IED and the online monitoring unit are installed in the circuit breaker control cabinet, according to the partition of interval, as shown in Figure 2.4.

(2) Keeping the actuator and its electromechanical control loop unchanged, the CBM IED with online monitoring function is installed in the circuit breaker control cabinet dispersedly, according to the partition of interval, as shown in Figure 2.5.

(3) Keeping the actuator unchanged, the CBM IED performs electromechanical control and drives a circuit breaker tripping/closing coil, motors of isolator, a hydraulic pump, and a spring directly. Moreover, the CBM IED also has the online monitoring function, which is called "intelligent agencies," as shown in Figure 2.6.

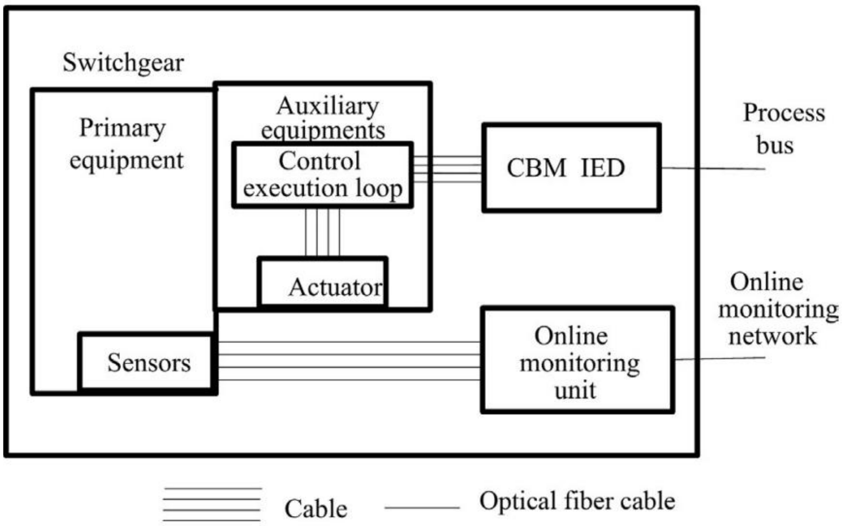

Figure 2.4 Switchgears+CBM IED+online monitoring units

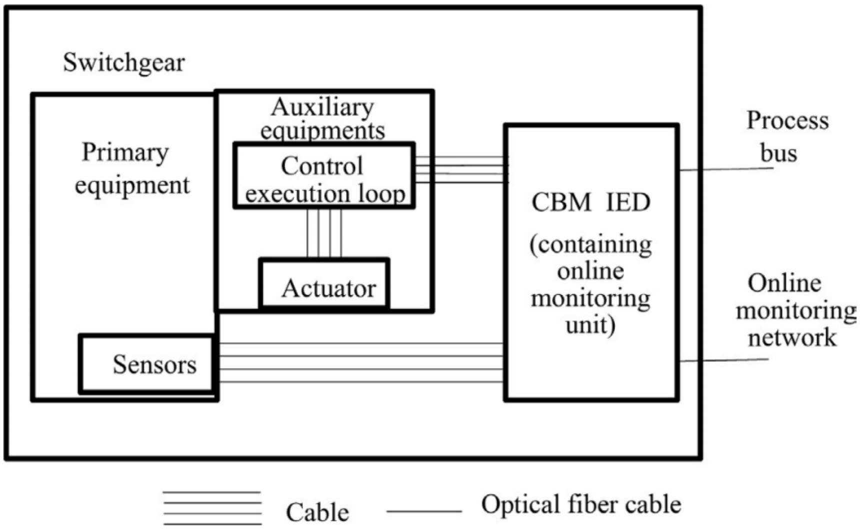

Figure 2.5 Switchgears+CBM IED (containing online monitoring unit)

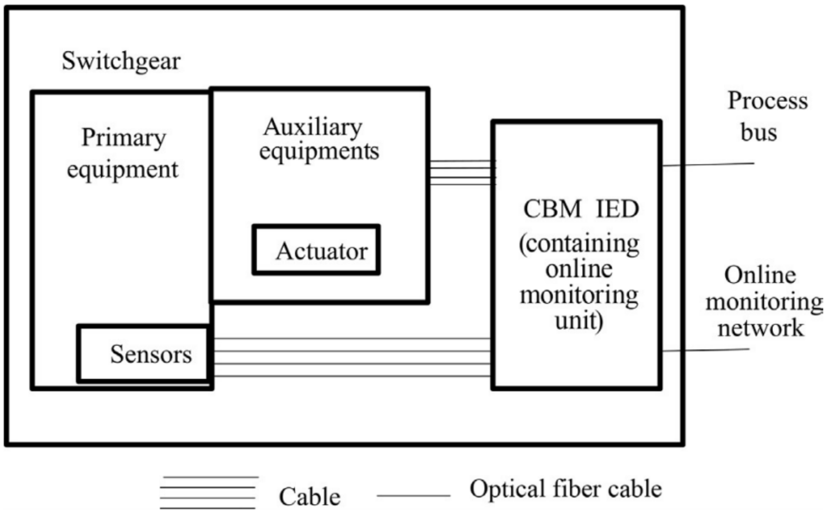

Figure 2.6 Intelligent switchgears

At the same time, the switchgear is gradually being more widely monitored to ensure the safety and reliability of the power grid. The online monitoring technology can not only detect early defects of electrical equipment in time to prevent sudden accidents but also reduce unnecessary power-off maintenance and make certain pretest items online to avoid the power losses caused by traditional tests and maintenance. Diagnosing the equipment operating conditions synthetically, the online monitoring technology promotes the power equipment from the regular tests to the state maintenance, and effectively lengthens the equipment life.

Exercises

1. Choose one True statement:

a) The primary equipment is applied for controlling and monitoring of the main components.

b) The tasks of high-voltage insulation, current-carrying, and opening-closing are implemented by the auxiliary equipment.

c) Switchgears are the main part of auxiliary equipment.

d) Transmission and distribution systems include two main parts: primary equipment and auxiliary equipment.

2. ***Read the sentences and choose the best answer A, B, C or D:***

1. The concept of intelligent switchgear appeared as a result of:

a) the high failure rate of control equipment.

b) the need to achieve higher levels of reliability and automation.

c) attempts to use advanced electronic technologies.

d) the need to replace old elements of traditional devices.

2. The circuit breaker management (CBM) IED cannot be installed:

a) in the circuit breaker control cabinet separately from the online monitoring unit.

b) in the circuit breaker control cabinet together with the online monitoring unit.

c) directly to motors of an isolator, hydraulic pump, and a spring keeping the actuator and its electromechanical control loop unchanged.

d) directly to the circuit breaker tripping/closing coil.

3. The online monitoring technology is able to:

a) detect malfunctions of primary equipment timely.

b) completely eliminate the possibility of power-off.

c) perform traditional tests and maintenance with the lower power losses.

d) prevent sudden accidents by avoiding high power losses.

2.2.3. Intelligent primary equipment condition monitoring

The deterioration and defects of electric power equipment have early signs, manifested as the gradual changes of electrical, physical, chemical, and other characteristic parameters. Through the technologies of sensor, computer, and communication networks, the characteristic parameters of equipment can be obtained in time and analyzed and processed by the expert system, which can determine reliability of equipment and estimate the remaining life. Thus, the potential failure can be found early, and the power supply reliability can be improved. The online monitoring can monitor and judge the running power equipment continuously to provide the necessary judgment basis for the state maintenance of the power equipment.

Transformers, circuit breakers, and other substation primary equipment used to be equipped with regular maintenance and pre-commissioning systems. That is, preventive tests (offline) were carried out after a regular power outage to grasp the information to determine whether the primary equipment continues operation or not. This preventive method requires a power outage, and the authenticity and real-time need to be improved.

As the technology advances, the online monitoring technology of some parameters was born. Take transformers, for example, the transformer dielectric loss, core current, gas in oil, partial discharge, micro-water in oil, hot spot temperature, and winding deformation can be monitored online. The online monitoring technology has solved some shortcomings of the power outage tests and has obtained some experience and effectiveness in recent years. However, there are still many shortcomings, such as incomplete testing parameters, poor compatibility, and difficulty in implementation. It cannot comprehensively reflect the operation of equipment in real-time and lacks corresponding standards. Therefore, it cannot meet all the requirements of the smart grid construction for substation online monitoring.

Transformer online monitoring

The power transformer is one of the most important and expensive devices in the power system. Its safe operation is of great significance to ensure reliability of power supply. In order to improve reliability of the operation and reduce the economic losses caused by faults and accidents, preventive tests on the insulation of the transformers should be carried out regularly. However, if the preventive tests are carried out after power blackout, the normal power supply will be affected. Therefore, the online monitoring of the transformer operation has been paid more attention. The development and extensive application of online monitoring technology is the foundation of power system condition-based maintenance, which will play an important role in the power system.

At present, the transformer monitoring mainly includes the following aspects:

(1) Online monitoring for transformer partial discharge.

(2) Online monitoring for transformer on-load tap-changer.

(3) Online monitoring for transformer bushing insulation.

(4) Online monitoring for transformer oil temperature, winding temperature, and load.

(5) Online monitoring for transformer micro-water in oil.

(6) Transformer oil's gas chromatography monitoring.

Gas insulated switchgear (GIS) condition monitoring

Monitoring, maintenance, and overhaul of switching devices are important means to ensure safe operation of electric power equipment and power systems. In the condition monitoring, physical and chemical quantities that reflect the operating status of equipment are detected via various sensors and measuring means to determine whether equipment is in normal condition, including online or offline monitoring, measurement, testing, and related performance parameters of equipment and related components.

There is no exposed energized part in GIS, except for the bushing of inlet-outlet line, and SF6 gas insulation is adopted to ensure high reliability and less maintenance. In addition, external diagnostics and surveillance can reduce unnecessary disassembly and maintenance workload. That is, without disassembling the equipment, a precise and easy way is adopted to measure, monitor, and diagnose the internal state and performance of equipment from outside (online, offline, electrification, blackout), including fault location.

(1) Partial discharge. The insulation performance of GIS is an important condition to ensure its safe operation. The metal particles, powder, and moisture inside the GIS equipment play an important role in leading to GIS failures. The presence of conductive impurities in GIS brings the abnormal sound, vibration, discharge charge, luminescence, decomposition gas,

and other abnormal phenomena because of partial discharge. Therefore, the partial discharge will be one of the important objects of GIS condition monitoring.

(2) Monitoring of SF_6 gas. Used for insulation and arc extinguishing, the performance of SF_6 gas will be an important parameter of GIS. Hence, it is necessary to monitor pressure, leakage, and micro-water content of SF_6 gas.

(3) Monitoring of mechanical characteristics of a circuit breaker. Monitoring for currents of closing and tripping coils: a compensated Holzer current transformer is used to monitor the current waveforms of the closing and tripping coils online. And the current waveforms are compared with the normal current waveforms, which can monitor the abnormal mechanical characteristics of the circuit breaker.

Stroke and speed monitoring: The mechanical characteristics (stroke, closing and tripping time, average speed, etc.) of the circuit breaker are optically determined by a non-contact method using a barcode reader and comprehensively diagnosed. Compressed air pressure monitoring: by monitoring the air pressure, the compressor starting frequency, or the motor current, the operation of compressed air stations and institutions can be known.

Online monitoring of arresters

The online monitoring of arresters uses the grounding current of the lightning arrester as the power for a sampling device. The magnitude of the leakage current is converted into the change of optical pulse frequency, and a series of high-tech means, such as fiber sampling, microcomputer data processing, and data communication, are adopted. The key problems are solved, such as leakage current measurement of lightning arresters, passive sampling in transmission, high-voltage isolation, data remote transmission, and over-standard leakage current alarm. Furthermore, the automation of online monitoring of arresters insulation status in non-attended substations is realized.

Exercises

1. How was the primary equipment condition monitoring carried out earlier? What were the disadvantages of this approach?

2. Fill in the table using the information from the text:

Type of primary equipment	Necessity of online monitoring	Possible failures	Types of monitoring

3. What are the advantages of SF6 gas compared to other insulating medium?

4. What is leakage current and what possible damage does the value of the leakage current indicate?

5. Watching

Watch the video “Digital Substations Made Simple” and choose the best answer for questions 1-4.

5.1. What was not mentioned among many challenges in meeting the demands of tomorrow?

a) Global warming.
b) Aging infrastructure.
c) Budget cuts.
d) A rapid increase of energy usage.

5.2. According to the video, the task of Schneider Electric is to:

a) change the way we distribute power.
b) develop a smart grid.
c) ensure physical security of the network.
d) collect data about asset lifetimes.

5.3. The use of a digital substation allows a client to:

a) create new open standards.
b) become independent from the energy vendor.
c) improve compatibility of his equipment.
d) reduce cybersecurity costs.

5.4. More efficient predictive maintenance in a digital substation is provided by the use of:

a) reduced wiring.
b) smart terminal blocks.
c) simplified electrical diagram.
d) thermal sensors and smart panels.

2.3. Electronic current and voltage transformers of a smart substation

Current and voltage transformers provide current and voltage signals respectively for electric energy measurement, relay protection, as well as measuring and control devices [9, 10, 12]. [1] [__] Traditional current and voltage transformers are electromagnetic-inducted, of which a series of inherent defects gradually emerge with the increase of capacity and voltage level in the power system. Since 1970s, researchers have been looking for a new way to realize the measurement of high voltage and current, which is expected to be safe, reliable, perfect in theory and superior in performance. Some kinds of transformers have attracted much attention and are researched for a long time. They are optical current transformers (OCTs), optical voltage transformers (OVTs), electronic current transformers (ECTs) using air core coil or low power iron core coil, and electronic voltage transformers (EVTs), respectively. [2] ____

Compared with conventional electromagnetic transformers, electronic transformers are superior in the following aspects:

(1) Excellent insulating property. Magnetic fields of the primary and secondary sides of an electromagnetic transformer are coupled through the iron coil. Its insulating structure is complicated, and the cost grows rapidly with the increase of voltage level. [3] ____

(2) Freedom from magnetic saturation and ferroresonance. Iron coils are no longer used in electronic transformers, thus they are free of magnetic saturation and ferroresonance, which results in the desirable transient response and stability, ensuring the reliability of the system.

(3) Anti-electromagnetic interference. The circuit in the secondary side cannot be open for an electromagnetic current transformer, and it cannot be short for an electromagnetic voltage transformer, otherwise it would be dangerous. For electronic transformers, optical fiber connects the two sides, which ensures the electrical isolation between them. [4] ____ Furthermore, since magnetic coupling does not exist, the transformer has anti-electromagnetic interference.

(4) Wide scope of transient response and high measuring accuracy. In a normal situation, current flowing through a transformer is not large. However, the short circuit current grows fast. An electromagnetic current transformer is unable to realize a wide scope measurement because of magnetic saturation. It is also difficult for an electromagnetic transformer to satisfy the requirement of high accuracy measurement and protection. Nevertheless, electronic transformers have a wide scope of transient response. [5] ____ The over-current can be up to tens of thousands of amperes. Therefore, they meet the demand of both measurement and relay protection. Besides, they can avoid the complex structure of multiple channels in electromagnetic current transformers.

(5) Wide range of frequency response. The transducer of an electronic transformer has a wide range of frequency response. The real measuring range depends on the electronic circuit part. [6] ____ In contrast, the frequency response range of an electromagnetic transformer is narrow. Its response to high frequency signals is flawed.

(6) Adapted to electric power measurement and digitization, computerization, automation, and intelligentization of protection. Microcomputer and digital electronic technologies have been widely used in the power system. [7] ____ Electronic transformers, connected with optical fiber, can transmit sig-

nals quickly and accurately. The application of power electronic devices and digital electronic technology is capable of satisfying the requirements of precise measurement and quick action of protection in the situation of smart grids.

In practical engineering application, electronic transformers are classified into two types: active electronic transformers and passive electronic transformers. Figure 2.7 shows the classification. The principles, formation, and key technology are diverse for different transformers.

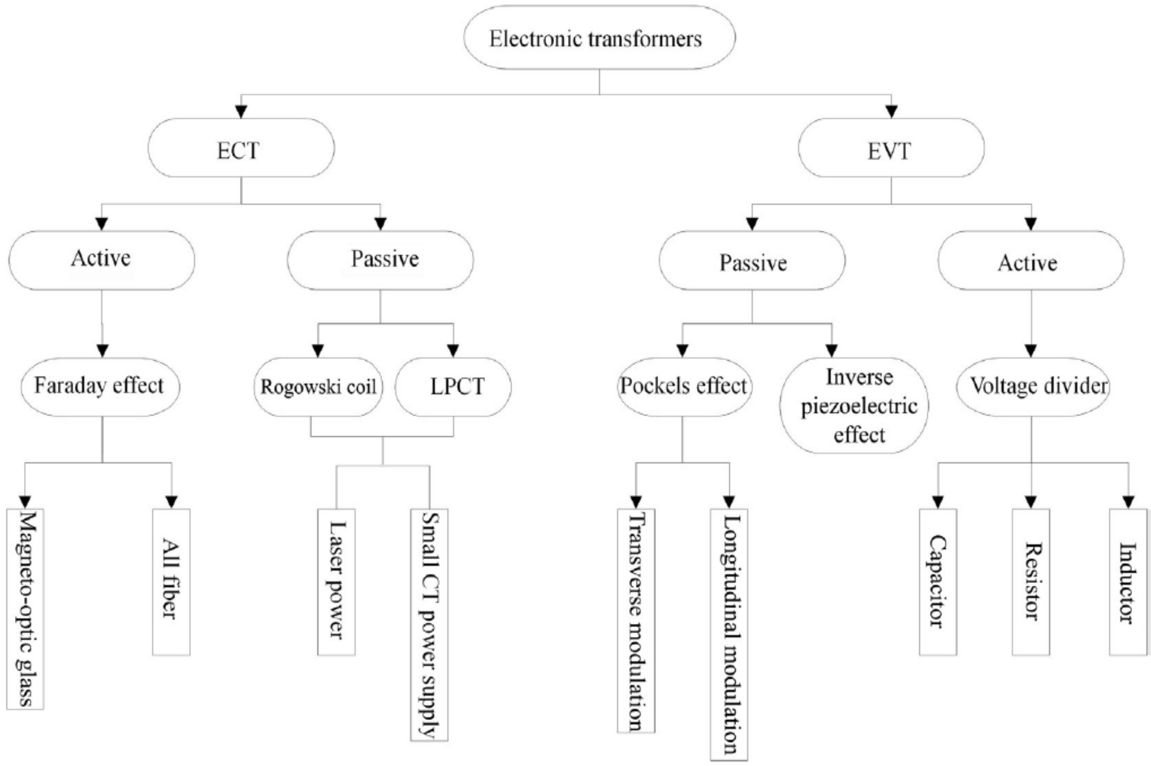

Figure 2.7 Classification of electronic transformers

Exercises

1. Seven sentences have been removed from the first part of the article. Choose from the sentences A-F the one which fits each gap (1-7). There is one extra sentence which you do not need to use.

A. Their rated current can range from dozens of amperes to thousands of amperes.

B. Therefore, there are no risks of short or open circuits.

C. This kind of transformer is able to measure the harmonic waves in the high voltage lines.

D. To date, ECTs and OCTs have been applied in the field with the realization of temperature stability and craft consistency.

E. Conventional electromagnetic transformers cannot be connected to the smart grid smoothly due to their weakness on interface.

F. Their accuracy and reliability are closely related to the safety, reliability and economy of the power system.

G. Unlike conventional transformers, the electronic transformer consists of one or more current or voltage sensors connected to a transmission system and a secondary converter.

H. In contrast, for electronic transformers, signals from the primary side are transmitted to the secondary side using optical fiber, whose insulating structure is simple, and cost grows slowly with the increase of voltage level.

2. Which problems of traditional current and voltage transformers do OCTs, OVTs, ECTs and EVTs solve?

3. Why do electronic transformers provide greater measurement accuracy than traditional types?

4. Describe the classification of electronic transformers using Figure 2.7. What are the principles of classification?

5. Watching

Watch the video and fill in the gaps with the words and expressions toy hear.

Fiber Optic Current Sensors for high voltage applications

An optical fiber functions at …(1)… than wire cables.

Conventional instrument transformers …(2)… or …(3)… have been used for many decades.

The FOCS freestanding high voltage current sensor is a …(4)… current sensor for …(5)… to …(6)… substations.

The optoelectronic module …(7)… the reflected polarized light from the sensor coil and uses a closed …(8)… system to compare phase displacement in the polarized light in proportion with a magnetic field of the primary current.

FOCS FS is suitable for capturing …(9)… currents, …(10)… currents and …(11)… current with DC offset.

2.4. Station and process buses of smart substation

2.4.1. Three levels of communication within substations

Figure 2.8 shows three typical levels of control architecture in a smart substation [9-11]. The station level contains common equipment for the substation – the HMI, communications interfaces, etc. – while the bay level is more circuit specific and the equipment for each circuit (such as protection relays and local control units) reside here. The primary equipment (such as instrument transformers, disconnectors and circuit breakers) is within the process level. While the connections between levels have traditionally been copper wiring, the application of substation communication buses led to a reduction of cabling. IEC 61850 now enables devices from different manufacturers to be connected to the same communication bus and share information in a truly interoperable way. Not only can devices from different manufacturers be applied, but status signals can be shared between devices, meaning that multiple connections of plant status signals, etc. are no longer necessary – once the signal is configured for one device, it can be shared to others connected to the network in the substation. 1

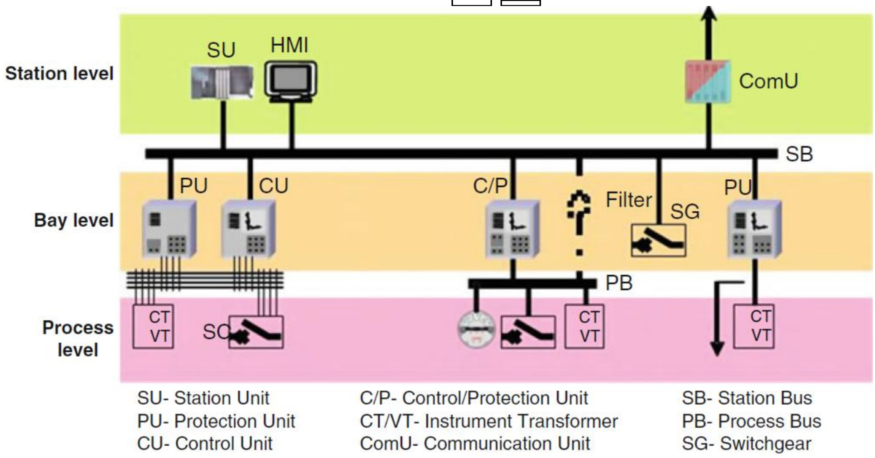

Figure 2.8 Three levels of communication within substations

In a further advancement, IEC 61850 has now enabled the copper wiring connections between the process and bay levels to be replaced by fiber optics with the so-called process bus, replacing analogue signals with digitized versions. 2 Instrument transformer signals from conventional CTs and VTs can be digitized via merging units in the switchyard or modern non-conventional CTs using fiber optics and Faraday effect or voltage dividers to replace a VT, each with inherent analogue-to-digital conversion can be used.

Tripping signals, too, can be issued via GOOSE (generic object-oriented system events) message over the network rather than conventional wiring, and a truly digital substation has become a possibility and reality.

Figure 2.9 shows some of the standards used at substations prior to the release of IEC 61850 and the comparable IEC 61850 parts. 3 As implied by the diagram, it is possible to apply a substation bus while devices at the process level are still hardwired to bay level units, meaning that users can establish and adopt a degree of automation which they can comfortably manage and control.

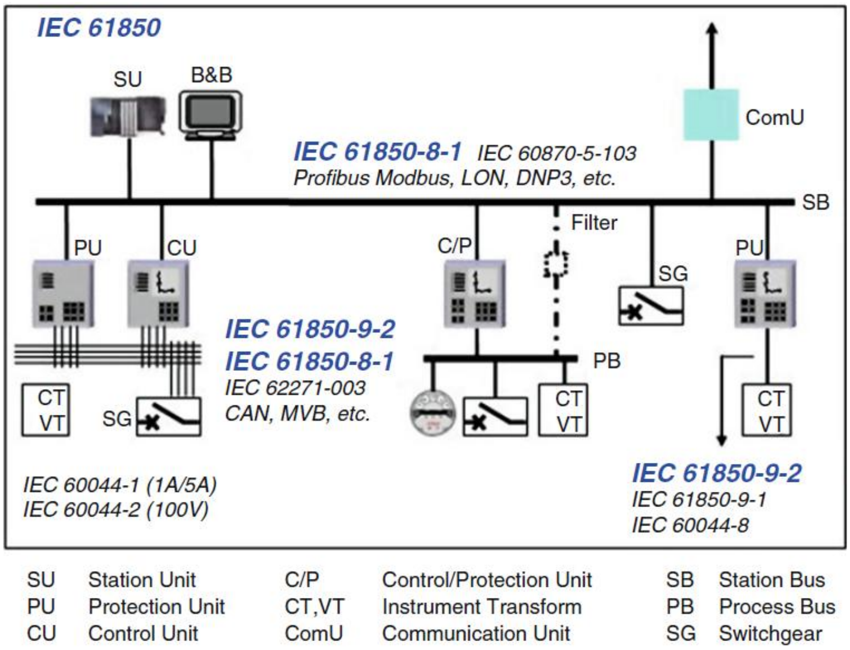

Figure 2.9 Protocols at substations

Figure 2.10 shows a block diagram representation of a substation, differing communication levels and possible connections between them. As the substation automation equipment has become digital, so too has the commissioning and testing equipment. Modern test equipment can be programmed to run specific test sequences, reducing time and cost. 4 ☐ The use of process bus and “sampled values” of the primary current and voltages has also facilitated this.

5 ☐ There are many networks which still contain electromechanical relays in working order 40–50 years after installation. By contrast, digital devices have a lifetime nearer 10–15 years due to obsolescence of components and difficulty of continuing support by manufacturers. This means that during the typical 40-year life span of a substation, the substation automation system would be replaced at least once, if not twice, during the life of the primary equipment. This may at least in part be offset by the fact that the relative cost of digital equipment and the engineering tends to be lower than that for electromechanical devices. Ease of replacement of the secondary equipment is best considered during initial construction of the substation, to avoid potential problems later.

The use of IEC 61850 can assist with the upgrading of equipment – the reduction of copper connections and use of Ethernet-type connections, instead, mean that new devices can be connected to the substation bus, configured, and tested in the substation environment before replacing the older unit. 6 ☐ At the digital substation, it is possible to monitor so much more than previously by gathering additional information regarding the status of the plant. Trend analysis is also possible, enabling condition-based maintenance rather than fixed time schedule maintenance. Novel techniques such as dynamic line rating can also be applied by measuring wind speed to vary the current capacity of the line.

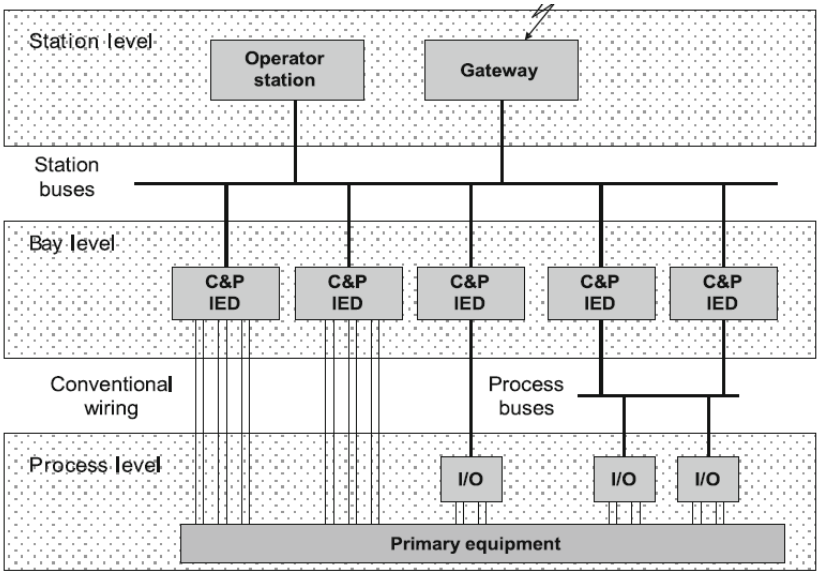

Figure 2.10 Substation terminology

Exercises

1. Six sentences have been removed from the first part of the article. Choose from the sentences A-G the one which fits each gap (1-6). There is one extra sentence which you do not need to use.

A. However, all these interoperability and interchangeability features require a standard configuration specification.

B. To many, this represents a significant change in philosophy with the fundamental signals to and from the plant no longer being hardwired in copper.

C. Note that while the substation bus and process bus are shown as being separate networks, they could in practice both be part of one single network.

D. Some test equipment is also IEC 61850 compatible and does not need to be connected directly to the device under test anymore but can be connected to the substation bus and “address” the device requiring testing.

E. An aspect of modern digital devices which also must be considered is their life span, which is generally much shorter than electromechanical devices.

F. Modern digital devices and control systems are also able to provide and handle additional monitoring functions.

G. It has facilitated the replacement of traditional copper wiring/cable connections with fiber optics, reducing cabling costs.

2. What specific changes does IEC 61850 allow to make in the substation structure at every level?

3. What problem should be considered while using digital devices? How is this problem compensated?

4. Describe the relationship between substation levels based on the block diagram representation of a substation (Figure 2.10).

2.4.2. Integrated information platform and advanced applications

As shown in Figure 2.11, the information integration platform provides standardized information access interfaces for intelligent applications and remote systems by collecting the whole substation supervisory control and data acquisition (SCADA) data, protecting information data, recording data, metering data, and online monitoring data. The platform solves the problems of too many station control systems and interfaces, poor data sharing and applying synthetically, and meets the requirements of intelligent substations in digitization of information, integration of functions, compactness of structures, and visualization of status.

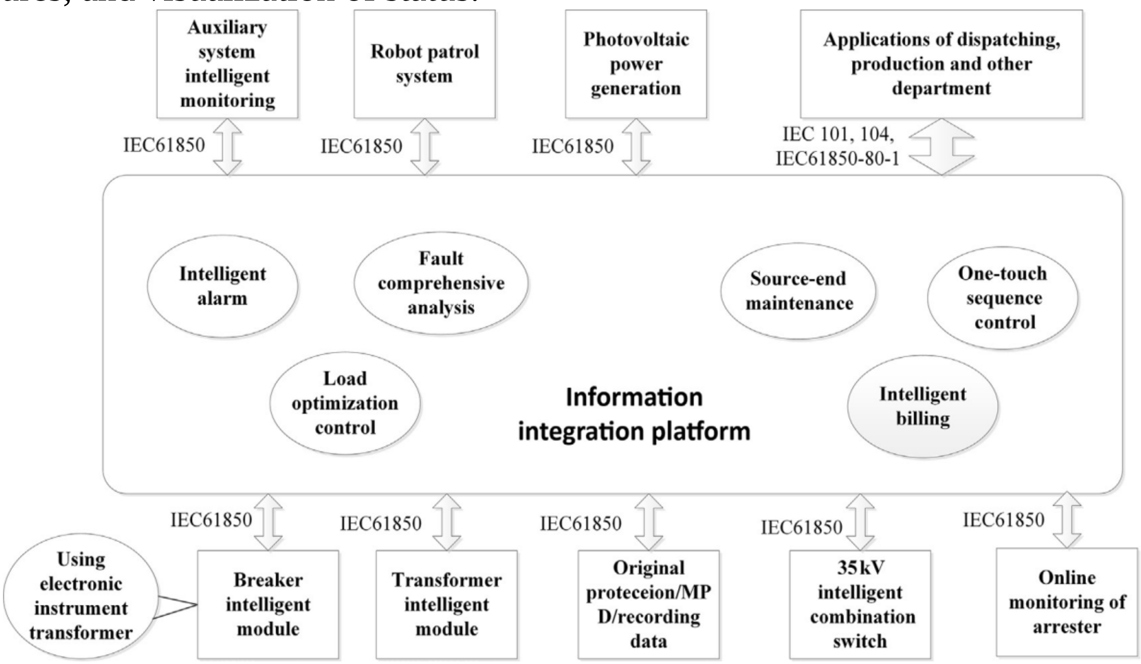

Figure 2.11 Intelligent substation information integration platform

Based on the information integration platform, advanced functions, such as one-touch sequence control, source-end maintenance, intelligent alarm and fault comprehensive analysis, intelligent billing, and load optimization control can be developed, as follows:

(1) One-touch sequence control. As a basic function of a smart substation, the sequence control is to perform relevant operation tasks automatically according to the operation order on the premise of substation standardization operation, and can complete multiple control steps at one time. The sequence control checks the anti-misoperation lockout logic automatically before each step operation, and has the functions of interruption and sudden stop.

The sequence control system combines one-touch sequence control and a video system through an intelligent patrol robot. When a primary device is operated, the video system is guided to turn the camera to the device, and the status of the device is judged by image recognition technology and transmitted to the sequence control system. The sequence system judges the status of the equipment synthetically according to the information collected by the measurement and the information returned by the video system to ensure reliable operation.

(2) Source-end maintenance. As a source terminal of data acquisition of a dispatching/centralized control system, the substation shall provide various self-describing configuration parameters, which could be configured with the uniform configuration tool just at the substation during maintenance. Moreover, the substation can generate standard configuration files, including parameters such as the main wiring diagram, network topology, and other data model.

The main wiring diagram and sub-screen graphic files of the substation automation system shall be provided to the dispatching and centralized control system in the network graphic standard scalable vector graphics (SVG) format as shown in Figure 2.12. The mapping relationship between the substation model (IEC 61850) and the master dispatching model (IEC 61970) is established to implement primary-maintenance data model and graphic pictures on the substation side and used in various automation systems of dispatching center in real time to reduce the maintenance workload and ensure that system models and data of each substation and main station are consistent. Source-end maintenance greatly reduces the maintenance workload of diagram mode in the dispatching system and eliminates the checking work of the substation and the dispatching information.

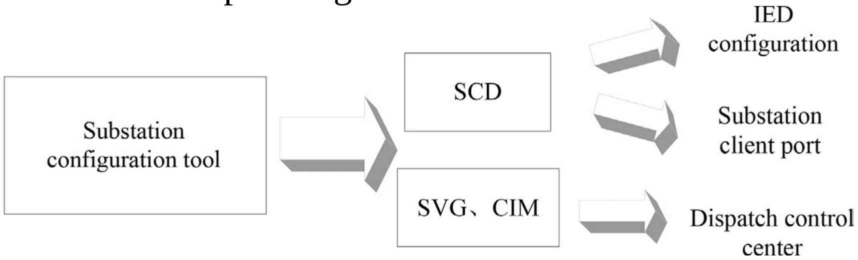

Figure 2.12 Source-end maintenance

(3) Intelligent alarm and fault comprehensive analysis. The intelligent alarm system preprocesses the alarm information and establishes an expert system knowledge base of the fault processing, which analyzes the alarm information, fault brief report, waveform recording, and other information synthetically, and integrates the intelligent alarm system with HMI.

Fault information analysis software based on an information integration platform provides fault diagnosis, fault location, equipment operation monitoring and evaluation, harmonic analysis, waveform processing, and other failure analysis functions, and put forwards a feasible comprehensive analysis of fault information.

(4) Smart ticketing. Smart ticketing can automatically write various types of operation tickets according to the operation mode and the actual operation of the substation, and operators can make operation tickets only by clicking the mouse.

The key of the smart ticketing system is designing the reasonable operation rules to intelligentize the ticket and simplify the user maintenance. The definition of rules should consider not only the constraints of operating procedures but also those of substation operation. When the operation ticket is generated, the real-time system interface is used to read the device attributes and the device status in the real-time base. Then all the obtained information is matched with the selected operation task and operation rule to obtain the unique rule. When the smart ticketing is selected, the system will automatically generate the required operation ticket according to the actual running status of the device and rule base.

(5) Optimization control of intelligent load. Voltage quality control (VQC) module is embedded in the substation controller (remote device) system software. The real-time data and equipment parameters required by its algorithm are completely based on the information integration platform system. VQC is controlled by the main station system, and its running voltage and reactive target value are obtained from the dispatch center. Optimized control equipment that participates in VQC operation can automatically decide whether to participate in VQC adjustment according to the inspection status of the equipment. Based on real-time data and current optimization control target value, VQC automatically adopts the optimal method to select the appropriate equipment to control. It can adapt to a variety of different wiring operation modes. All the actions are completed within the substation, and the results will be sent to the main station system.

Overload shedding is also embedded in the system software of the substation controller as the software module, which is controlled by the main station system. The real-time data and the device parameters of the algorithm are based on the information integration platform system. The priority of the line is also decided by the main station system. When the system breaks down and the main transformer is overloaded, the advanced application will automatically cut off the loads of the non-important lines in the station.

Exercises

1. What does the information integration platform allow to do?

a) online data monitoring,

b) solving problems of inadequate availability of station control systems and interfaces,

c) protecting power devices.

d) collecting the whole substation supervisory control and data acquisition (SCADA) data,

e) recording data.

2. The basic principle of one-touch sequence control is:

a) automatic step operation.

b) interruption and sudden stop operation.

c) substation standardization operation.

d) misoperation lockout.

3. *Read the sentences and choose the best answer A, B, C or D:*

1. An intelligent patrol robot allows the sequence control system to:

a) judge the status of the primary device by image recognition technology.

b) video record a work process of the primary device.

c) turn the camera to the primary device.

d) collect measurement information.

2. The dispatching and centralized control system gets the main wiring diagram and sub-screen graphic files:

a) in the network graphic standard scalable raster graphics format from the substation protection system.

b) in the network graphic standard scalable raster graphics format from the substation automation system.

c) in the network graphic standard scalable vector graphics format from the substation automation system.

d) in the network graphic standard scalable vector graphics format from the substation protection system.

3. The use of the smart ticketing system will allow to:

1) take into account the actual operation of the substation in operation tickets.

2) manually write various types of operation tickets.

3) intelligentize the operation mode.

4) simplify the maintenance of the primary device.

2.4.3. Station and Process Bus Architecture

Full advantage of all the features available in the new communication standard can be taken if both the station and process bus are used. Figure 2.13 shows the functional hierarchy of such a system.

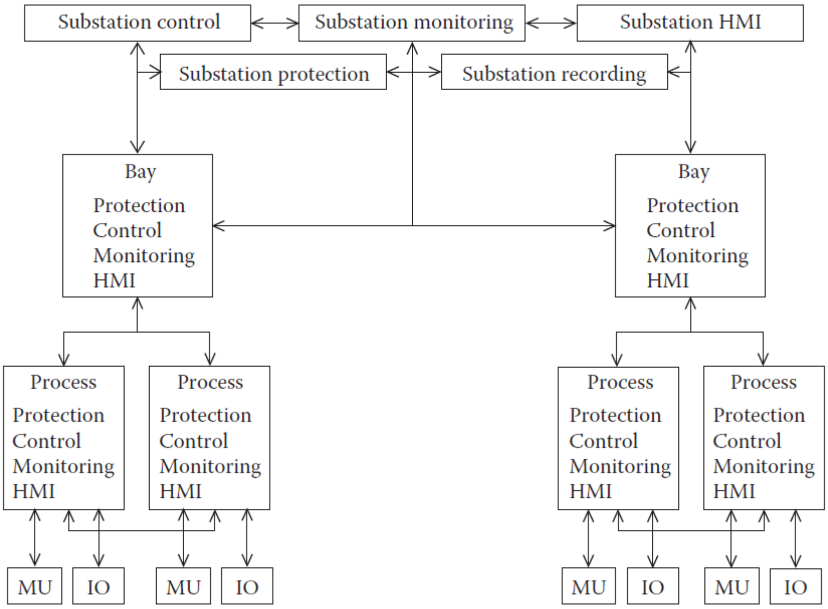

Figure 2.13 Station and process bus functional architecture

IEC 61850 communication-based distributed applications involve several different devices connected to a substation LAN. MUs will process the sensor inputs, generate the sampled values for the three phase and neutral currents and voltages, format a communication message, and multicast it on the substation LAN so that it can be received and used by all the IEDs that need it to perform their functions. 1 Another device, the IO unit (IOU) will process the status inputs, generate status data, format a communication message, and multicast it on the substation LAN using GOOSE messages. All multifunctional IEDs will receive the sampled value messages as well as the binary status messages. The ones that have subscribed to these data, then process the data, make a decision, and operate by sending another GOOSE message to trip the breaker or perform any other required action.

Figure 2.14 shows the simplified communication architecture of the complete implementation of IEC 61850. The number of switches for both the process and substation busses can be more than one depending on the size of the substation and the requirements for reliability, availability, and maintainability.

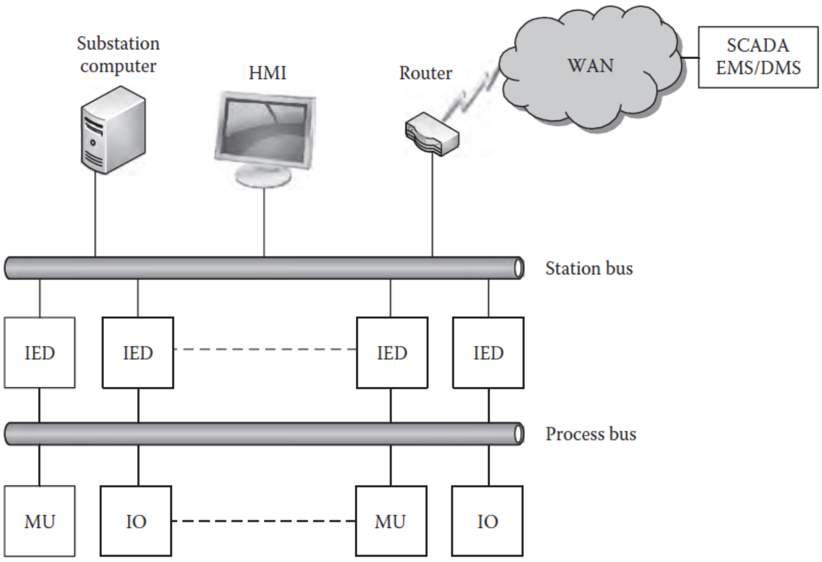

Figure 2.14 Communication architecture for process and station bus

Figure 2.15 is an illustration of how the substation design changes when the full implementation of IEC 61850 takes place. All copper cables used for analog and binary signals exchange between devices are replaced by communication messages over fiber. If the DC circuits between the substation battery and the IEDs or breakers are put aside, the "copper-less" substation is a fact. 2 Of course the opposite is also possible. Since all the information is available on a communication bus, we can choose to implement relatively simple or even single function devices that share their information on the network, thus creating a distributed function.

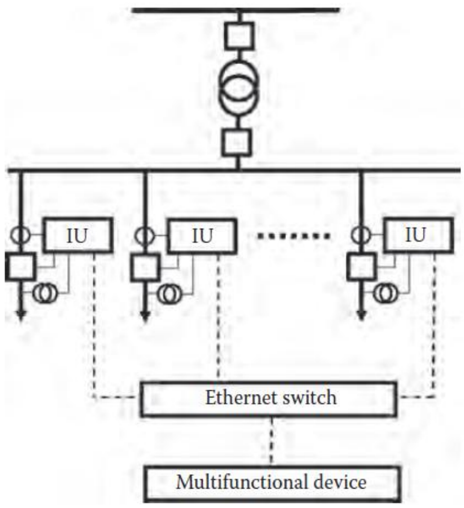

Figure 2.15 Alternative substation design

The next possible step when using station and process bus is the optimization of the switchgear. In order for the protection, control, and monitoring functions in a substation to operate correctly, several instrument transformers are placed throughout the high-voltage installation. 3 One example is the voltage measurements needed by distance protections. Traditionally, voltage transformers are installed in each outgoing feeder. However, if voltage transformers are installed on the bus bar, the voltage measurements can be transmitted over the LAN to each function requiring these measurements. These concepts are not new and have already been applied at conventional substations. At conventional substations, however, it requires many (long) cables and several auxiliary relays limiting or even eliminating the benefit of having less voltage transformers.

Process bus–based applications offer important advantages over conventional hardwired analog circuits. 4 ___

Using a process bus also results in the practical elimination of CT saturation of conventional CTs because of the elimination of the current leads resistance. As the impedance of the MU current inputs is very small, this results in the significant reduction in the possibility for CT saturation and all associated with its protection issues. 5 ___ Process bus–based solutions also improve the safety of the substation by eliminating one of the main safety related problems—an open current circuit condition. 6 ___

7 ___ Since current circuits cannot be easily switched due to open circuit concerns, the application of bus differential protection, as well as some backup protection schemes, becomes more complicated. This is not an issue with process bus because any changes will only require modifications in the subscription of the protection IEDs receiving the sampled analog values over IEC 61850 9-2.

Exercises

1. Seven sentences have been removed from the text. Choose from the sentences A-H the one which fits each gap (1-7). There is one extra sentence which you do not need to use.

A. If nonconventional instrument transformers can be used in combination with the MUs and process bus, the issue of CT saturation will be eliminated completely as these nonconventional CTs do not use inductive circuits to transduce the current.

B. However, with the capability to send voltage and current measurements as sampled values over a LAN, it is possible to eliminate some of these instrument transformers.

C. High-speed peer-to-peer communications between IEDs connected to the substation LAN based on exchange of GOOSE messages can successfully be used to replace hardwiring for different protection and control applications.

D. This “one-to-many” principle similar to that used to distribute the GOOSE messages provides significant advantages as it not only eliminates current and voltage transformer wiring but also supports the addition of new ideas and/or applications using the sampled values in a later stage as these can simply subscribe to receive the same sample stream.

E. Last, but not least, the process bus improves the flexibility of the protection, monitoring, and control systems.

F. The first very important one is the significant reduction in the cost of the system due to the fact that multiple copper cables are replaced with a small number of fiber-optic cables.

G. We can then even go a step further and combine all the functions necessary for multiple feeders into one multifunctional device, thus eliminating a significant amount of individual IEDs.

H. Since the only current circuit is between the secondary of a current transformer (CT) and the input of the MU is located right next to it, the probability for an open current circuit condition is very small. It becomes nonexistent if optical current sensors are used.

2. What does "copper-less" substation mean? How can it be implemented?

3. What problem connected with the use of current transformers can be solved by a process bus and how?

2.5. Protection of smart substation

For the secondary equipment in the new generation smart substation, the locally installed equipment is adopted to solve the environment, electromagnetic interference, and other protective devices, and improve reliability of locally installed equipment [9, 11, 13]. The integration of a merging unit and CBM IED (circuit breaker management intelligent electronic devices) integration devices, multi-function monitoring and control devices are used to reduce the number of devices and simplify the secondary cabling. [1] [___] The integration of digital metering and other professions are promoted for achieving further information sharing and simplifying the metering system.

The new generation smart substation protection system adopts the hierarchical construction idea, synthesizes the panoramic data information of a power grid, and constructs the hierarchical protection control systems consisting of time dimension, space dimension, and functional dimension. [2] [___] It is helpful for building a more stringent security system of a power grid. The new generation smart substation hierarchical protection system is shown in Figure 2.16.

In the local protection for a single object to be protected, the independent information of the protected object is used for judging and the fault is cutoff reliably and rapidly. The station area protection control for the substation is used for a wide protection system, and the instruction is sent through the station area protection. The station area protection control collects the protection operation and alarm information, and directly sends the instruction without passing the locally installed protection. [3]

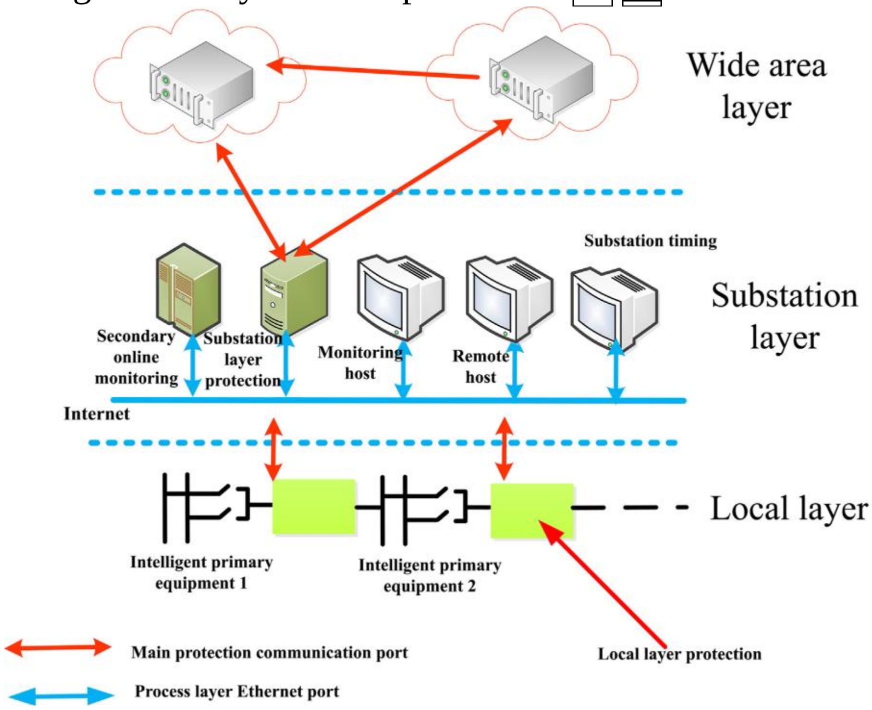

Figure 2.16 Schematic diagram of the hierarchical protection system

In the time dimension, the local protection of the various types of primary protection has no time delay (20–30ms). [4] In order to meet the selectivity and reliability, the speed of the protection is sacrificed (0.8–1.2s). Station-level and wide-area protection can utilize the comprehensive information to speed up local backup protection (0.3–0.5 s). The protection and stability control of each level cooperates with each other, and their relationship is shown in Figure 2.17 to enhance the relay protection performance and stability control level.

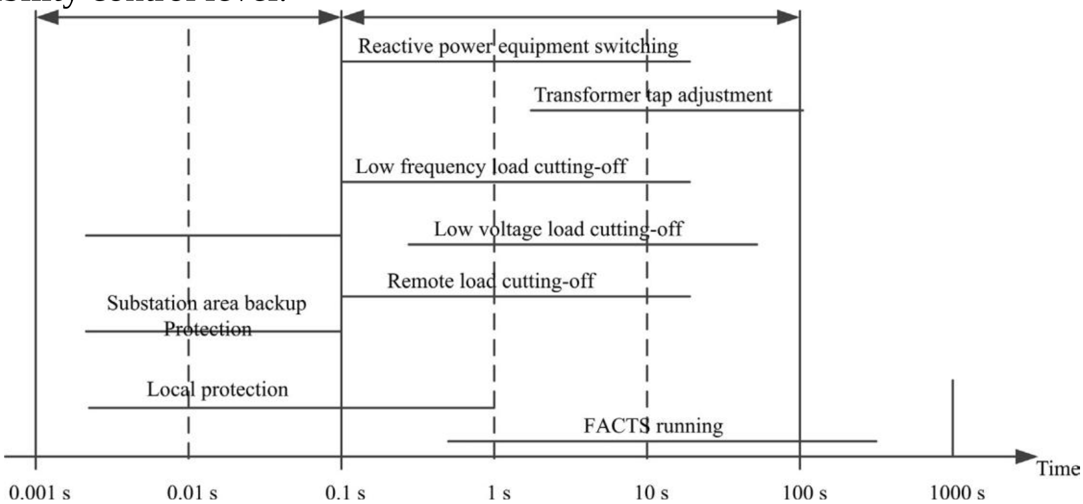

Figure 2.17 Protection control system-related functions of the time range

In the spatial dimension, personal defense is achieved for the signal locally installed protection. [5] ⎵ Hierarchical protection control is combined from different viewpoints to achieve the full range of regional power grid protection. The system of hierarchical protection control is shown in Figure 2.18.

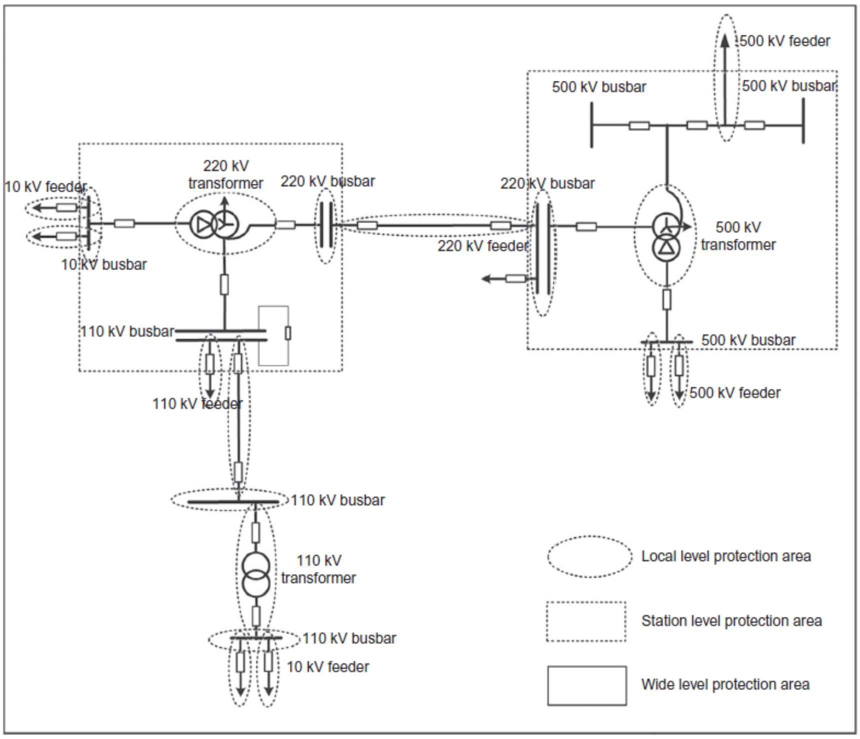

Figure 2.18 The system of hierarchical protection control

In the functional dimension, aiming at the purpose of a quick and rapidly cutoff fault component in the local level protection, information of the individual components can be used independently to achieve fast and reliable component protection. In order to optimize the protection control configuration and enhance protection and control performance, the site protection makes centralized use of the whole station information and exhibits flexible, adaptive bus protection, failure protection, and component backup protection, and prepares load shedding control function. [6] ⎵

Local protection and station-level protection do not depend on external communication channels, and the protection functions can be achieved even if the communication channel is damaged. Wide-area protection control relies on optical fiber communication to achieve inter-station data exchange, and its reliability is often subject to the reliability of optical fiber communication network restrictions. [7] ⎵

Exercises

1. Seven sentences have been removed from the first part of the article. Choose from the sentences A-H the one which fits each gap (1-6). There is one extra sentence which you do not need to use.

A. Outdoor installation of merging units, CBM IEDs, and other equipment on the operating environment requirements are higher, its long-term operation to be investigated.

B. Aiming at improving the stability of the system control automation and intelligence, wide-area protection uses regional substation panorama data information to implement wide-area backup protection and adjust the protection settings, optimize the stability control strategy, and finally achieve regional coordination between area protection and control.

C. The comprehensive station information is used by the station level protection and control to achieve "comprehensive defense within the station," and it is used by the wide-level protection and control between stations to achieve "the whole network comprehensive defense."

D. With the sub-delay, the backup protection achieves mutual cooperation.

E. The local level, station level, and wide-level multi-level protection control cooperate with each other to achieve the full range of power protection control coverage.

F. The hierarchical protection control system is composed of the local protection for the protected object, the station area protection control for the substation, and the wide-area protection control for the multiple substations in the area, which improves the existing relay protection performance, safety, and stability control levels and strengthens the first line of defense and the cooperation between the second and third line.

G. The hierarchical protection control system is applied to break through the limitations of space-saving protection control and achieve site-based backup protection and station-level intelligent control strategy.

H. In extreme cases, it will lose some or even all control functions, but as a whole protection system performance, the failure of the wide-area protection control system does not affect the local protection and the station level protection control functions.

2. What does "hierarchical protection" mean? Why is such a protection system used?

3. Describe the structure of the hierarchical protection system and purposes of its elements using Figure 2.16.

4. What is selectivity of protection? How can it be implemented?

Unit 3. Smart Grid and Distributed Generation

Introduction

The document adopted by the Russian government states: “The main directions of strategic development of the electric power industry at the present time and in the medium term". Thus, it follows that the development of smart grids and distributed generation are both the goal and instrument of this directive. Such strategies have been approved by the governments of many rapidly developing energy countries.

Among the main directions of the strategic development of the electric power industry are the following:

- Improving reliability of power supply;
- Creation of new functional properties of the power system;
- Motivation of active behavior of the end user;
- Ensuring reliability and quality of energy efficiency;
- Self-healing during emergency disturbances;
- Resistance to negative influences;
- Diversification of power plants and energy storage systems;
- Expansion of capacity and energy markets to the end consumer;
- Optimization of asset management;
- Preservation of the environment.

3.1. Smart Grid

3.1.1. Introduction to the concept of Smart Grid

According to the concept of Smart Grid (SG), the future power system is considered as an infrastructure similar to the Internet intended for maintenance of power, information, economic and financial relations between all participants of the power market and other interested parties. SG is the concept of innovative transformation of electric power engineering as a whole rather than of its individual functional or technological segments. It based on revision of the existing basic principles, purposes, and problems in the development of electric power engineering (EPE) and scales following from it, and character of problems to be solved considering predicted social, economic, scientific, technical, ecological, and other consequences of their implementation [1-5].

SG represents an integral automated mechanism uniting manufacturers of the electric power, electric grids, and consumers. This mechanism is controlled by a computer center which collects data on electric power consumption level from millions of digital controllers in real time. Specialized software helps to trace the operating regime of all participants of the process of electric energy generation, transmission, and consumption.

There are two main trends in the development of power engineering at present and in the foreseeable future that have stimulated the development and implementation of the concept of "Smart Grid":

- an increase of the power of individual electric generators and PPs in general, the length and power of transmission lines. This increases the severity of the consequences of accidents at these facilities and, therefore, the requirements for the reliability of both objects;
- an increase of the role of distributed generation in the electric power industry, as a branch of the economy of any highly developed country.

These trends stimulate the use of the most modern devices and systems for digital monitoring and control.

3.1.2. Principles of construction and expected benefits

The main advantage of the SG is that it automatically responds to changes in various parameters in the power supply system and allows uninterrupted electrical supply with maximum economic efficiency. In this case, the influence of the human factor in the SG operation is reduced to a minimum.

In fact, the SG is a combination of possibilities of information technologies that already became habitual in many spheres of industrial activity with high-power electronics and electrical power engineering.

Table 3.1 shows the basic connection technologies according to the SG concept.

Table 3.1

Integrated connections

Technology type	Basic components
Wireless technologies	•multiaddress radio system •notification grids •radio systems of expanded spectrum •Wi-Fi •WiMAX •cellular structure of next generation •time partition multiple access •code division multiple access (CDMA) •small satellite terminal
Other technologies	•Internet of new generation (Internet-2) •broadband power line (BPL) •grid with optical cable delivered to the user •fiber-optical coaxial cable •radio frequency identification (RFID)

Within the limits of the SG concept a variety of requirements of all interested parties (state, consumers, regulators, power companies, sales and municipal institutions, proprietors, manufacturers of equipment, etc.) is reduced to a group of the so-called key requirements (values) of the new EPE formulated as follows:

- Availability – supply of consumers with energy without restrictions depending on when and where it is necessary for them and on its paid amount;
- Reliability – possibility of overcoming negative physical and information consequences without total power switching-off or high expenses for operation recovery, restoration (self-restoration) as fast as possible;
- Profitability – optimization of tariffs for electric energy for consumers;
- Efficiency – maximization of the efficiency of utilization of resources of all kinds, technologies, and equipment in the process of power generation, transmission, distribution, and consumption;
- Eco-friendliness – the maximum possible decrease of negative ecological effect;
- Safety – avoiding situations in electric power engineering dangerous to people and environment.

The SG concept, leaning against the strategic vision of EPE in future, involves principles of construction of such grids and key requirements to them from which functional properties (characteristic) also follow: administrative, technological, standard, and informational.

A simplified diagram of the SG concept implementation is shown in Figure 3.1.

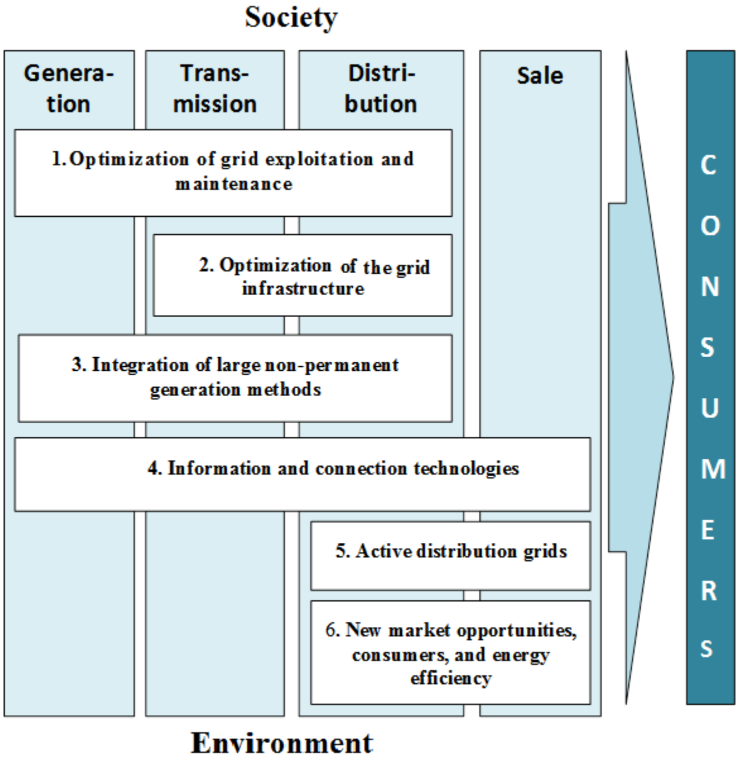

Figure 3.1 Priorities in the development of SG in the EU countries

An increase in efficiency in all links of the technological chain during implementation of the SG concept will be achieved through the following:

- Generation: an increase of reliability and profitability of electric power production using modern highly intelligent control and management devices, including IT, integration of renewable energy sources, distributed generation and energy storage devices;
- Transmission network: ensuring reliability of electric power transmission and electric grid controllability via large-scale monitoring of regimes and control over them taking advantage of new means and technologies (FACTS, Power Management Units (PMU), artificial intelligence, etc.) as well as via the increased use of pilotless flying machines (drones) for control over technical power transmission line (PTL) state as scheduled (every 1.5 years) and off-scheduled (after each natural anomaly) inspections;
- Substations: maintenance of reliability and controllability of substations at the expense of modern electro technical equipment and automation based on modern diagnostic tools, monitoring, and management using information and computer technologies (i.e. transition to digital substations);
- Distribution network: an increase of controllability and reliability by means of distributed automatics and protection systems on modern microprocessor basis using new information, computer, and Internet technologies;
- Consumers: their supply with highly-intellectual systems for monitoring and accounting of the consumed electric power, regulation of power consumption and management by loading, including emergency cases.

Creation of an intellectual (smart) grid provides application of a large set of new technical means and processing methods based on the concept of EPE digitalization.

In the countries with limited mineral power resources, the strategy is largely focused on the creation of favorable conditions for the development of renewable power sources, stimulation of energy saving, and increase in the efficiency of consumption of power resources.

For Russia with its large reserves of power resources, lengthy electric grids, and high degree of depreciation of equipment, maintenance of reliability and efficiency of the electric grid complex operation with limited investments and pressure of time is urgent. The scale of expected transformations in the process of future intellectualization of EPE is comparable with that of revolutionary changes in communication and information spheres that have made the Internet, mobile communication and a number of other contemporary achievements which have unrecognizably changed our life an everyday reality.

Exercises

1. Answer the following questions:

1) What are two trends in modernization of electric power engineering that are driving implementation of the Smart Grid concept?

2) What are wireless technologies?

3) Which components of the process flow increase their potential due to realization of a smart grid concept?

4) Is the scope of the smart grid concept limited to networks only?

5) Why is the smart grid concept especially relevant for the Russian electric power engineering?

6) Which document sets out the main directions for improving the energy sector in Russia based on the implementation of the Smart Grid concept?

2. Translate into Russian the following English word combinations:

Distribution network
Transmission network
Optimization of grid exploitation and maintenance
Information and connection technology
Eco-friendliness
Cellular structure of next generation
Automatic response to changes in various parameters

3. Read the text again and briefly explain the concept of the smart grid

3.2. Distributed generation

3.2.1. Scope and benefits of distributed power generation

Distributed Generation (DG) is an approach that uses small-scale technologies to generate electricity close to the end-users. DG technologies often consist of modular generators (sometimes based on renewable energy sources) and they have several advantages. In many cases, distributed generators can provide cheaper electricity and higher reliability and energy security with less environmental impact than traditional generators. Unlike the traditional power industry, which uses several large power plants located far from the load centers, the DG uses many small sources of electricity supplying power locally with little dependence on distribution and transmission networks. DG technologies provide power from fractions of a kilowatt to 100 megawatts. Generator sets for utility companies generate electricity with a capacity often exceeding 1,000 MW. In fact, there are significant shortcomings in the production of electricity in a centralized way (using high-power power plant). One of them is the need to transfer electricity over long distances, which involves: a) energy losses in the line (5-15%), b) high cost of their construction and operation, c) land alienation and negative environmental impacts.

These problems can be mitigated through DG. Distributed generation is a power plant aggregate located close to the place of energy consumption and connected either directly to the consumers, or to the distribution electric grid (in the case when there are several consumers). The type of a primary energy source used at the power plant, as well as the power plant ownership (a consumer, a generating or grid company, or the third party), is irrelevant. When the energy source is close to the consumer, the problems associated with transmission can be neglected.

Small generating units are often more energy efficient, economical and more reliable. Their owners better understand the local specifics and needs of the population and tend not to damage the environment.

Millions of people worldwide do not have an adequate central power supply and, as a result, suffer from interruptions or an inaccessibility of electricity and heat supply.

For such territories of Russia and other countries, the most promising way of small-scale power generation development seems to be renewable energy sources. However, according to the energy strategy up to 2030-2035 and judging by the real pace of increase in URPS utilization, mineral fuel will be the main power resource for small-scale power generation during several decades (probably till 2040–2050).

In the near future, the production methods of power and heat energy from mineral fuel at low power plants will be able to make low (distributed) energy sector competitive in comparison with the system energy sector. Their competitive advantages are:

- short construction period (9–18 months);
- quick payback (from 5 years (provided that only electrical energy is produced) to 2–3 years with full heat utilization in conditions of cogeneration and 3-generation (combined cooling, heating, and power);
- adaptation of both consumers and power structures to the market uncertainty of power development and prices for power resources that promotes increase in power safety and decrease in investment risks;
- development of new highly effective technologies;
- growth in the share of high-quality power resources, first of all, gas, in energy saving.

Today the costs to connect a new house to the centralized heat supply are comparable to the capital expenses for constructing a mini boiler house. The important advantages of small-scale power generation are modularity of generation systems, scalability, and mobility, i.e., capacity delivery to their blocks to meet consumer needs, fast connection of new blocks to an already working station, and their dismantle and relocation.

Some of the most important characteristics for gas-fired mini-CHPs are shown in Table 3.2.

Table 3.2

Technical characteristics of the most common gas-fired mini-CHPP

Power (electr.), kW	**Power (heat), kW**	**Fuel consumption, kg/hour**	**Weight, kg**
5	200	80	1500
16	610	250	5000
30	1200	400	8000
120	1500	800	1500
200	2800	1400	28000

For example, in Belgium centralization of power now does not exceed 20 %, though recently it accounted for 40 %. Experts consider that for Russia a decrease in centralization by 10–15 % in the next 10–15 years would be optimum. Alongside with other benefits, it will increase efficiency of gas utilization.

On the market there are specialized companies manufacturing highly effective equipment for small-scale power generation. Their customers are enterprises and municipal unions, oil and gas companies, builders, owners of summer residences, cottages, farms; rescuers and firemen, etc.

Systems of independent power supply (IPS) are used in three cases:

- absence of centralized power supply: consumers can choose between the next IPS kinds – traditional fuel, URPS, or two-three diverse energy assembly combinations;
- poor quality of electric supply (frequent power outages, fluctuations and voltage slumps);
- recognition of IPS competitive advantages.

Thus, the market laws state: a consumer makes the choice of a power supply source to meet his/hers needs.

Construction of an emergency power supply system for a private sector is economically proved both in large-scale residential areas and outside cities. In the first case, additional effect is achieved due to the cost cutout on capital construction: old boiler-houses and boiler rooms can be converted into thermal mini power plants. In the second case, there is no need to construct transmission and distribution networks. In conditions of restricting the maximum power consumption and application of a double-rate tariff the use of emergency power supply system to meet power demand during peak times is vital. It is more economical for the users of the given generating units due to reduction of power consumption from the centralized source during peak times when the price is far higher than the average.

Moreover, because DG technologies operate independently of the grid, they can provide emergency power for numerous public services, such as hospitals, schools, airports, fire and police stations, military bases, prisons, water supply and sewage treatment plants, natural gas transmission and distribution systems, and communications stations. Finally, DG can help the nation increase its diversity of energy sources. Some of the DG technologies, such as wind turbines, solar photovoltaic panels, and hydroelectric turbines (see unit 1), consume no fossil fuels, while others, such as fuel cells, microturbines, and some internal combustion units burn natural gas, much of which is produced in the developed countries, including Russia. The increasing diversity helps protect the economy from price shocks, interruptions, and fuel shortages. The matrix of DG benefits and services is represented in figure 3.2.

		Benefit Categories							
		Energy Cost Savings	Savings in T&D Losses and Congestion Costs	Deferred Generation Capacity	Deferred T&D Capacity	System Reliability Benefits	Power Quality Benefits	Land Use Effects	Reduced Vulnerability to Terrorism
DG Services	Reduction in Peak Power Requirements	✓	✓	✓	✓	✓	✓	✓	✓
	Provision of Ancillary Services –Operating Reserves – Regulation – Blackstart –Reactive Power	✓	✓	✓	✓	✓	✓	✓	✓
	Emergency Power Supply	✓	✓			✓	✓		

T&D= transmission and distribution.

Figure 3.2 Matrix of DG benefits and services

3.2.2. Small-scale power installations using fossil fuels

Generating plants using URPS are particularly effective in DG. However, as indicated above, their share in the total energy balance is not large yet, and in the coming decades fossil fuels will remain the dominant primary source of energy. Therefore, the two most common small-scale power installations using fossil fuels will be considered: gas-turbine power installations (GTI), piston installations (GPI).

3.2.2.1. Gas-turbine power installations

Achievements in designing turbines for aviation, automobile-building, and ship-building contribute to the development of gas-turbine methods of electric power productions within the limits of independent power. Utilization of highly effective gas-turbines (GTI) and steam and gas installations (SGI) of a wide capacity range (efficiency factor up to 55–60 %), including small ones (from one or two tens of megawatts units) for power production began in the 1980s. On their basis small GTI heat and power plants for combined electric power and heat production (mini-CHPP) were constructed.

Russia can rank high on the world gas turbine technical equipment market due to successful development of science and production association “Saturn” and more than ten other enterprises in the last 2–3 decades. “Saturn” sells a complex of industrial programs, including those focused on needs of electrical power engineering in Russia, gas and oil companies, and municipal unions.

The favorable conditions for small-scale power generation and rapid technical and technological progress in this area make GTPI-heat and power plants more and more attractive. Due to high availability of GTI factory such power plants can be commissioned within a year. The cost of energy produced at GTI-heat and power plants in many regions is competitive with large power stations. Their competitiveness essentially increases if to combine gas turbines with steam; this provides the efficiency factor close to 70%. GTI in the cogeneration mode has effective operating ratio of fuel of 90%. Thus, from 1 kWh of electric capacity, 1.3 kWh of thermal one is produced.

The main advantages of GTI over steam-turbine installations (STI) are:

- low specific weight, small size and easy transportation and installation; modern gas turbines (especially with capacity not exceeding 16 MW) are available as one or more blocks ready-to-use, requiring minimum installation works, and meeting low demands to construction works and infrastructure;
- low emissions;
- quick replacement of the gas turbine units;
- relatively low capital investment and low (for power plants) payback period;
- high flexibility in case of load change and load set; even for large GTI it takes tens of minutes to achieve full operational capability, as compared to tens of hours to start STPI;
- most GTI permit overload, i.e. increases in power above the nominal. This is achieved by raising the temperature of the working fluid. The duration of such conditions should not exceed a few hundred hours in order to avoid significant reduction of the design service life of the installation;

- high economic efficiency of GTI is achieved through cogeneration (GTI-CHPP). In the cogeneration mode GTI have a fuel efficiency of 90 % and at the same time produce 1.3–2.5 kW of heat per 1 kW of electrical power. In the cogeneration mode the electricity cost is reduced by 20–45 %, which makes GTI-CHPP in many regions competitive with the large power plants in terms of cost of the energy produced. The payback period is 3 – 4 years.

It is notable that in many countries, where significant amount of gas is used in the energy sector, other technologies are banned. The increase in the share of GTPI-heat and power plants in the EU countries is illustrated by Table 3.3.

Table 3.3

Predicted dynamics of GTI-CHPP implementation (mostly small capacity) in the EU

Year	**Capacity, GW**	**The share in total installed capacity, %**
2000	74	12
2010	91–135	13–18
2020	124–195	15–22

Optimistic views concerning the future of small GTI heat and power plants inspire high interest in them from oil and gas companies, which are challenged with needs for heat and electricity supply and have available financial resources. Gas-turbine technology allows utilizing associated gas, ensures lower cost of produced energy, and cuts down expenses on environmental protection.

Increased gasification of towns and cities ensures their involvement in generation of capacity in many regions of the country. In the long term construction of small GTI heat and power plants instead of uneconomical and outdated boiler-houses in cities and towns will make 25–35 GW by 2020 and 35–50 GW by 2050, i.e., up to 10–15 % of the total installed capacity.

GTI has a number of disadvantages, decreasing their competitive advantage:

- relatively high requirements for the quality of gas fuel to prevent high-temperature corrosion of turbine blades (restrictions are usually imposed on the total content of sulfur and alkali metals);
- pre-compression of gas fuel significantly increases the cost of energy produced (especially for small gas turbines) and in some cases prevents their implementation in the energy sector. For modern GTPI with high degrees of air compression, the required fuel gas pressure may exceed 25–30 kg/cm^2;
- sharp decline in efficiency at lower loads, especially for HD GTI (heavy-duty GTI). However, the efficiency of gas turbine engine loads below 60–50 % is challenging;

• GTI service life is considerably smaller than that of other power plants and is generally in the range of 45–125 thousand hours (for different types of GTI). There is significant progress in increasing GTI service life.

3.2.2.2. Piston installations

Historically, for many decades and up to now the majority of small power installations use piston engines, working on liquid fuel (mainly diesel, rarely – gasoline). With the increase of gas share in the general volume of power raw material the number of gas-piston installations (GPI) has also increased.

Currently, GPI in low-power engineering successfully compete with diesel piston engines and with GTI due to their benefits:

- slower rate of increase of gas fuel cost compared to liquid fuel;
- significantly lower emissions from gas-fueled engine compared to liquid-fueled engine (figure 3.3);

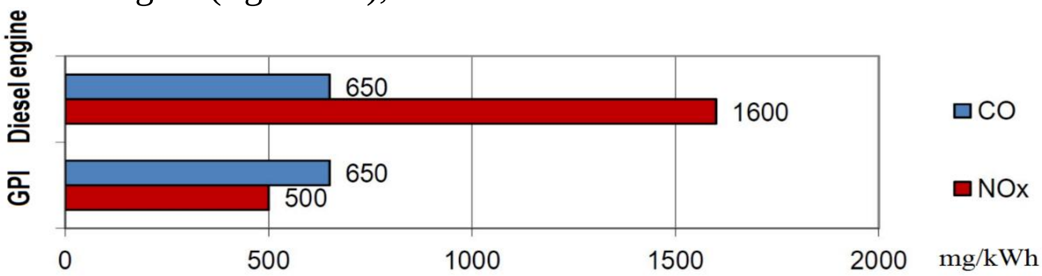

Figure 3.3 Emissions during operation of a diesel engine and GPI

- rapid development of the gas network;
- low cost of the installed capacity of the unit. 10 MW CHPP on the basis of GPI requires about $ 7.5 million investment, the unit based on GPI – about $ 9.5 million;
- the best indicator of specific weight (power to weight ratio). The reason is that the equipment provides gas supply to the engine much easier than the complex aggregates for storage and supply of fuel oil;
- higher efficiency factor less dependent on the load;
- specific fuel rate of GPI per an over 15 kW cylinder almost does not depend on capacity. This means that to ensure flexibility of energy production, it is reasonable to construct several mini-TPPs based on GPI at one enterprise;
- security: no high temperatures, pressures, moments of inertia;
- long service life of GPI: up to 300,000 hours or 37 years in operation for 8000 hours per year. It makes mini-CHPPs a reliable uninterruptible power supply;

- GPI can be started and stopped numerous times, which does not affect the overall lifespan of the engine. However, 100 GTI starts reduce its lifespan for 500 hours;
- time before the load after the GPI start is 2–3 min, while with GTI it is 15–17 min;
- lesser dependence of the GPI efficiency factor on the ambient temperature;
- mobility;
- a wide range of operating modes – from 15-20 % to 110 % (in peak mode) rated capacity in proportion to fuel consumption;
- short payback period – 3-5 years;
- autonomy of mini-CHPPs based on GPI, producing electricity and heat at the area of consumption and protection from interruptions, outages, or additional energy losses;
- managing uneven daily electricity consumption;
- GPI can run on natural gas, propane, butane, associated petroleum gas, coke oven gas, and biogas.

On the global market stand-alone power plants vary by capacity, weight, size, and primary energy source. The demand is shifting from emergency power to permanent power supply.

It is economically preferable to construct mini-CHPPs with the combined energy production on the basis of GPI with capacity up to 3 MW and on the basis of GTI – with 30-50 MW capacity. In developed countries the most common mini-TPPs based on GPI are those with individual capacity from 30 kW to 12 MW.

Among the disadvantages of piston installations, the following must be outlined:

- limited capacity is 5 MW for a single machine . However, this is not critical, as several units working in parallel can be installed, if necessary. There are examples of installations of up to 40 units in a local system. In addition, a Finnish company "Wartsila" produces powerful GPIs with an over 16 MW unit;
- increased need for lubricating oil in comparison with gas and steam turbines. GPI lubrication (diesel engines) is not only a technical, but also an economic problem. To produce 50–200 kW of power oil consumption can reach 2.5-3 g/kWh, which significantly contributes to the total operating costs, particularly, if an engine runs on cheap gas fuel.

3.2.3. Microgrids

An increase in distributed generation stimulates creation of micro-grids (MG) often called *virtual power stations*, since they are, in fact, program packages for control over electricity demand and distributed energy sources that allow the operator to model them as electricity resources. A microgrid is a localized group of electricity sources and loads that normally operates connected to the traditional wide area grid (macrogrid), but can also be disconnected and function autonomously (in an island mode) as physical or economic conditions require.

In this way, a microgrid can effectively integrate various sources of DG, especially URPS, and can supply emergency power, changing between island and connected modes.

Control and protection are challenges to microgrids. A very important feature is also to provide multiple end-use needs such as heating, cooling, and electricity at the same time since this allows energy carrier substitution and increased energy efficiency due to waste heat utilization for heating, domestic hot water, and cooling purposes (cross sectoral energy usage). MGs allow the electric power companies to control over considerable number of consumers with large volume of energy consumption (energy capacity), influencing a set of their options concerning commercial operations. In this respect, the application of MGs provides a closer interaction of retail markets via the control over the system of the main transmission lines and the distribution system that form a bilateral electricity and money streams that provides deeply integrated system of optimization of everything that is necessary for efficient control over complex SG.

For consumers making decisions concerning the use of services of power supplying organizations and guided by the efficiency and utility criteria, creation of MG is a natural stage of creating conditions for the development of their own generating and accumulating capacities, firstly, non-polluting energy sources based on URPS. The development of the MG, integrated both into a grid and the electric power and capacity market, will promote the increased role of the consumer in control over the power supply system.

Intellectual MG includes local sources of backup power supply and energy accumulation, which are more flexible, and allow wider range of generating energy sources to be connected, including EPP harnessing wind, solar, and other energy types using URPS. Such integration is challenging for the central EPS.

Electric power generation by small-distributed generators becomes economically expedient if there is a system *support* in the form of the main connection line. Electric power from microgrids will be delivered to consumers and back into the regional grid depending on the supply and demand conditions. Real time monitoring and regulation will provide information exchange and will allow all supplies to be fulfilled on the national level. In this case, consumers can correct the electricity supply according to their requirements. Energy consuming devices inside residential buildings and factories are connected with a microgrid via systems of gauges and regulators.

In the last few years, great attention has been given to the development of microgrids of four basic types (designations):

- remote MG isolated from the unified electric power grid and intended for power supply to remote consumers (settlements, military bases, or individual consumers);
- microgrids of enterprises/campuses with an individual owner;
- commercial/industrial microgrids with several owners;
- microgrids of municipalities and electric power supplying companies interconnected with larger microstructural objects.

Microgrids of the first three types are, in essence, hybrid power complexes. Their distinctive feature (except the first type) is the ability to be disconnected from the grid belonging to a power supplying company in the case of voltage dip or failure. In the process of MG exploitation, electric power suppliers and consumers had some disagreements on the ownership and control over MG. The problem is being addressed.

Few experts believe that small-scale power generation plants and microgrids can completely replace powerful PP and powerful grids in the near future, as this is difficult to implement due to economic and technological constraints. However, the rapid increase in the proportion of energy produced by low-power installations is guaranteed by their advantages mentioned above.

Exercises

1. Answer the following questions:

1. What is distributed generation?
2. When is distributed generation (DG) in high demand?
3. How many people in Russia do not have access to centralized power supply?
4. What are the potential benefits of DG systems?
5. What advantages of small-scale power generation make it competitive in comparison with traditional power engineering?
6. Why are DG technologies not so widespread?
7. What are the main advantages of gas turbine installations over steam turbine ones?

8. What are the main disadvantages of gas turbine installations limiting their competitive advantages?

9. What are the main advantages (name 5-7) of piston gas engines over gas turbines?

10. What is a mini-TPP?

11. What are the functions (purposes) of microgrids?

12. What are the main types of microgrids?

13. What, in your opinion, are the prospects for DG?

2. Translate into Russian the following English word combinations:

End-users of electricity
Environmental impact
Traditional electric power paradigm
Significant shortcomings in the production of electricity
Land alienation
Problems can be mitigated through…
Competitiveness with large power stations
Fast replacement of gas turbine units
High-speed maneuverability and load set
High requirements for the quality of gas fuel
Sharp drop in the efficiency
Gas turbine installations in cogeneration mode have a fuel efficiency of…
Gas-turbine technology allows utilizing associated petroleum gas

3. Watch the video Distributed energy resources in e-learning course and write your answer the questions

1. How can distributed energy resources help business use energy more efficiently?

2. What does the distributed energy system consist of?

3. How efficiently does this system integrate alternative energy sources?

4. What is the function of island inverters?

5. Why is a control unit a critical component of the system?

6. Why should you conduct a thorough energy assessment of your facility before implementing a distributed energy system?

7. What are the possible barriers to making the energy improvements?

8. How will consumers benefit from an on-site micro grid style system?

4. Watch the video again and find the English equivalents to the Russian expressions

Удовлетворить возросшие потребности в электроэнергии
Потерянный доход
Доступная энергия
Вырабатывать энергию на месте
Период пиковой нагрузки

Энергонакопитель
Обесточивание \ отключение линий
Предотвратить вывод на изолированную работу
Избыток электроэнергии
Направить энергию в энергонакопитель
Снизить стоимость электроэнергии от энергетической компании
Раздельный режим работы
Повышенная надежность
Снизить стоимость в период пиковой нагрузки
Разрешение выданное местными властями
Текущая структура потребления
Производительная мощность оборудования
Требования к прокладке кабелей
Система в рабочем состоянии
Низкие счета за электроэнергию

Unit 4. Modern collecting and transmission systems

Introduction

Electric power systems as we know them began developing in the early twentieth century. Initially, generating plants were associated only with local loads that typically consisted of lighting and electric transportation [20, 21]. If anything in the system failed – generating plant, power lines, or connections – the lights would quite literally be "out." Customers had not yet learned to depend on electricity being nearly 100% reliable, so outages, whether routine or emergency, were taken as a matter of course.

As reliance on electric power grew, so did the need to find ways to improve reliability. Generating stations and power lines were interconnected to provide redundancy and higher voltages were used for longer distance transportation of electricity. Points where power lines came together or where voltages were transformed came to be known as "substations." Substations often employed protective devices to allow system failures to be isolated so that faults would not bring down the entire system and operating personnel were often stationed at these important points in the electrical system so that they could monitor and quickly respond to any problems that might arise. They would communicate with central system dispatchers by any means available – often by telephone – to keep them apprised of the condition of the system. Such "manned" substations were normative throughout the first half of the twentieth century.

Modern electric power systems have been dubbed "the largest machine made by mankind" because they are both physically large – literally thousands of miles in dimension – and operate in precise synchronism. The task of keeping such a large machine functioning without breaking itself apart is not trivial. The fact that power systems work as reliably as they do is a tribute to the level of sophistication that is built into them. Substation communication plays a vital role in power system operation. The modern level of reliability of power systems is based, among other things, on the use of technologies known as "supervisory control and data acquisition," or SCADA, which allow remote monitoring and even control of key system parameters.

The use of IEC 61850 and SCADA has led to the creation of smart substations that have played a significant role in power system operation, becoming increasingly complex and interconnected as state-of-the-art information and communication technologies (ICTs) are adopted. The increased complexity and interconnection of SCADA systems have exposed them to a wide range of cybersecurity threats. These threats are not only from external entities, such as terrorists, hackers, competitors, or industrial espionage, but also from internal entities, such as ex-employees, disgruntled employees, vendor personnel for maintenance and troubleshooting, and site engineers. In practice, a threat actor may gain unauthorized cyber access to SCADA systems, exploit vulnerabilities, and thereafter launch simple or elaborate attacks that may have consequences, including information harvesting, undesirable behavior, or even catastrophic physical damage.

In recent years, malicious cybersecurity incidents have occurred in industrial control systems around the world. For instance, in July 2010 the Stuxnet worm that attacked Iranian nuclear facilities is the most famous malware attack to damage an industrial infrastructure directly; in December 2015, a coordinated intentional cyberattack via the BlackEnergy malware was directly responsible for power outages for at least 80,000 customers in western Ukraine. The incident is the first known power outage caused by a cyberattack. Further attacks have since came to light, including attacks in Ukraine again in 2015, and the TRITON/TRISIS malware that affected plants using Schneider Electric instruments in 2017. These incidents have demonstrated that “security by obscurity” is no longer an adequate scheme for critical infrastructures. Many governments and government agencies have expressed concern at the possibility of catastrophic damage to their critical infrastructures from Stuxnet-like or BlackEnergy-like attacks in the future.

This section is devoted to the modern principles of building SCADA systems and cybersecurity in smart substations.

4.1. Supervisory control and data acquisition (SCADA) systems and cybersecurity in smart substations

4.1.1. SCADA systems. Functional and communication requirements

SCADA (supervisory control and data acquisition system) refers to the combination of telemetry and data acquisition. SCADA encompasses the collecting of the information via a RTU (remote terminal unit), transferring it back to the central site, carrying out any necessary analysis and control and then displaying that information on a number of operator screens or displays. The required control actions are then conveyed back to the process [20, 22].

In the early days of data acquisition relay logic was used to control production and plant systems. With the advent of the CPU (as part of the microprocessor) and other electronic devices, manufacturers incorporated digital electronics into relay logic equipment, creating the PLC or programmable logic controller, which is still one of the most widely used control systems in industry. As needs grew to monitor and control more devices in the plant, the PLCs were distributed and the systems became more intelligent and smaller in size. PLCs and/or DCS (distributed control systems) are used as shown below. Although initially RTU was often a dedicated device, PLCs are often used as RTUs these days.

The advantages of the PLC/DCS/SCADA system are:

• The computer can record and store a very large amount of data.
• The data can be displayed in any way the user requires.
• Thousands of sensors over a wide area can be connected to the system.
• The operator can incorporate real data simulations into the system.
• Many types of data can be collected from the RTUs.
• The data can be viewed from anywhere, not just on site.

The disadvantages are:

• The system is more complicated than the sensor to panel type.
• Different operating skills are required, such as system analysts and programmer.
• With thousands of sensors there is still a lot of wire to deal with.
• The operator can see only as far as the PLC.

As the requirement for smaller and smarter systems grew, sensors were designed with the intelligence of PLCs and DCSs. These devices are known as IEDs (intelligent electronic devices). The IEDs are connected on a fieldbus such as Profibus, DeviceNet or Foundation Fieldbus to the PC. They include enough intelligence to acquire data, communicate to other devices and hold their part of the overall program. Each of these super smart sensors can have more than one sensor on board. Typically an IED could combine an analog input sensor, analog output, PID control, and communication system and program memory in the one device.

The advantages of the PC to IED fieldbus system are:

• Minimal wiring is needed.
• The operator can see down to the sensor level.
• The data received from the device can include information such as serial numbers, model numbers, when it was installed and by whom.
• All devices are plug_and_play; so installation and replacement are easy.
• Smaller devices mean less physical space for the data acquisition system.

The disadvantages of a PC to IED system are:

• The more sophisticated system requires better trained employees.
• Sensor prices are higher (but this is offset somewhat by the lack of PLCs).
• The IEDs rely more on the communication system.

Design of any system should always be preceded by a formal determination of the business and corresponding technical requirements that drive the design. Such a formal statement is known as a “functional requirements specification.” Functional requirements capture the intended behavior of the system. This behavior may be expressed as services, tasks, or functions the system is required to perform.

In the case of SCADA, it will contain such information as system status points to be monitored, desired control points, and analog quantities to be monitored. It will also include identification of acceptable delays between when an event happens and when it is reported, required precision for analog quantities, and acceptable reliability levels. The functional requirements analysis will also include a determination of the number of remote points to be monitored and controlled. It should also include identification of communication stakeholders other than the control center, such as maintenance engineers and system planners who may need communication with the substation for reasons other than real-time operating functionality.

The functional requirements analysis should also include a formal recognition of the physical, electrical, communications, and security environment in which the communication is expected to operate. Considerations here include recognizing the possible (likely) existence of electromagnetic interference from nearby power systems, identifying available communication facilities, identifying functionally the locations between which communication is expected to take place, and identifying communication security threats that might be presented to the system.

It is sometimes difficult to identify all of the items to be included in the functional requirements, and a technique that has been found useful in the industry is to construct a number of example "use cases," which detail particular individual sets of requirements. Aggregate use cases can form a basis for a more formal collection of requirements.

After the functional requirements have been articulated, the corresponding architectural design for the communication system can be set forth. Communication requirements include those elements that must be included in order to meet the functional requirements.

Some elements of the communication requirements include:

- Identification of communication traffic flows – source / destination / quantity.
- Overall system topology – for example, star, mesh.
- Identification of end system locations.
- Device/processor capabilities.
- Communication session/dialog characteristics.
- Device addressing schemes.
- Communication network traffic characteristics.
- Performance requirements.
- Timing issues.
- Reliability/backup/failover.

• Application service requirements.
• Application data formats.
• Operational requirements (directory, security, and management of the network).
• Quantification of electromagnetic interference with stand requirements.

Relay systems perform vital functions to isolate local failures in generation, transmission, and distribution systems so that they will not spread to other parts of an interconnected power system. Communication systems are a vital component of wide area power system relaying. They provide the information links needed for the relay and control systems to operate. Because of potential loss of communication, relay systems must be designed to detect and tolerate failures in the communication system and must be independent of the communication system and not subject to the same failure modes. The communication system must be designed for fast, robust, and reliable operation. Factors that can influence the performance of the relay system include communication system bandwidth, delay, latency, jitter, reliability, and error handling. Relay systems frequently require communication delays not to exceed a few milliseconds and often cannot tolerate timing jitter. There are several data communication systems, which can be used for either relay or SCADA communications. It should be noted that frequently relay applications have more stringent requirements for speed, latency, and jitter than do SCADA applications. Electric utilities use a combination of analog and digital communication systems for their operations consisting of power line carrier (PLC), radio, microwave, leased phone lines, satellite systems, and fiber optics. Each of these systems has characteristics that make them well suited to particular applications. The advantages and disadvantages of each are briefly summarized in the following:

• Transmission PLC is usually an economic choice for relay communication but has limited distance of coverage and low bandwidth. It is best suited to station-to-station protection as well as communications to small stations that are difficult or costly to access otherwise.
• Company-owned microwave is cost-effective and reliable but is maintenance intensive. Microwave is useful for general communications for all types of applications.
• Radio systems provide narrower bandwidths but are nonetheless useful for mobile applications or communication to locations difficult to reach otherwise.
• Satellite systems likewise are effective for reaching difficult-to-access locations but are not good where the long delay is a problem. They also tend to be expensive.

• Leased phone lines are very effective where a solid link is needed to a site served by standard telephone service. They tend to be expensive in the long term, so are usually not the best solution where many channels are required.

• Fiber-optic systems are a new option. They are expensive to install and provision but are expected to be very cost-effective. They have the advantage of using existing rights-of-way and delivering communications directly between points of use. In addition, they have the very high bandwidth needed for modern data communications.

• Spread spectrum radio is a new option, which can provide affordable solutions using unlicensed services. Advances in this field are appearing rapidly and they should be examined closely to determine their usability to satisfy relaying requirements.

The increasing speed of wide area networks combined with the availability of high-precision satellite time references is increasingly making it possible to share communication facilities between corporate information, SCADA, and relaying applications. The IEC 61850 standard (based on the UCA) provides specifications for communication facilities using wide area network techniques, which will not only serve SCADA needs but also provide functionality for relay systems.

Exercises

1. Restore the beginning of the sentences.

1) … so routine and emergency outages were quite common in the early 20th century.

2) … are known as "manned" substations.

3) The … has led to the creation of smart substations.

4) … have occurred in industrial control systems around the world threatening their security.

5) … which are reported to be the most famous malware attacks.

6) … was used to control production and plant systems.

7) … which is still one of the most widely used control systems in industry.

8) … thus making the PLC/DCS/SCADA systems state-of-the-art technologies for remote monitoring of key system parameters.

9) … are viewed as their disadvantages.

10) … to meet the requirement for smaller and smarter systems.

11) … which contributed to wide application of the PC.

12) … which makes IED field-bus system better than a PC one.

13) … is known as a "functional requirements specification."

14) … are included in SCADA functional requirements specification.

15) … are some of the elements included in the communication requirements.

16) … can influence the performance of the relay system.

17) … therefore, they are best suited to station-to-station protection as well as communications to small stations.

18) … that is why they are expected to be very cost-effective.

19) … and can be used in difficult-to-access locations.

2. Listening

2.1. You will hear a radio program about SCADA. For questions 1-10, complete the sentences

The loosely switchgear SCADA system is designed to **1** ________ and ________ and ________ the operation of large electrical networks.

Let's see how the SCADA system is used to **2** ________ and ________ the network during a fault.

The SCADA system **3** ________ notification of the circuit breaker trip then uses the **4** ________ positioned around the network to determine where the fault has occurred.

The operator remotely opens the **5** ________ from the primary substation to substation two. And then opens the **6** ________ from substation 2 to the rural community.

Typically the network will be **7** ________ within three minutes of the original fault.

The **8** ________ from substation 3 is no longer required and so the **9** ________ can open its outgoing switch.

The final step for the SCADA operator is to reopen the GX switch to disable the back feed to the rural community **10** ________ of the whole network.

2.2. Listen again and find the English equivalents to the given Russian expressions:

1) собирать и обрабатывать данные
2) первичная подстанция
3) обслуживать сеть
4) причинить ущерб
5) перерыв в электроснабжении
6) отключение электроэнергии
7) отключение автоматического выключателя
8) выявить неисправность
9) индикаторы сбоя прохождения
10) перераспределить энергию

11) вводной автоматический выключатель
12) выходной выключатель
13) возобновить подачу энергии
14) восстановить электроснабжение
15) избежать перегрузки
16) поврежденный участок
17) первичное повреждение
18) восстановить привычную работу

2.3. Fill in the gaps in the sentences with the expressions from Task 2.

1. SCADA system is designed to ________________________ (collect and process data) sent from other substations.

2. The __________________________(primary substation) provides a feed out to residential areas, commercial city districts and other local facilities.

3. When the SCADA system receives notification of the circuit breaker trip it uses the __________________________(fault passage indicators) to determine where the fault has occurred.

4. The operator uses the Luci switchgear SCADA system to isolate the affected area and __________________________ (reroute power) to customers without a supply.

5. The SCADA system is used to manage and ______________________ (maintain the network) during a fault.

6. The break in supply causes the circuit breaker ____________________(trip) at the primary substation leading to a total power outage.

7. To isolate the fault area from the rest of the network the operator remotely opens the ______________________ (incoming switch) from the primary substation to substation two and then opens the 8) ___________________________ (outgoing switch) from substation 2 to the rural community.

9. It is possible to sectionalize the network and ____________________ (reinstate) the supply within three minutes of the original fault.

10. Finally, the SCADA operator reopens the GX switch to disable the back feed to the rural community and restores the ____________________ (standard operation) of the whole network.

4.1.2. Components of a SCADA System

Traditional SCADA systems grew up with the notion of a SCADA "master" and a SCADA "slave" or "remote." The implicit topology was that of a "star" or "spoke and hub," with the master in charge. In the historical context, the master was a hardwired device with the functional equivalent of indicator lamps and pushbuttons (Figure 4.1).

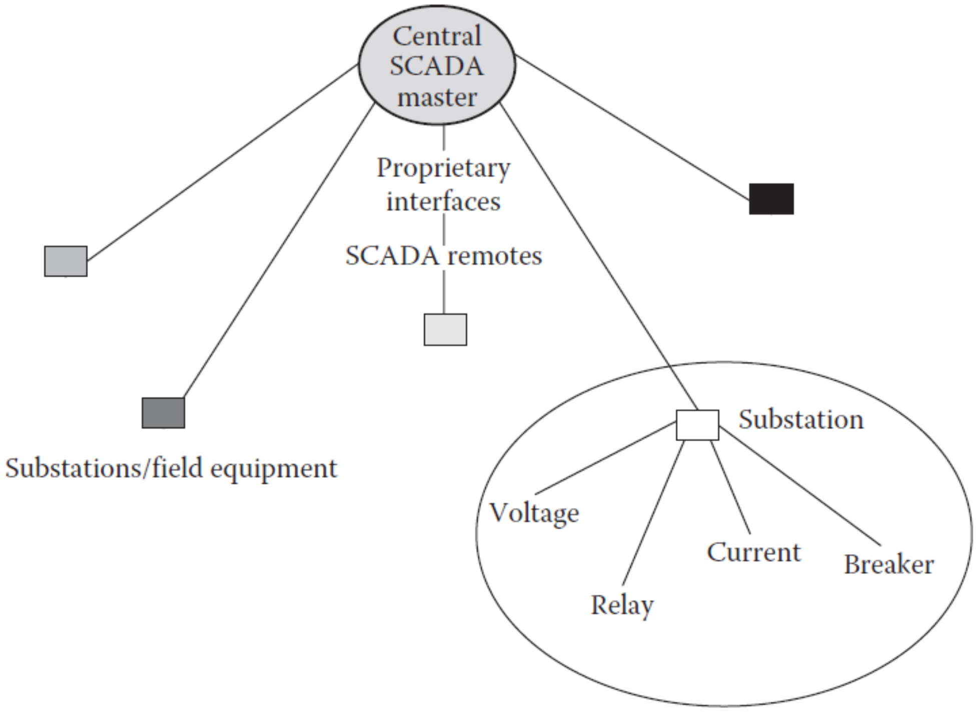

Figure 4.1 Traditional SCADA system topology

Modern SCADA systems employ a computerized SCADA master in which the remote information is either displayed on an operator's computer terminal or made available to a larger "energy management system" through networked connections. The substation RTU is either hardwired to digital, analog, and control points or frequently acts as a "submaster" or "data concentrator" in which connections to intelligent devices inside the substation are made using communication links. Most interfaces in these systems are proprietary, although in recent years standards-based communication protocols to the RTUs have become popular. In these systems if other stakeholders such as engineers or system planners need access to the substation for configuration or diagnostic information, separate, often ad hoc, provision is usually made using technologies such as dial-up telephone circuits.

With the introduction of networkable communication protocols, typified by the IEC 61850 series of standards, it is now possible to simultaneously support communication with multiple clients located at multiple remote locations. Figure 4.2 shows how such a network might look. This configuration will support clients located at multiple sites simultaneously accessing substation devices for applications as diverse as SCADA, device administration, system fault analysis, metering, and system load studies.

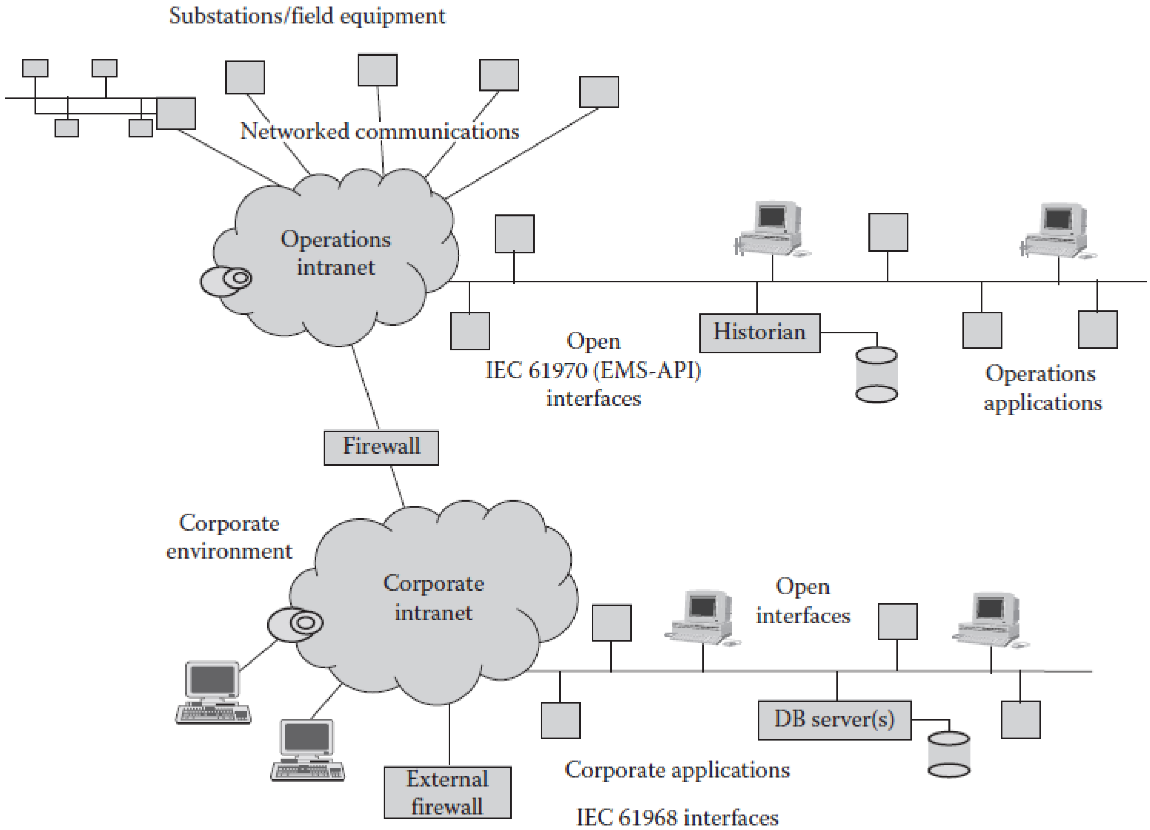

Figure 4.2 Networked SCADA communications

SCADA systems as traditionally conceived report only real-time information, but interfaces built according to standards IEC 61968 and IEC 61970 will allow integration of both control center and enterprise information systems as shown in Figure 4.2. A feature that may be included in a modern SCADA system is that of a historian, which time-tags each change of state of selected status parameters or each change (beyond a chosen deadband) of analog parameters and then stores this information in an efficient data store, which can be used to rebuild the system state at any selected time for system performance analyses.

Exercises

Compare the traditional SCADA system topology with modern SCADA systems (use fig. 4.1 and fig. 4.2). Use the next comparative structures:

Comparative structures:

- as... as...
- not nearly as...
- a good deal more...
- a lot more ...
- much …
- less...

- not quite as ...
- twice as computerized as ...
- half as efficient as …
- a little / a bit / slightly slower than …

4.1.3. SCADA hardware and software

A SCADA system consists of a number of remote terminal units (or RTUs) collecting field data and sending that data back to a master station via a communications system. The master station displays the acquired data and also allows the operator to perform remote control tasks.

The accurate and timely data allows for optimization of the plant operation and process. A further benefit is more efficient, reliable and most importantly, safer operations. This all results in a lower cost of operation compared to earlier non-automated systems.

On a more complex SCADA system there are essentially five levels or hierarchies:

- Field level instrumentation and control devices.
- Marshalling terminals and RTUs.
- Communications system.
- The master station(s).
- The commercial information technology (IT) or data processing department computer system.

The RTU provides an interface to the field analog and digital sensors situated at each remote site.

The communications system provides the pathway for communications between the master station and the remote sites. This communication system can be wire, fiber optic, radio, telephone line, microwave and possibly even satellite. Specific protocols and error detection philosophies are used for efficient and optimum transfer of data.

The master station (or sub-masters) gather data from the various RTUs and generally provide an operator interface for display of information and control of the remote sites. In large telemetry systems, sub-master sites gather information from remote sites and act as a relay back to the control master station.

SCADA software can be divided into two types, proprietary or open. Companies develop proprietary software to communicate to their hardware. These systems are sold as ‘turn key’ solutions. The main problem with these systems is the overwhelming reliance on the supplier of the system. Open software systems have gained popularity because of the interoperability they bring to the system. Interoperability is the ability to mix different manufacturers' equipment on the same system.

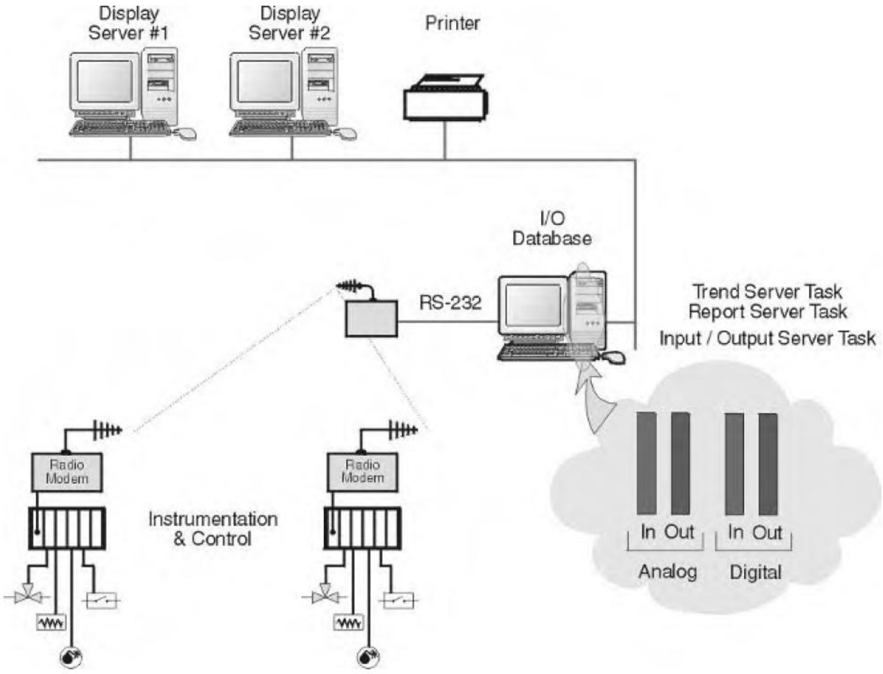

Figure 4.3 Typical SCADA system

Citect and WonderWare are just two of the open software packages available on the market for SCADA systems. Some packages are now including asset management integrated within the SCADA system. The typical components of a SCADA system are indicated in the diagram (Figure 4.3).

Exercises

Agree or disagree with the following statements. Correct the inaccurate information.

1) The master station collects field data to be processed by RTUs.

2) SCADA is a low cost option compared to earlier non-automated systems.

3) Complex SCADA system has seven levels.

4) Proprietary SCADA software is more interoperable than the open one.

4.2. Cyber-induced attacks and cybersecurity threats to substation systems

In the past, substation control and protection schemes typically consisted of single function devices that were mainly hardwired interconnected [21, 23]. However, over the decades, taking advantage of the multifunction intelligent electronic devices (IEDs), it became possible to increase the functionalities and hence reduce the number of devices. Furthermore substation control has introduced local area networks (LAN) for station and bay control replacing the traditional hardwired solution. More recently the International Electrotechnical Commission (IEC) has published a number of communication standards including IEC 61850 which is becoming the dominant basis of protection and automation systems not only within substations but also between substations and between substations and other remote locations such as control centers.

However this deployment of electronic devices renders substation secondary systems vulnerable to malicious interference or attack from two sources:

- Cyber-induced attacks.
- Intentional electromagnetic interference (IEMI).

One feature of IEC 61850 is its strong emphasis on interoperability between intelligent electronic devices (IEDs) manufactured by different vendors. Another strong feature is the open publication of the IED data dictionary and communication services supported for most protection and automation functions. Furthermore, IEC 61850 and other communication standards include the specifications for peer-to-peer operation over high-speed communication channels using the Internet Protocol (IP). This raises significant cyber security concerns. Therefore, there is a need to introduce requirements for prevention against unauthorized cyber-based access to and use of IEDs.

Cyberattacks can be grouped into four categories as defined in CIGRE Technical Brochure 603 *Application and Management of Cybersensitivity Measures for Protection and Control Systems*.

Gathering attacks involve skimming or tampering with substation automation data, eavesdropping (listening and recording communication between P&C IEDs and authorized users), and performing traffic analysis of repeated patterns of communication.

Imitation attacks such as spoofing, cloning, and replay to impersonate legitimate access to substation IEDs, and between substation IEDs, to obtain authorized access.

Blocking attacks designed to deplete substation IED resources and network resources or interfere with communications using tactics such as denial of service, jamming, and malware.

Privacy attacks designed to disclose sensitive information about legitimate protection and control (P&C) users or groups.

Prerequisites to successful cyber defense are:

- Clear unambiguous utility security policies and procedures.
- Robust and reliable security mechanism provided in the substation devices and services.

Cybersecurity Threats to Substation Systems include:

Vulnerabilities Introduced During Development

Vulnerabilities introduced into the hardware and software by protection and control system manufacturers are typically difficult for the utility substation engineers to discover and patch.

The most common cybersecurity flaw is a vulnerability that provides the means to inject malicious code into the system software.

This can allow an individual to bypass the access control restrictions set by the developer or utility engineer, for instance, to gain complete control of a protection relay from a remote location or to escalate user privileges to "administrator" on a protection relay. Typically, administrator privilege includes the capability to change the privileges of other users.

Code injection attacks can be realized as binary code injection attacks or source code injection attacks. A binary code injection attack involves insertion of malicious code in a binary program to alter how the program behaves. Source code injection attacks involve interaction with protection and control system applications written in programming languages that do not require compilation, e.g., JavaScript, Hypertext (PHP), and Structured Query Language (SQL). Consequently, this attack type primarily concerns web applications. Common vulnerabilities of this category include cross-site scripting (XSS) and SQL injection. XSS involves adding malicious JavaScript code to existing web applications which then enables any visitor (or visitor specified by the attacker) access to the particular application

Deployment and Maintenance Vulnerabilities

A common type of vulnerability concerns enabled software services that are either not utilized or are unknown to the engineers responsible for the security of the protection and control system. These types of services are often vulnerable because no one is concerned about them. An example of a service often employed, but seldom used in systems, is Window's file sharing, which is enabled per default on modern Windows operating systems. Another example of a service unknown to the utility engineer could be a file transfer protocol (FTP) server that is enabled to allow remote data access to system files for a user, without consent from the utility engineer.

Firewall Configuration Errors

Assuming that the firewall within the substation is in a gateway or local area network (LAN) routers, appropriately configuring a firewall is a difficult task for the substation engineer due to the complexity of the firewall rules. However, the engineer must 882 M. Mackey be confident that the firewall configuration is correct because of the trust invested in its security. To gain this confidence, SAT and maintenance testing should always include verification that the firewall configuration is correct. Regardless of where the firewall is located, frequent misconfigurations provide the means for an attacker to reach vulnerable P&C system components and their data.

Online Password Guessing

For system software using passwords, a back-off function should be in place that limits the number of password attempts allowed (typically a maximum of three tries). If the software does not have a back-off function, attackers can brute-force the authentication mechanism to gain entry. If the password is weak, the vulnerability is serious because using a dictionary of common words the attacker can easily guess the password.

Off-Line Password Guessing

Sometimes it is possible for an attacker to retrieve whole databases of substation system user credentials, for example, from active directory servers. If the information is poorly encrypted (or not at all), of low entropy (i.e., easy to guess), then the attacker can simply extract the information from the database.

For this reason, protection and control engineering managers must strictly enforce applicable cybersecurity policies and organizational directives.

Inadequate Access Controls

Poorly specified access controls can result in giving a system user too many or too fewprivileges, for example, providing administrator access to an individual or to a group of individuals who should have read-only access. Overly restrictive access control can also result in problems due to services not properly shutdown or sensitive credentials shared among personnel. Protection and control system engineers should routinely review who has what access control privileges and ensure that they properly align with those privileges associated with their job role and responsibilities.

Network Traffic Analysis and Manipulation

An attacker that is able to listen to and record data in transit has the potential capability to conduct a number of different attacks, e.g., the attacker could replay previously sent messages and thus fool the system operators regarding the state of the power system. Intercepting passwords sent in clear text is not difficult. Simply adding a randomly selected encryption mechanism is not enough to prevent an attacker from listening to and recording the message traffic. Although applicable to both wired and wireless communications, special attention to deployment of wireless communications is advisable. For example, utilities that have in operation Wired Equivalent Privacy (WEP) for IEEE 802.11 wireless networks whose encryption mechanisms can be easily broken. Protection and control system engineers should review all wireless remote access to the automation system. Depreciate wireless access using WEP encryption and their interface to the P&C system network declared “untrusted.”

4.2.1. Practical cybersecurity solutions

Figure 4.4 shows the global vulnerabilities management process indicating the responsibilities of the various entities involved in the provision of the system.

- P1: Vendor protection and control engineer.
- P2: Third-party service provider.
- P3: Protection and control system integrator.
- P4: Electrical power utility (EPU) protection and control engineer.

Vendors need to have in place a well-defined cybersecurity threat-survey process to address the vulnerability issues in a timely manner. This survey process requires up-to-date information about cybersecurity problems coming from various thirdparty components providers (e.g., Microsoft, Sybase, etc.) as well as entities like CERT (computer emergency response team).

Collaboration Efforts

Practical solutions for implementing cybersecurity require a cooperative effort between protection and control engineers, network engineers, and others with specialized skills. For example, managing network devices (router, switches, firewall, etc.) are usually the responsibility of the network engineer. However, the P&C engineer must work with the network engineer to ensure that configuration settings for the network devices do not impact P&C systems performance, reliability, and availability.

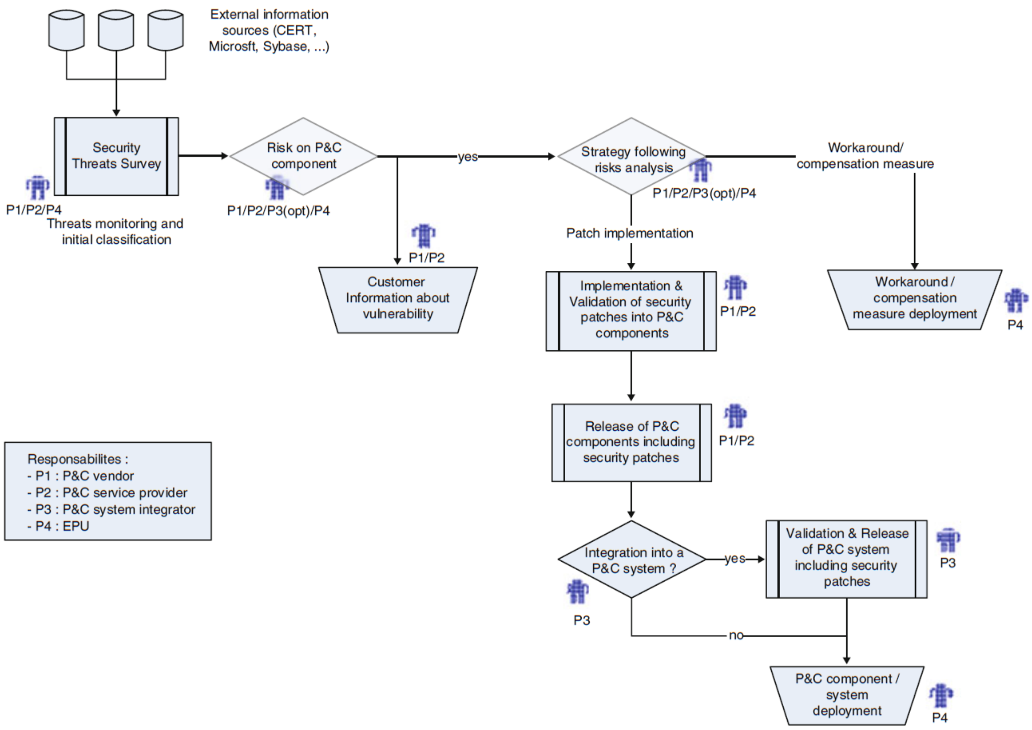

Figure 4.4 Vulnerability management process

Physical Security for Protection and Control Systems

Physical security involves many different aspects from locked gates and doors allowing access to the IEDs to prevention of unauthorized access to the automation systems. The access security for the IEDs is the role-based access control (RBAC) involving password and user permission levels. The utility should keep a database of permissible functions by personnel that links to the password for that person. For the many different aspects of RBAC, see CIGRE Technical Brochure 427 The Impact of Implementing Cyber Security Requirements using IEC 61850.

Endpoint Security of Protection and Control Systems

Common Malware Issues

Sophisticated malware is proliferating, especially at the endpoints that connect protection and control networks to unprotected devices. Ponemon Institute, an independent research organization, reported that their surveys identified the most frequently encountered network incidents as malware attacks, botnet attacks, and SQL injections. The most challenging types of incidents were zero-day attacks, SQL injections, and the exploitation of software vulnerabilities more than 3 months old. The greatest concern is related to employees working from remote locations, downloading unfamiliar third-party apps, and increasing the threat of destructive, hard-to-detect malware attacks. According to Verizon's 2010 Data Breach Investigations Report, the most common attack pathways are web applications, remote access and control services and software, and backdoor or control channel.

Emerging Endpoint Security Stack

An emerging solution is the creation of an endpoint security stack. This places patch and configuration management at the center and then surrounds it with layers of coordinated application control, device control, and antivirus. Protection and control engineers should consider the following strategies and tactics:

- Improve patch management: IEC 62443-2-3 offers an improved patch management approach that should be considered.
- Put antivirus in place.
- Whitelist protection and control apps: these allow only approved applications to execute and block everything else; by default, it protects the network – including against "zero-day" attacks – as it does not need to wait for the latest vulnerability patch or antivirus definition.

Engineers understand patch management and antivirus perimeter defenses. They need a better understanding of whitelisting management procedures.

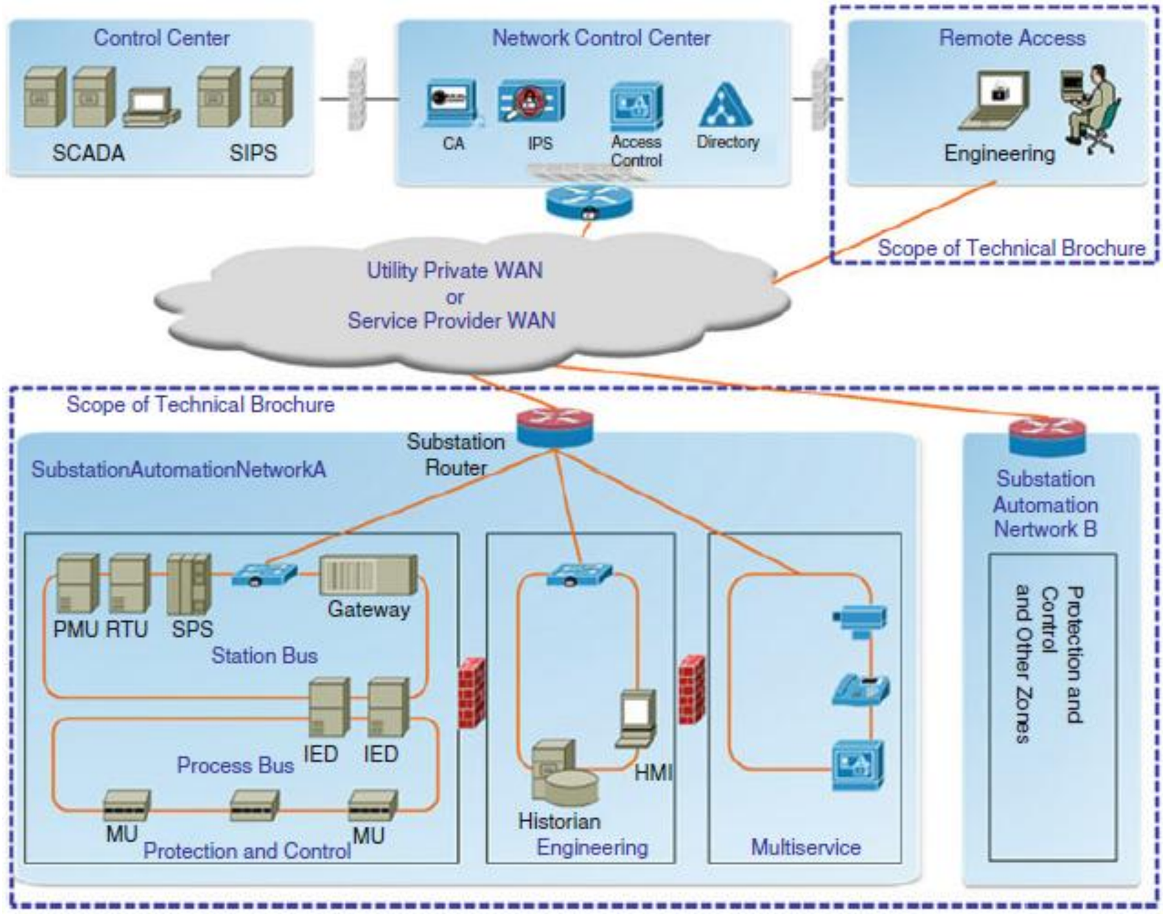

Figure 4.5 Notional architecture used for this section

Network Security Control of Protection and Control Systems

Network security is an important building block to achieve a layered defense for automation systems. In addition, it is an essential part of the notional architecture (Figure 4.5). It affects the communication aspects of the main use cases: substation automation, substation-to-substation, substation-to-control center, as well as remote engineering. In general, network security fulfils the following security functions:

• Access control – strong identity mechanisms for all elements of a protection and control system connected to a network: users, devices, and applications.

• Data confidentiality and integrity – encryption is optional, except where requirements and regulations mandate data confidentiality.

• Threat detection and mitigation – the objective is to protect critical assets against cyberattacks and insider threats.

• Device and platform integrity – device protection against compromise must be resistant to cyber-induced attacks.

• Network traffic analysis to evaluate deviations from the norm to detect cyberinduced attacks on the protection and control system.

• Performance management monitors and maintains the performance of the network.

• Fault detection and notification of all protection and control network components and associated IEDs attached to the network.

• In terms of network architecture, topology, and hardware, a correct and use case driven network design regarding capacity, bandwidth, and QoS as well as a proper selection and configuration of routers and switches including redundancy aspects are essential preconditions.

Operational Constraints: Enabling Trusted Access to Substation Automation Assets

There is a clear need relating to substation automation systems for the comprehensive management of role-based access control. This must include various independent entities required for substation operations such as support contractors and regulatory agencies that have legitimate needs for access to and control of substation assets. Some situations require access on-site and others require access from remote locations. In either case, the protection and control engineer's view is to declare those requiring access to protection and control assets as untrusted. To warrant trusted access and use of substation assets, use digital certificates to vet and control access privileges and user privileges. Further details on access enabling mechanisms for key management life cycle are described in CIGRE Technical Brochure 603, Application and Management of Cybersensitivity Measures for Protection and Control, Annex M.

Maximizing the Use of Compensating Security Mechanisms

Protection and control engineers recognize three reasons to provide compensating security controls to protect critical assets and functions. First, legacy systems, subsystems, and components have inadequate security mechanisms and must rely on perimeter defense systems for protection. Second, many new protection and control components do not have adequate memory or computing resources to embed security mechanisms. Third, response time for power system protection cannot afford either the communication latency or processing time to perform complex tasks such as encryption and decryption to protect the confidentiality and data integrity of information exchanged. For these reasons, protection and control engineers need to insist on maximizing their first line of defense, specifically, substation LAN access control from interfaces that are declared "untrusted." The second line of defense is comprised of multiple security mechanisms that enforce use control (e.g., read/write privileges specified in digital certificates), restricted data flow managed by substation network routers, and management of network resources embedded in all P&C IEDs.

Exercises

1. Match the type of cyberattack to its definition:

1) Gathering attacks	**a)** Spoofing, cloning, and replay to impersonate legitimate access to substation IEDs, and between substation IEDs, to obtain authorized access.
2) Imitation attacks	**b)** disclosure of sensitive information about legitimate protection and control (P&C) users or groups.
3) Blocking attacks	**c)** Skimming or tampering with substation automation data, eavesdropping and performing traffic analysis of repeated patterns of communication.
4) Privacy attacks	**d)** depletion of substation IED resources and network resources or interference with communications using tactics.

2. Fill in the table with the key information about cybersecurity threats to substation systems and solutions to the problem.

Cybersecurity threat	Key Information	Solution
1) Firewall configuration errors		
2) Online Password Guessing		
3) Off-line Password Guessing		
4) Inadequate Access Controls		
5) Network Traffic Analysis and Manipulation		

3. Match the English expressions to their Russian equivalents. Use them to describe the vulnerability management process shown in fig. 4.4.

1) address the vulnerability	**a)** управление доступом на основе ролей
2) implement cybersecurity	**b)** скачать незнакомые приложения
3) systems performance	**c)** полномочия пользователя
4) allow access to	**d)** разрешенное приложение
5) prevent unauthorized access	**e)** предпринять меры против уязвимости
6) role-based access control (RBAC)	**f)** минимизация последствий угроз
7) user permission	**g)** отклонения от нормы
8) unprotected devices	**h)** эксплуатационные характеристики системы
9) malware attacks	**i)** определение угрозы
10) zero-day attack	**j)** встроенный механизм защиты
11) download unfamiliar apps	**k)** не допустить неавторизованный доступ

12) hard-to-detect malware attacks	**l)** атака нулевого дня
13) approved application	**m)** внедрить кибербезопасноть
14) layered defense	**n)** быстрота реагирования
15) threat detection	**o)** выполнять сложные задачи
16) threat mitigation	**p)** незащищенные устройства
17) deviations from the norm	**q)** время обработки данных
18) fault detection	**r)** сложно обнаруживаемые хакерские атаки
19) embed security mechanism	**s)** обнаружение неисправности
20) response time	**t)** многослойная оборона
21) processing time	**u)** разрешить доступ к …
22) perform complex tasks	**v)** хакерские атаки

4.2.2. Action summary for substation automation engineers to counter cyber-induced attacks

The important actions are summarized as follows:

• Protection and control engineers (and IT engineers) should review and approve the factory acceptance and site acceptance test plans and procedures, including test scripts, to ensure they adequately include consideration of cybersecurity mitigation requirements.

• Although antivirus is helpless against zero-day attacks, protection and control engineers should ensure that up-to-date patches are installed for perimeter defense of the protection and control network to block known threats.

• Protection and control engineers should use security scanners to obtain an objective assessment of the state of cybersecurity vulnerabilities. They should periodically selectively scan individual sites and mission critical applications. They should perform automated penetration testing and system audits to support compliance management policies, procedures, and organizational directives.

• In addition to antivirus perimeter defense, engineers should implement a strong whitelisting policy to protect access to the protection and control network and components.

• Engineers should periodically review all wireless remote access to the protection and control system. Wireless access using Wired Equivalent Privacy (WEP) encryption should be depreciated and their interface to the system declared “untrusted.”

• Role-based access control requires effective key management to protect access control and user control privileges specified in the digital certificate issued to users. Key management is not the sole responsibility of the protection and control engineers. However, these engineers should be part of the key management team with the responsibility to influence the design and operation of key management support functions that directly relate to the substation automation systems, subsystems, and components that use keying material for security protection.

CIGRE Technical Brochure 603, *Application and Management of Cybersensitivity Measures for Protection and Control* describes ten important points to be considered:

1. The scope and level of cybersecurity protection should be specific and appropriate to the protection and control assets at risk. One approach does not fit all; risk-based tailoring provides the proper context that is responsive to organizational structures and policies.

2. Cybersecurity mechanisms must be pervasive, simple, scalable, and easy to manage by protection and control engineers as part of their normal duties.

3. Where applicable, based on the utility's risk assessment, IEDs and applications must communicate using open, secure protocols such as those described in IEC 62351.

4. All protection and control devices must be capable of maintaining their own cybersecurity policy (or provided compensating protection) on an untrusted network.

5. All protection and control engineers, technicians, and managers, including the processes they control and the cybersecurity technology they use, must have declared and transparent levels of trust for any exchange of data to take place. 6. IEDs must be capable of appropriate levels of (mutual) authentication for accessing systems and data.

7. Outside of the area of control specific to protection and control, authentication, authorization, and accountability requires careful attention to the trustworthiness of external interfaces.

8. In accordance with the attributes in IEC 62351, access to protection and control data is controlled.

9. Data privacy (and the cybersecurity of any asset of sufficiently high value) requires a segregation of duties and privileges enforced by strong role-based access control (RBAC) mechanisms.

10. When stored, in transit or in use, by default, enabling security mechanisms protects protection and control data.

Exercises

Continue the sentences:

1) Protection and control engineers (and IT engineers) should approve …

2) Antivirus is helpless against …

3) Engineers should implement …
4) Engineers should periodically review …
5) Role-based access control requires …
6) Cybersecurity mechanisms must be …
7) All protection and control engineers, technicians, and managers must have …
8) Data privacy requires …

4.2.3. Cybersecurity test-bed of IEC 61850 smart substations

Although the IEC 62351 standard provides a framework for the cybersecurity design of the IEC 61850 protocol, problems remain, and major manufacturers do not generally implement adequate security in their intelligent electronic devices (IEDs). In recent years, during the construction of smart substations, utilities and manufacturers have paid more attention to the interoperation of devices and implementation of functions than to cybersecurity consideration and testing. Nevertheless, research on cost-effective cybersecurity for IEC 61850-based smart substations is still at an early stage. Much more in-depth investigation and analysis of specific vulnerabilities and cyberattacks are required. To this end, this section proposes a comprehensive and realistic SCADA-specific cyber-physical test-bed to investigate potential vulnerabilities using simulated cyberattacks. This test-bed environment meets this challenge by enabling real attack scenarios to be analyzed and effective cybersecurity countermeasure technologies to be proposed and evaluated for the smart substation cyber domain.

In order to investigate potential cybersecurity vulnerabilities in IEC 61850-based smart substations, Yi Yang et al. have built a cyber-physical test-bed in State Grid Jiangsu Electric Power Research Institute (Nanjing, China), as shown in Figure 4.6. The test-bed consists of the simulation level, process level, bay level, and substation level.

In the simulation level, a real-time digital simulator (RTDS) is utilized to model multiple power system scenarios and simulate transient characteristics and behaviors of modeled power systems. A universal relay test set and commissioning tool, as a programmable voltage and current source, is an optional simulator to realize steady and transient simulation.

In the process level, merging units (MUs) are connected in the sample value (SV)/IEEE1588 network, and intelligent terminals (ITs) are connected in the generic object oriented substation event (GOOSE)/IEEE1588 network. The process level networks are Ethernet switch-based fiber-optic networks.

The bay level IEDs include relays, measure-control devices, fault recorder, network analyzer, and time synchronization IED. The bay level IEDs are connected in the process level networks and the substation level network.

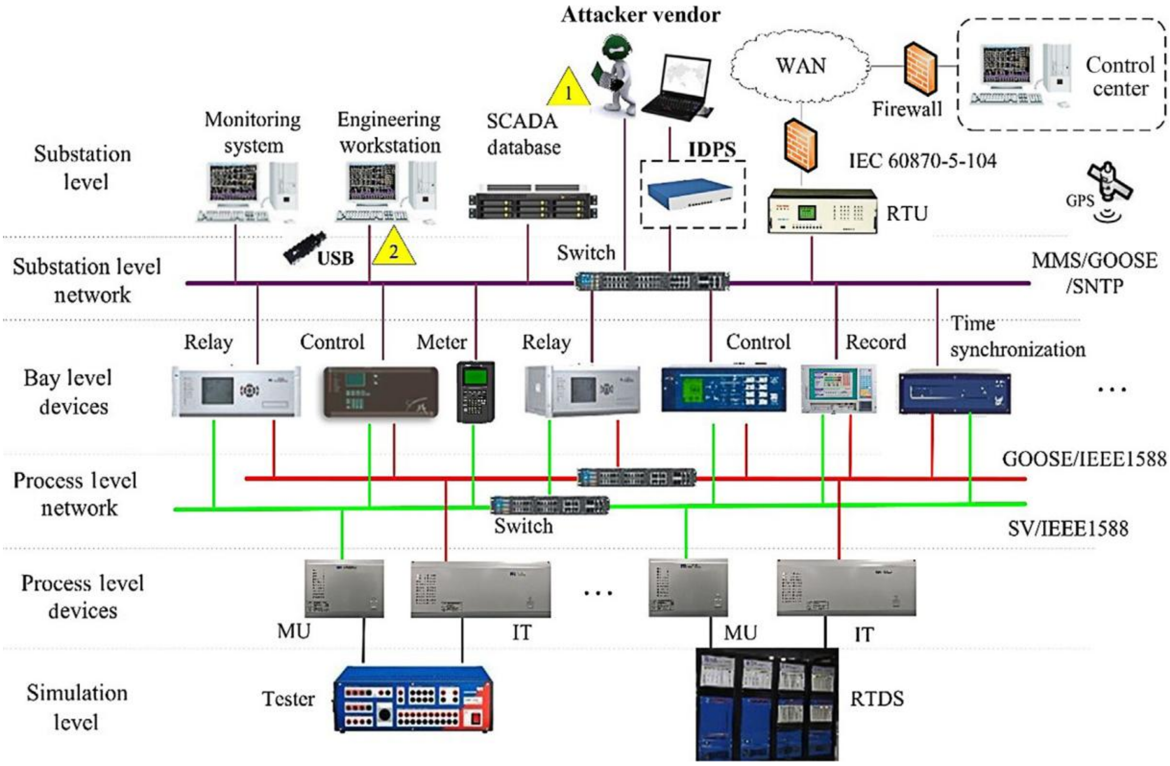

Figure 4.6 Cyber-physical test-bed of IEC 61850-based smart substation

The substation level consists of the monitoring system, engineering workstation, SCADA database, remote terminal unit (RTU), and a laptop to launch cyberattacks (equally, the attack may propagate from an infected host in the network rather than a laptop). The substation level network, a switch-based cable network, supports manufacturing message specification (MMS), GOOSE, and simple network time protocol (SNTP). The control center communicates with the smart substation using IEC 60870-5-104.

Exercises

Translate the sentences from English into Russian.

1) Major manufacturers do not generally implement adequate security in their intelligent electronic devices.

2) Much more in-depth investigation and analysis of specific vulnerabilities and cyberattacks are required.

3) The test-bed environment enables real attack scenarios to be analyzed and effective cybersecurity countermeasure technologies to be proposed and evaluated.

4) The test-bed consists of the simulation level, process level, bay level, and substation level.

5) A real-time digital simulator is utilized to model multiple power system scenarios and simulate transient characteristics and behaviors of modeled power systems.

6) The merging units are connected in the sample value network, and intelligent terminals are connected in the generic object oriented substation event network.

7) The substation level consists of the monitoring system, engineering workstation, SCADA database, remote terminal unit, and a laptop to launch cyberattacks

4.2.4. Cyber vulnerability investigation in smart substations

In the test-bed, a number of cyberattacks are simulated and investigated as follows:

Reconnaissance attack: A reconnaissance attack allows an attacker to identify potential targets before attacking. In this test-bed, the reconnaissance attack is launched by the laptop, as shown by the yellow triangle with the number 1 in Figure 4.6, to obtain the online IED information such as internet protocol (IP) addresses. For example, the Havex malware is believed to have primarily acted to achieve reconnaissance. An attacker could utilize this information to launch more effective attacks.

Malformed packet attack: In this test-bed, malicious IEC 61850 client software generates malformed packets based on the IEC 61850 protocol and sends them to IEDs. The malformed packet may crash the IEC 61850 protocol stack and cause IED communication failure or status exception, which could threaten secure and reliable operation of the smart substation.

Denial-of-service (DoS) attack: A DoS attack is launched to occupy all the enable report control blocks of IEDs, which are instantiated at configuration time in the logical node (LN) in this test-bed. Consequently, the targeted IED cannot respond to normal connection requests.

Address resolution protocol (ARP) spoofing attack: In the test-bed environment, an ARP spoofing attack is launched by the laptop to broadcast ARP packets with the IP address of the monitoring system in the substation level network. After the attack, the IEDs communicate with the malicious laptop rather than the monitoring system.

Man-in-the-middle (MITM) attack: The MITM attack allows an attacker to redirect communication traffic between the monitoring system and the IED to the malicious laptop in the substation level network. On one hand, the attacker sends malicious remote control commands and modified protective setting values by impersonating the monitoring system; on the other hand, the attacker, the impersonated IEDs, sends false, abnormal, or even malformed messages to the original monitoring system. In this test-bed environment, the MITM attacks can make the monitoring system and the IEDs behave abnormally and even make failures in grid operations possible.

Configuration tampering: Substation configuration description language (SCL) files are the foundation of the secure, steady, and reliable operations of IEC 61850-based smart substations. In this test-bed, the threat actor tampers with the configured IED description (CID) file in the protection relay, and the relay operates incorrectly when simulated grid faults appear.

Operation system/database attack: The operation system/database is exploited using known vulnerabilities in this test-bed. For example, VxWorks, the embedded real-time operating system in some IEDs, is attacked using the Wind River debug vulnerability (WDV).

The possible effects of the cyberattacks on smart substations, as outlined in this section, are shown in Table 4.1.

Table 4.1

The impacts of cyberattacks on smart substations

	MITM Attack	**Configuration Tampering**	**Operation System/ Database Attack**	**Malformed Packet Attack**	**DoS Attack**	**ARP Spoofing Attack**
Failure to tripping protection	+	+				
Unwanted operation of protection	+	+				
Blocking protection	+	+				
Disruption of communication for protection	+	+	+	+	+	+
Network disruption within substation			+	+	+	
Abnormal behavior or disruption of monitoring system	+	+	+	+	+	+
Denial of service from control center	+	+	+	+	+	+

	MITM Attack	Configuration Tampering	Operation System/ Database Attack	Malformed Packet Attack	DoS Attack	ARP Spoofing Attack
Misjudgment of dispatchers	+					
Erroneous post analysis	+		+			

According to the previously mentioned investigation in the test-bed, potential substation attack scenarios are identified as follows:

• Malware can propagate via infected removable USB drives and LAN communications, as shown by the yellow triangle with the number 2 in Figure 4.6, and can be designed to sabotage SCADA systems with direct physical consequences.

• In this use-case, a maintenance engineer's laptop is directly connected to the network switch in the smart substation, as shown by the yellow triangle with the number 1 in Figure 4.6.

• Due to the maintenance engineer's unintended misuse, the laptop may gain access to unauthorized IEDs from other manufacturers, which may cause communication disruption, or even operation failure. Traditional malware, such as worms, or advanced Stuxnet-like malware may penetrate the IT control environment of the smart substation via a laptop. Furthermore, the same laptop has the potential to infect a number of smart substations by the same maintenance engineer.

• During maintenance, the engineer may access the Internet by wireless to download electronic materials or perform remote maintenance. This may be utilized by a threat actor as a conduit to penetrate the substation automation system.

The smart substation is also vulnerable to further exploitation: it lacks real-time detection approaches for cybersecurity; the IEDs lack the ability to identify whether control commands are from a legitimate user; and the IEDs in the smart substation typically lack cybersecurity penetration testing before being put into operation. To attempt to address these practical cybersecurity problems, the next section proposes a fuzz testing approach to detect IEC 61850 protocol vulnerabilities for IEDs in the test-bed.

Exercises

Answer the questions. Then describe the cyber-physical test-bed shown in fig. 4.6.

1) What can the crash of the IEC 61850 protocol stack caused by the malformed packet result in?

2) Why is the denial-of-service attack launched?

3) What are the consequences of the address resolution protocol spoofing attack?

4) How does an attacker redirects communication traffic in the course of man-in-the-middle (MITM) attack?

5) What is configuration tampering?

6) What happens if the laptop gains access to unauthorized IEDs from other manufacturers?

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Учебное издание

Цифровая энергетика

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Учебное пособие

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Издано в авторской редакции

Корректура *И.О. Фамилия*
Компьютерная верстка *И.О. Фамилия*
Дизайн обложки *И.О. Фамилия*

Подписано к печати 00.00.2020. Формат 60.84/16. Бумага «Снегурочка».
Печать CANON. Усл. печ. л. 0,00. Уч.-изд. л. 0,00
Заказ 000-18. Тираж 100 экз.

Издательство
ТОМСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ

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