Czech Technical University in Prague
Faculty of Electrical Engineering
Department of Economics, Management and Humanities

Elements of analyzing and testing an electric power system

Master Thesis

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Scientific supervisor: Mgr. Sherzod Tashpulatov, M.A., Ph.D.

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Elements of analyzing and testing an electric power system

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Pokyny pro vypracování:

1. Analysis of the power system in Sakhalin and verification of its steady state.
2. International experience of managing isolated power systems.
3. Testing the preservation of transient stability.
4. Application of the optimal capacitor banks` placement and harmonic analysis of current and voltage based on cores.
5. Evaluation of the economic efficiency and feasibility when using capacitors and active filter-compensating devices.

Seznam doporučené literatury:

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III. PŘEVZETÍ ZADÁNÍ

Diplomant bere na vědomí, že je povinen vypracovat diplomovou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací.
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Datum převzetí zadání	Podpis studenta

Declaration

I hereby declare that this master's thesis is the product of my own independent work and that I have clearly stated all information sources used in the thesis according to Methodological Instruction No. 1/2009 – "On maintaining ethical principles when working on a university final project, CTU in Prague".

Date *Signature*

Abstract

The problem with managing isolated power systems is that shunt links cannot be used to control system parameters and transient stability. The consequences of perturbations in the power system are borne by automation and relay protection systems. But they cannot prevent deviations of system parameters such as voltage or power factor from the limits specified in GOST. The purpose of this dissertation is to identify possible solutions to restore the system parameters to their limits, thereby normalising the operation of the rest of the grid and increasing the life of the electrical equipment.

The solution will be found by modelling the existing isolated power system of the Sakhalin region and analysing it using the ETAP software tools. In turn, the tools provided by the software package are software kernels with their own algorithms. For example, the transient stability kernel is able to determine the behaviour of the power system in the event of regulatory perturbations. The optimal capacitor bank placement kernel determines the locations, number and nominal parameters of capacitor banks required to maintain the parameters specified in the kernel settings.

Based on the results of the work, the task of managing system parameters within the limits established by GOST, as well as the preservation of transient stability of the power system was performed. An economic assessment of the given solution to the problem has also been given. Economic benefit can be achieved through the sale of compensated losses, the possible increase in transmitted energy could be realised through future consumers, thereby benefiting from reduced losses. However, the project still remains unprofitable, not taking into account the increase in the service life of the consumer's appliances.

It is the responsibility of every owner of a generation, transmission or distribution network, whether the owner is a private investor or a state-owned company, to keep the grid within its specified limits. This means that this solution can be implemented in the same power system in the Sakhalin region, as the mathematical model has been generated using the existing parameters of the same power system.

Contents

List of appendices

List of abbreviations

AD	Autonomous District
ANSI	American National Standards Institute
CHPP	Combined Heat Power Plant
DG	Diesel Generator
DPP	Diesel Power Plant
ETAP	Electrical Transient and Analysis Program
EJT	Economically Justified Tariffs
FEFD	Far Eastern Federal District
GOST	State Standart
HPP	Hydro Power Plant
HV	High Voltage
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
LV	Low Voltage
MTF	Mean Time to Failure
MV	Medium Voltage
NPP	Nuclear Power Plant
OCP	Optimal Capacitor Placement
PL	Power Line
RES	Renewable Energy Sources
RPS	Regional Power Station
SDP	Scheme and Development Program
THD	Total Harmonic Distortion
TIF	Telephone Influence Factor
TPP	Thermal Power Plant
TS	Transformer Substations
UNPS	United National Power System

Introduction

Management has always been crucial to the development and exploration of new regions. The development of infrastructure in regions begins with the development of the power system, which, in turn, must have both a technical and economic justification. Usually, the new power grid becomes part of one big power system. In Russia, this large power system is called the United National Power System (UNPS). The majority of new power systems are connected to UNPS by shunt links through which the balance power flows. These flows help manage the power system, in case of accidents, the adjacent power systems will help both to compensate for the lack of power generation and to adjust the system parameters. However, not all regions are economically profitable to join UNPS. Furthermore, remote regions have to rely on their own power supply systems. Such isolated systems have no electrical connection to UNPS, which means that they can only be controlled by their own available park reserve. To be more specific, preservation of system parameters within admissible limits at occurrence of small fluctuations, and even more so at normative disturbance is impossible due to supply through shunt links. In such situations, we have to rely only on our own forces.

The international experience of managing isolated power systems relate us to the such centralized power systems of New Zealand. This large isolated power systems are in many ways similar to Russian systems. The main problem in New Zealand is the instability of power generation. It is largely provided by hydropower plants (57%) whose generation drops during droughts, which leads to significant fluctuations in electricity prices [7].

This dissertation presents the results of isolated power system tests in Sakhalin region. The one I have created accurately represents the behavior of the power system in reality under various circuit-mode parameters. The model covers power system elements from 6 kV to 220 kV, namely distribution and backbone networks. As of 2019, the energy consumption load is mainly residential (about 51% of consumption is residential and municipal). However, it is not possible to assess economically the direct load impact due to the lack of necessary consumer data.

Before the experiments, the steady-state mode was verified by control measurements of winter maximum load. In addition, experiments were conducted to identify static aperiodic stability, as well as transient stability under the occurrence of regulatory perturbations of the first and second kind. The perturbations were modeled as the occurrence of a short-circuit on a transit power line when a successful and unsuccessful automatic reclosure was triggered.

In UNPS power systems, system parameters can be adjusted by external powerflows of adjacent power systems coming through bypass links. The parameters of such flows are usually closer to the nominal ones, which creates the resulting current and voltage in the power system to higher quality powerflows. In contrast to UNPS, an isolated power system cannot help itself to adjust the grid parameters due to the external balance of powerflows. In such cases, compensating equipment is installed.

In the continuation of the work, I considered ways to improve the quality of electricity through the optimal installation of static capacitors batteries. In this paper, I modeled cross compensation of reactive power by increasing the capacitive component of reactive power from the inclusion of capacitor banks on the consumer buses. When the capacitor banks are switched on, the voltage at the connection nodes and also at the network nodes upstream of the connection bus increases. It also reduces the share of reactive power transmitted through transmission lines, thereby reducing power losses. However, this impact cannot be assessed economically as the reduction in losses only increases the service life of the transmission equipment and the consumer's equipment. Recommendations for optimal placement of capacitor banks have been generated based on the results of the software package. The software has been configured to comply with GOST 32144-13 [24].

I also evaluated the magnitude of losses from changes in the harmonic composition of current and voltage due to the introduction of higher harmonics. The load that created the higher harmonics was modeled as a static load with control of active and reactive power and the presence of six-pulsed harmonics on the 220 kV side.

Practical experience of using batteries of static capacitors as a method of increasing the flow of active power shows considerable success with relatively pure harmonic composition of current and voltage. However, in the presence of a large number of higher harmonics, capacitors show little effectiveness in improving power quality. In this dissertation, both cases of using batteries of static capacitors are considered and their economic advantages are evaluated.

1. Overview of Sakhalin region and the formation of the calculation model

This dissertation deals with the power system of Sakhalin region, which is isolated from the UNPS of Russia. Its autonomous operation strictly depends on the scheme and regime situations in the grid, which means that any fluctuations in parameters and even more so normative perturbations can lead to a strong deterioration in the quality of power output. Given the non-distributed generation, the selected section of the power system will be cut off from the rest of it by a transit line using a static load.

1.1 Data on existing power balance in the system

Sakhalin region is located on the eastern border of Russia and is part of the FEFD 50.6910 N, 142.9506 E. The population of the Sakhalin region is 485621 people as of 2018. All region is entirely located on island, the largest of which is Sakhalin [5]. In Figure 1, Sakhalin Island is presented.

Figure 1 – Power plants located in Sakhalin region [6]

The current state of the electric power industry of the Sakhalin Oblast, taking into account the territorial peculiarities of the region and a large service area of electric grids with low power consumption in rural areas, is characterized:

- Territorial isolation and a large number of decentralized energy districts;
- Operation of power grid facilities in difficult climatic conditions and in areas of high seismicity, which has a serious impact on the condition of equipment and leads to accelerated wear and tear.

The Sakhalin region power system is also characterized by its isolated operation from the UNPS of Russia and its division into separate three autonomous energy districts within the oblast itself [5]:

- Central energy district – covers the southern and central parts of Sakhalin region (Nogliki HPP and Sakhalin CHPP as a power nodes);
- Northern energy district (Okha power node) – supplies power to Okha district (Okhinskaya CHPP as a power node);

- Novikovsky energy district – supplies power to the Novikovo-Korsakov district (Yuzhno-Sakhalinsk CHPP-1 as an energy node);

Isolated energy districts on the Kuril Islands and remote settlements of a number of municipal entities of Sakhalin Island.

The main generation facilities of the Sakhalin Region are:

- The Central Energy District: Yuzhno-Sakhalinskaya CHPP-1 and Sakhalinskaya RPS, both part of Sakhalinenergo; and Nogliki Gas Power Plant, part of Nogliki Gas Power Plant;
- The Northern Energy District: Ohinskaya CHPP, which is part of Ohinskaya CHPP, is also the only enterprise that generates and sells electricity for the needs of communities.

Data on the installed capacity of power plants are shown in Table 1.

Table 1. The main generation of region [5]

No	Name of power plant	Installed capacity, MW	Share of generating capacity, %
1	Yuzhno-Sakhalinsk CHPP-1	455.24	66.34
2	Sakhalin CHPP	84	12.24
3	Nogliki HPP	48	6.99
4	Ohinskaya CHPP	99	14.43
	Total generation capacity	686.24	100

1.2 Installed high voltage equipment on substations

The Yuzhno-Sakhalinsk CHPP-1 (66.34%) supplies the entire south of the district, maintains a steady mode of operation in the power grid, and provides heat to consumers of the city. This is the largest generating station in the region, so the power system that is supplied by this plant will be chosen for the experiments. Also, this power system has also difficulties to operate. The main difficulties in the operation of Sakhalin region equipment are [5]:

- Sakhalin TPP: the power plant was often operated in peak mode with daily starts and stops, which means that the fleet resource of turbine units has been exhausted by the number of starts. In accordance with SDP 2015–2019, construction of Sakhalin TPP-2 was started to solve this problem;
- Yuzhno-Sakhalinskaya CHPP-1: the fleet resource of turbine units has been exhausted by operating hours, as the power plant is operated in the base operating mode;
- Noglinskaya HPP: The gas turbine engines are subjected to heavy wear and tear due to the station's operating life in excess of the park life;
- Large depreciation of 0.4–6 kV transmission lines, reaching 90%;
- Lack of adjustment of protection devices under local operating conditions of power transmission lines on commissioned and newly commissioned DGs, which leads to frequent stops of Yuzhno-Kurilskaya DPP and the corresponding shutdown of consumers.

Generation sources, represented by generators of Yuzhno-Sakhalinskaya CHPP-1 (Eight turbogenerators), eight transmission lines, seven transformer substations (TS). First, power generation begins with the generation of power by generators at medium voltage (MV).

Parameters of installed generators are given in Table 2.

Table 2. Parameters of the installed generators on Yuzhno-Sakhalinskaya CHPP-1 [4]

Generator brand	**Quantity, pcs.**	**Total power, MVA**	**Active power, MW**	**cos(φ), r.u.**	**U_{NOM}, kV**	**x''_d, r.u.**
TVF-63-2M3	2	78.75	63	0.8	6.3	0.140
TVF-120-2M3	1	150	120	0.8	10.5	0.278
DG185ZL-04	5	63.13	50.5	0.8	10.5	0.183

where cos(φ) is power factor of the generator;

U_{NOM} is generator rated voltage;

x''_d, is superjunction resistance of the transverse branch.

After the production of electricity at medium voltage, its voltage and absolute value are transferred to high voltage by means of power voltage transformers. Parameters of installed transformers are given in Table 3.

Table 3. Parameters of transformers [4]

Name of substation	**Transformer brand**	**N, pcs**	**Calculation parameters**								**I_{allow}, A**		
			***R*, Ohm**			***X*, Ohm**			***B*, μSm**	***G*, μSm**	**HV**	**MV**	**LV**
			HV	**MV**	**LV**	**HV**	**MV**	**LV**					
Yuzhno-Sakhalinskaya CHPP-1	TRDCN (TRDN)-80000 / 110	2	0.6			17.4			7.1	1.5	402	–	3666
	TRDCN-125000 / 110	1	0.4			11.1			5.3	1.1	596	–	6873
	TRDCN-63000 / 110 (TRDN)	5	0.87			22			4.46	–	301	–	3464
TS 220 kV Yuzhno-Sakhalinskaya	ATDCN-125000/220/110	2	0.3	0.3	0.6	30.4	0	54.2	18.9	2.4	314	596.4	–
TS 110 kV Yuzhnaya	TDTN-40000 / 110	2	0.8	0.8	0.8	33.5	0	20.7	5.5	–	190.9	328.2	–
TS 110 kV Khomutovo-2	TDTN-40000 / 110	2	0.8	0.8	0.8	33.5	0	20.7	5.5	–	190.9	328.2	–
TS 110 kV Korsakovskaya	TDTN-40000 / 110	2	0.8	0.8	0.8	33.5	0	20.7	5.5	–	190.9	328.2	–
TS 110 kV Promouzel	TDTN-25000 / 110	2	1.5	1.5	1.5	56.9	0	35.7	2.34	–	105	153	–
TS 110 kV Centr	TDTN-63000 / 110	2	0.5	0.5	0.5	22	0	13.6	6.2	1.3	452	635	–

Where R is active resistance between windings; X is reactive resistance between windings; B is active conductivity between windings; G is active conductivity between windings; I_{allow} is long-time allowable current.

Electricity is transported between the nodes of the power system via branches, often consisting of overhead lines or cable lines. In our power system, there are also cable-overhead lines. They differ from overhead lines in that when approaching a substation, the overhead line wire is connected through a sleeve to a cable insert which leads all the way to the high-voltage bushings in the substation. Parameters of installed transformers are given in Table 4.

Table 4. Parameters of 110 kV branches at Yuzhno-Sakhalinskaya CHPP-1 power system [4]

Name of power line	***R*, Ohm/km**	***X*, Ohm/km**	***B*, µSm/km**
Yuzhno-Sakhalinsk – CHPP (G2)	0.249	0.436	-2.7
Yuzhno-Sakhalinsk – Lugovaya	0.29	0.51	-3.2
Yuzhno-Sakhalinsk – branch to Center	0.83	1.45	-9
Yuzhno-Sakhalinsk – Yuzhnaya	1.4	2.42	-21
Branch C-14 to Center – Center	0.2	0.34	-2.1
Branch to the Center – Promousel	0.573	1	-6.2
Branch C-13 to Center – Center	0.2	0.34	-2.1
Branch C-1 C-14 C-3 – Promousel	0.2	0.34	-2.1
Promousel – Yugo-Zapadnaya	1.35	4.2	-29

where R is per linear active resistance;

X is per linear reactive resistance;

B is per linear conductivity.

1.3 Imputing and verifying steady state parameters in the mathematical model

The steady state of the power system implies a state when the system parameters do not change over time or change very slowly and can be assumed to be unchanged.

Prolonged fluctuations include root-mean-square (RMS) deviations at power frequencies for more than 1 minute. ANSI C84.1 defines the steady-state voltage tolerances expected in a power system. Voltage variation is considered prolonged if the ANSI limits are exceeded by more than 1 minute. Prolonged variations can be either overvoltages or undervoltages. Overvoltages and undervoltages are usually not the result of system faults, but are caused by system load changes and system switching operations. Such changes are usually displayed in the form of RMS voltage vs. time graphs.

An overvoltage is an increase in the rms AC voltage of more than 110 percent at the supply frequency for more than 1 minute. Overvoltages are usually the result of load switching (for example, turning off a large load or turning on a capacitor bank). Overvoltages occur either because the system is too weak for the desired voltage regulation or because of insufficient voltage control. Incorrect tap settings on the transformers can also cause overvoltages in the system.

Undervoltage is the reduction of the rms AC voltage to less than 90 percent at the supply frequency for more than 1 minute. Undervoltages are the result of switching events that are The opposite of overvoltage events. Turning on a load or disconnecting a capacitor bank can cause undervoltages until the system voltage regulation equipment can return the voltage to acceptable limits. Overloaded circuits can also result in undervoltage.

The term “outage” is often used to describe extended periods of undervoltage initiated as a specific utility dispatching strategy to reduce power demand. Because there is no formal definition of disconnection, and it is not as clear as the term “undervoltage” the term “disconnection” should be avoided when attempting to characterize interference.

Sustained interruptions. When the supply voltage is zero for a period of time greater than 1 minute, a long voltage change is considered a long interruption. Voltage interruptions longer than 1 minute are often permanent and require human intervention to repair the system to restore it. The term “prolonged interruption’ refers to specific phenomena in the power system and, in general, has nothing to do with the use of the term “outage”. Utilities use outage or interruption to describe phenomena of a similar nature for reliability reporting purposes. However, this causes confusion for end users who think of a power outage as any shutdown that ends a process. It may only be halfway through the cycle. An interruption, as defined in IEEE Standard 100, does not refer to a specific phenomenon, but rather to the state of a component in the system that is not functioning properly. In addition, the use of the term “interruption” in the context of power quality monitoring has nothing to do with reliability or other continuity of service statistics. Thus, the term has been defined as being more specific to the absence of voltage for extended periods of time [15].

Consumer bus voltage is represented in the model without regulating measures, because there was no data on the position of the regulator benches. Voltages at the nodes of the system in steady-state mode are shown in Table 5

Table 5. Voltage at substations

Name of substation	**Voltage under normal operation**		
	HV	**MV**	**LV**
TS 220 kV Yuzhno-Sakhalinskaya	218.7	113	5.78
TS 110 kV Yuzhnaya	111.9	36.5	5.14
TS 110 kV Khomutovo-2	111.4	36.71	10.21
TS 110 kV Korsakovskaya	111.2	36.2	10.61
TS 110 kV Centr	112.7	–	6.03
TS 110 kV Promouzel	112.4	–	6.29
TS 110 kV Yugo-Zapadnaya	112.1	36.88	6.28

Source: Data are obtained at steady-state model.

Power flow through the branches of the system in steady-state mode are shown in Table 6

The flows on the line circuits were distributed according to their impedances as well as the generating units installed at their ends. The flows on the branches of the model are divided by busbars simulating the connection of the socket of the wire with the cable insert.

Table 6. Power flow through the PLs 110kV

Name of branch		***S*. (MW+jMVAr)**
Yuzhno-Sakhalinskaya	CHPP-1 (G1) – TS	6.27+j3.95
	CHPP-1 (G2) – TS	46.5-j37.5
	CHPP-1 (G3) – TS	63.3+j19.7
	CHPP-1 (Power Unit 4) – TS 1st chain	32.6+j10.2
	CHPP-1 (Power Unit 4) – TS 2nd chain	32.6+j10.2
	CHPP-1 (Power Unit 5) – TS	32.5+j26.6
	TS – Centr 1st chain	10.8+j5.24
	TS – Centr 2nd chain	17.71+j9.53
	TS – Centr with branch on Promouzel 2nd chain	12+j2.49
	TS – Korsakovskaya	20.4+j6.08
	TS – Lugovaya 1st chain	10.4+j3.55
	TS – Lugovaya 2nd chain	7.91+j2.39
	TS – Yuzhnaya 1st chain	14.3+j8.75
	TS – Yuzhnaya 2nd chain	31+j13.2
Centr – Promouzel with branch on Yugo-Zapadnaya		9.89+j3.08
Khomutovo-2 – Korsakovskaya		2.45+j0.539
Yuzhnaya – Khomutovo-2		19.6+j4.42

Source: Data are obtained at steady-state model.

where *S* is full power flow through the branch.

The model is verified with respect to the steady-state control measurements. . The relative error is presented in Tables 7–8.

Table 7. The error of voltage at substations [8]

Name of substation	**Voltage under normal operation**						**Relative error, %**		
	Computational model			**Control measurements**					
	HV	**MV**	**LV**	**HV**	**MV**	**LV**	**HV**	**MV**	**LV**
TS 220 kV Yuzhno-Sakhalinskaya	218.7	113	5.78	223	113	6.1	1.93	0	5.25
TS110 kV Yuzhnaya	111.9	36.5	5.14	112	37.5	6.3	0.09	2.67	18.41
TS 110 kV Khomutovo-2	111.4	36.71	10.21	112.6	36.4	10.4	1.07	0.84	1.83
TS 110 kV Korsakovskaya	111.2	36.2	10.61	113	37	10.5	1.59	2.16	1.04
TS 110 kV Centr	112.7	–	6.03	112.5	–	6.4	0.18	–	5.78
TS 110 kV Promouzel	112.4	–	6.29	112.2	–	6.4	0.18	–	1.72
TS 110 kV Yugo-Zapadnaya	112.1	36.88	6.28	112.3	37	6	0.18	0.32	4.46

Table 8. The error of powerflow through the PLs 110 kV [8]

Name of branch		*S.* (MW+jMVAr)		Relative error. %
		Computational model	**Control measurements**	
Yuzhno-Sakhalinskaya	CHPP-1 (G1) – TS	6.27+j3.95	6.5+j4.3	4.92
	CHPP-1 (G2) – TS	46.5-j37.5	48.1+j4.3	23.70
	CHPP-1 (G3) – TS	63.3+j19.7	81.0-j1.0	18.16
	CHPP-1 (Power Unit 4) – TS 1st chain	32.6+j10.2	41.7+j4.5	18.56
	CHPP-1 (Power Unit 4) – TS 2nd chain	32.6+j10.2	41.7+j4.5	18.56
	CHPP-1 (Power Unit 5) – TS	32.5+j26.6	42.0+j0.4	0.01
	TS – Centr 1st chain	10.8+j5.24	11.8+j3.3	2.03
	TS – Centr 2nd chain	17.71+j9.53	23.4+j6.1	16.83
	TS – Centr with branch on Promouzel 2nd chain	12+j2.49	12.3+j3.3	3.76
	TS – Korsakovskaya	20.4+j6.08	22.1+j6.3	7.37
	TS – Lugovaya 1st chain	10.4+j3.55	10.6+j4.1	3.31
	TS – Lugovaya 2nd chain	7.91+j2.39	8.0+j2.6	1.77
	TS – Yuzhnaya 1st chain	14.3+j8.75	18.8+j5.6	14.54
	TS – Yuzhnaya 2nd chain	31+j13.2	47.1+j10.3	30.12
Yuzhnaya – Khomutovo-2		19.6+j4.42	30.1+j6.5	34.75
Khomutovo-2 – Korsakovskaya		2.45+j0.539	2.4+j0.7	0.34
Centr – Promouzel with branch on Yugo-Zapadnaya		9.89+j3.08	10.1+j3.3	2.51

Source: The data are obtained at steady-state model.

1.4 Summary

According to the results of the steady-state mode calculation of the created model, I can conclude that the voltage levels in all nodes of the power system are within the range of acceptable values, and currents on overhead lines of 110–220 kV do not exceed the long-term allowable values.

Verification of the ETAP was carried out according to power flows through 110 kV transits and voltages on substation buses specified in the normal scheme of electrical connections. The error between the model and control measurements is higher than 10% due to the lack of considering the resistance of switching equipment in the ETAP software.

2. International experience in managing isolated power systems

The supply of energy to isolated areas is a problem in many parts of the world. Traditionally, Alaska, northern Canada, New Zealand, and Hawaii are considered analogues of the Russian regions of the North and Siberia. To be fair, we should mention the problems of island states – shipping fuel by tanker to Pacific islands at high oil prices can be extremely expensive.

There are also isolated territories in developing countries. In Russia, a systematic approach to solving these problems is absolutely necessary, because up to 5 million tons of fuel oil and 2 million tons of coal are spent to supply energy to isolated territories It is necessary to check the effectiveness of Russian regional development strategies for the decisions taken to develop alternative sources, use RES and reduce energy consumption through technological and managerial measures.

2.1 Issues of managing isolated power systems

Russian experience in solving the problems of isolated energy

The power supply of isolated territories in Russia is characterized by an insufficiently high level of reliability and significant subsidies from the budget (up to 60–65 billion rubles a year) to compensate for lost income of organizations. Support measures for territories are regional in nature and are not systemic. In developed countries, the problems of power supply of isolated territories are similar to the Russian ones, but are characterized by a systematic approach to the solution. Abroad, the main direction of state policy in the field is to actively stimulate the use of renewable energy sources through their support and reduction of subsidies on the prices of traditional energy resources.

Russia has quite a lot of technologically isolated and remote power supply systems, but most of them are located in the Far North and equated territories: some areas of the Sakha (Yakutia) and Karelia Republics, Murmansk, Arkhangelsk, Magadan, Amur and Sakhalin regions, Kamchatka Krai, Chukotka AD, Khanty-Mansi AD – Ugra and Yamalo-Nenets AD. These territories are characterized by a relatively small population: the northern territories account for about 20% of the area and not more than 2% of Russia's population [10].

The remote territories are characterized by unfavorable climatic conditions, low level of infrastructure development, insufficient supply of local fuels. Power supply facilities in such territories are rarely renewed and have low energy efficiency. One of the main problems for consumers of electricity and heat of isolated energy systems is their lack of reliability. Power outage period in such territories can reach 12–15 hours per day.

Another significant problem is the high cost of energy supply. The difference between economically justified tariffs (EJT) for resource supplying organizations operating in centralized energy systems and EJT operating in remote areas (decentralized isolated systems) is indicative. For example, in the Republic of Sakha (Yakutia) EJT in different zones differ by a factor of 5.5–6. In some settlements EJT for electricity can be as high as 70 rubles/kWh (according to the Ministry of Energy of Russia).

The increased cost of electricity and heat in isolated power systems is explained by the need to bring fuel from other areas or regions to hard-to-reach places, as well as the operation of equipment in difficult climatic conditions. The main types of imported fuel in such areas include fuel oil, diesel fuel and coal. Annual fuel supplies to the Far North amount to 4.5–5 million tons of oil products and 2 million tons of coal. The coverage of high tariffs does not fall in full on the consumers of isolated areas. The burden of increased costs is usually shared by regional budgets and certain groups of consumers in the region due to cross-subsidization. The population pays high tariffs to a much lesser extent: EJT for energy supply and tariffs for the population in such territories usually differ by several times. Although tariffs for households may also exceed the regional average (depending on regional policy).

Fallout income of resource supplying organizations is compensated from the regional budget, the volume of such budget expenditures of remote territories is estimated about 6–65 billion rubles a year (the upper limit of the estimate for the territories of the Far North). For comparison, subsidies to compensate for the difference in utility tariffs totaled 135 billion rubles in Russia in 2016. Subsidizing remote energy is a significant problem for regional budgets. Reducing the volume of subsidies may be one of the key objectives of the state with regard to ensuring power supply to remote territories along with improving the reliability of power supply to consumers. In Russia, the problems of isolated territories are regional, their solution at the state level is generally not systemic, the exception being support for the population through the establishment of preferential tariffs. In some regions, in addition, other consumer groups are supported by setting lower tariffs. An interesting example is the Murmansk region, where the electricity tariff in isolated villages for other consumer groups was reduced in 2017 from 20.53 to 7.95 rubles/kWh, in closed administrative-territorial formation Ostrovnoy – from 25 to 15 rubles/kWh, but with the obligation to include the shortfall in income, which the sales company will not receive in 2017, in its surcharge for future periods. Such actions can be attributed to temporary support measures, which in the future should be financed from the budget or consumers. Among other measures, some regions prefer to modernize generation on imported fuel with the implementation of renewable energy projects. These projects are implemented on a point-by-point basis; there is no general trend in the regions yet, although a number of mechanisms were adopted at the federal level in 2015 to support them [11].

International experience in solving isolated energy problems

In many countries of the world, there is a problem of providing energy to isolated areas. The problem is evident in the Arctic part of Canada, New Zealand, and two regions of the United States: Alaska and Hawaii. The specifics of energy supply problems in Alaska and in the Arctic part of Canada are largely comparable to those in Siberia and the Russian Far East: vast territories, low population density, and harsh climatic conditions. The main source of energy there is diesel generators. Remote communities in Alaska can cost as much as $1/kWh, compared to a state average of $0.22 and the U.S. average of $0.13. In northern Canada, the cost of electricity is 2.3 times the national average.

The main measure of support to consumers in Alaska is a program of subsidies: equalization of electricity cost for consumers ($38.5 mln. per year). However, it does not cover all communities and compensates only part of the costs, leaving opportunities and incentives to switch to alternative energy sources, which will be economically beneficial for companies and the population. Programs to improve energy efficiency of consumption (with the goal of a 15% increase in efficiency by 2020) are applied. Savings are estimated at 29 cents per dollar invested per year. Additionally, RES support is being implemented through grants and soft loans through the Alaska Renewable Energy Fund. Between 2008 and 2016, more than $200 million in public and private sources were leveraged for renewable energy projects through the grant program.

Thanks to the programs, Alaska is actively developing micro-grids for renewable energy, providing independent and uninterrupted energy supplies to small communities. The Alaska Energy Agency estimates that the programs will save about $46.5 million annually in diesel fuel costs. The Arctic part of Canada has similar support mechanisms to Alaska: The REACHE Northern Program, which funds renewable energy and energy efficiency projects, the Arctic Energy Fund to address energy security, and the ecoENERGY program to reduce greenhouse gas emissions in northern territories. However, the effectiveness of the programs and investments in them lags far behind neighboring Alaska, so we can only talk about minor changes in the northern Canadian energy system as a result of its actions. The large centralized isolated power systems of New Zealand and Hawaii are in many ways similar to similar Russian systems. The main problem in New Zealand is the volatility of electricity supply. It is largely provided by hydroelectric power plants (57%), whose generation falls during droughts, which leads to significant fluctuations in electricity prices. Privatization of state-owned power companies and adoption of the Electricity Act (2010) increased competition between power companies. They also introduced obligations to compensate the price to consumers in case of supply surges, which contributed to the improvement of backup storage systems and increased security of supply. Also interesting is the reform to eliminate fossil fuel subsidies, which increased the share of renewables in electricity generation (from 64% in 2008 to 84% in 2016).

Hawaii's energy system and its problems are in many ways similar to New Zealand's, but the situation is exacerbated by its high dependence on imported energy resources (oil and petroleum products). Generation of electricity from RES accounts for one-third of power generation, but the potential for its use is much higher. Therefore, incentives for RES producers through subsidies (grants, loans) are applied. Standards have been introduced for energy companies to produce at least 15% of energy from RES (U.S. Department of Energy). And according to the new state law, the share of renewable energy must increase to 100% by 2045 [12].

2.3 Examples of an isolated power system management

Subarctic territories with a large number of isolated consumers represent an ideal testing ground for demonstrating power system operation in isolated mode. At present, the countries whose territories are partially located in the Arctic zone include eight states: Russia, Canada, Denmark, Norway, the United

States, Sweden, Finland, and Iceland. It should be clarified that the territory of the Arctic is understood here as the territories located beyond the Arctic Circle.

Europe. *Greenland* is characterized by exceptionally harsh natural conditions: most of its territory is covered by thick continental ice; ice-free is a narrow strip in the southwest of Greenland, even narrower - in the southeast and slightly more significant - in the north. The northern coast is characterized by low temperatures, comparable to those in the north of Yakutiya. There is no centralized power supply on the island, each settlement has its own sources of power generation. Until the early 1990s, all electric power on the island was produced by diesel generators using imported fuel. In the following decades, active use of local wind and hydro resources began, which in recent years has provided about 70% of electricity generation from renewable resources.

Greenland now has five hydropower plants with capacities from 1.4 to 45 MW, including the Illulisat hydropower plant, the world's only underground hydroelectric power plant built in a permafrost zone. The plant is located in an isolated fjord 45 km from the town of Illulisat and is fully automated. Hydroelectric power plants currently generate over 70% of Greenland's electricity. Norway. The Arctic territory of Norway includes three counties: Nordland, Troms and Finnmark on the continent, as well as the archipelago of Spitsbergen and the island of Jan Mayen. Together, these areas make up nearly half of Norway's land area with a population of 470000 or about one-tenth of the country's total population. Norway's maritime areas in the Arctic account for about 1500000 square kilometres. Thanks to the warm currents of the Gulf Stream, northern Norway is a much more hospitable area than any other at this latitude is. The largest city in Northern Norway is Troms, often referred to as the “gateway to the Arctic”.

Finland. Approximately one-third of Finland's total electricity generation comes from each of the following sources: nuclear power plants (NPPs), CHPs using imported coal and natural gas, and plants using renewables (hydroelectric and biofuel power plants.

Only power plants in southern Finland, where there is a natural gas grid, run on natural gas. More than half of the natural gas used is burned in CHP plants. In March 2013, the world's largest wood-fired CHPP with a capacity of 140 MW opened in the city of Vaasa.

In northern and central Finland, thermal power plants run on biomass, wood and peat or their mixtures, which optimizes combustion and reduces emissions. More than 70% of the heat used in district heating systems is combined with electricity. Power plants can usually use several types of fuel, which increases the reliability of heat supply. The use of wood waste and biomass for heat supply plays a significant role.

In Finland, only Lapland belongs to the Arctic territories. Lapland is the largest region in Finland (its area is 92600 km^2) with a population of about 180000 people. At the same time, the region has the lowest population density (about 2 people per km^2). Lapland's is about twice as low as in the more developed southern parts of the country. The reason for this is the great natural and climatic differences and the proximity of the southern regions to the financial and industrial centres of Europe. Finland began to implement an active policy of regional financial regulation in the 1960s by implementing short-term development programs, which included subsidizing agriculture, implementation of infrastructure and social projects. At the same time, laws were passed to divide the country into developed industrial regions and developing regions lagging behind in terms of socio-economic indicators, which included the Lapland territories.

Iceland. Iceland's climate is maritime subarctic. Winters here are warm, wet, with frequent fogs and snowfalls, and summers are cool. Average annual temperatures are comparable to those in Khabarovsk Region, although the difference between summer and winter temperatures in Iceland is much lower. Currently, all the fuel used in the country is imported from abroad. For electricity and heating, fossil fuels are virtually non-existent in Iceland; its energy sector uses 100% hydraulic and geothermal resources. Currently, all residents of Iceland have access to a unified electric grid, despite the fact that the population density here is the lowest in Europe - barely more than 3 people per 1 km^2.

The development of renewable energy in the twentieth century not only ensured energy security in Iceland, but also allowed for a profound modernization of the economy: since the 1950s, the commissioning of new generating capacity in Iceland goes hand in hand with the development of industry [13].

North America. *Canada*. Canada is the second largest Arctic nation after Russia in terms of land area. The northern regions of Canada (the Yukon, the Northwest Territories and Nunavut) comprise almost 40% of the country. Just like the Russian North, these regions are rich in mineral resources, but because of their harsh climate, they remain difficult to reach and relatively sparsely populated. Funding for the northern territories increases every year. In 2007 the governments of the Yukon, the Northwest Territories and Nunavut drafted and approved a joint concept of development which pays special attention to the increase of the share of renewable energy in these regions.

The concept's authors also pay attention to the environmental aspect of the problem. Yukon, Northwest Territories and Nunavut have developed and are implementing plans to make their energy systems more efficient by using water, solar, wind and geothermal energy. Hydropower in Canada's north has historically been developed through federal investment and in conjunction with mining projects. According to official data, hydropower accounts for nearly 67% or 76 MW, of installed electric capacity in the Yukon, and about 30%, or 54 MW, in the Northwest Territories. These are mostly small hydroelectric plants built in the mid-20th century. The largest of them is the Whitehorse (Yukon) hydropower plant with a capacity of 40 MW. Most of the settlements that are supplied by hydropower plants retain diesel units as backup sources of energy supply. The largest hydropower development project in northern Canada was the installation of a third 7 MW generator at the Lake Eishihik (Yukon) hydropower plant. The work was completed in 2012. A year earlier, the project to expand the hydropower plant on the Talston River (Northwest Territories) was suspended for economic reasons. Despite this, Canadians are generally optimistic about the future of hydropower development in the North. Power engineers in the Northwest

Territories even calculated that the total potential for the development of hydro resources in their region alone reaches 11.5 GW, although in the near future the increase will most likely take place through the introduction of mini-hydro power plants with a capacity of less than 1 MW.

The largest solar energy project in the Canadian North was the installation of a system of 258 photovoltaic panels with a total capacity of 60.6 kW in the city of Fort Simpson, located just north of the 61st parallel. The 760000 USD project was completed in February 2012. Canadian experience shows that in the North to use solar energy are most effective hybrid systems, consisting of photovoltaic panels with batteries and small gas or diesel generators, allowing to reduce the amount of fuel consumed by conventional generators. The main limitation for the application of this technology in the North is the seasonality of solar energy use. In winter, with the polar night and peak demand for electricity, solar energy is virtually inaccessible.

Alaska. The northernmost U.S. state, Alaska is located in similar climatic conditions to northern Canada, so its power systems are much like those of its Canadian neighbours. With the exception of towns connected to the regional Railbelt power system along the railroad, most Alaskan communities use diesel generators.

In the winter, fuel is stored in tankers or, in extreme cases, flown in by air. Statistics from 2015 show that the most electricity, 303 GWh, is generated in Alaska using natural gas, hydroelectric power accounts for 102 GWh, followed by fuel oil and coal at about 50 GWh each. Rounding out the list are renewable sources (other than hydroelectric), which generate 8 GWh of electricity. The Alaska Legislature passed laws requiring that by 2025 50% of electricity must be generated from renewable sources. In 2008, the state created a special fund that allocates $50 million per year to support renewable energy. Alaska uses not only heat from the earth, but also biomass such as wood, waste from the fishing and wood processing industries and municipal waste for heating.

The use of photovoltaic panels in the municipal energy sector in Alaska is still considered unprofitable due to the small number of sunny days per year. A more promising direction is the use of solar energy for water heating. Pilot projects in this area are being implemented in the cities of Nome, Kotzebue and McKinley Village.

Wind energy has become more widespread in Alaska. Total installed capacity of the state's wind turbines - from small wind turbines that provide electricity to individual homes to turbines of more than 1 MW - reached 60 MW in 2012. By natural conditions, the west coast of Alaska is best suited for wind power. In 2009, the city of Kodiak installed the state's first 1.5 MW turbines. They now provide up to 9% of its electricity needs. At the same time, a wind farm of 18 turbines appeared in the town of Nome. The largest wind energy project in Alaska was the construction of a fleet of 11 turbines with a total capacity of nearly 17.6 MW near Anchorage. They are connected to the regional power system “Railbelt”. Wind energy saves 500 million cubic meters of natural gas annually; it is enough to provide electricity to about 6000 homes in the state capital [14].

2.3 Summary

Thus, the international experience of maintaining isolated energy systems demonstrates the material support of the state. Subsidy support is actively used to maintain isolated systems as well as to maintain the declared parameters of the energy system. Since isolated power systems are highly susceptible to regulatory perturbations of any kind, sophisticated automatic systems and regulators are required to maintain their transient stability. However, grid isolation does not always mean complete absence of electrical connection to other power systems, for example in the US it is also possible to connect individual state power systems into a single power system, but this is prevented both by each state's own legislation and by the technical difficulty in establishing synchronous operation of the power systems.

3. Transient stability analysis and power quality analysis

The power system model assembled in ETAP 16.0 will be used to establish the maintenance of dynamic stability using the Transient Stability Analysis kernel software.

The ETAP Transient Stability Analysis kernel is designed to study the dynamic characteristics of the system and the limits of power system stability before, during and after system changes or disturbances. It simulates the dynamic behaviour of the power system, implements user-defined events and actions, and solves the system network equation and machine differential equations interactively to determine the system and machine response in the time domain. In the future, the resulting data can be used to determine transient system behaviour, evaluate reliability, tune protection devices, and apply necessary remedies or improvements to improve system reliability [9]

3.1 Transient stability analysis

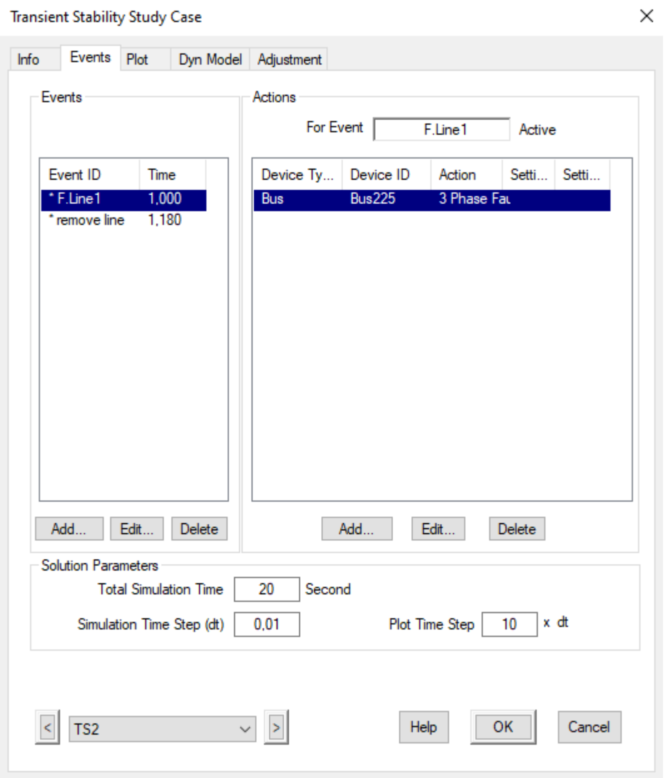
Experiment 1 – Successful line reclosure

The experience implies the occurrence of a normative disturbance of the second kind in the 110 kV network – tripping of the network element by the main protection during a three-phase short circuit with successful reclosure. The three-phase short-circuit trip threshold is 0.18 sec.

Scenario of the transient process:

1. Occurrence of three-phase short circuit in 1 sec;
2. Removal of short circuit in 0.18 sec after occurrence;
3. Switching the line on the steady-state short circuit in 1.35 sec.

Since the software complex does not allow manipulating the position of the switching equipment, in this and subsequent experiments will change the state of the three-phase short-circuit shunt – from on to off. The formation of the scenario in the software package is shown in Figure 2.



Events

Event ID	Time
* F.Line1	1,000
* remove line	1,180

Actions

For Event F.Line1 Active

Device Ty...	Device ID	Action	Setti...	Setti...
Bus	Bus225	3 Phase Fau		

Solution Parameters

Total Simulation Time 20 Second

Simulation Time Step (dt) 0,01

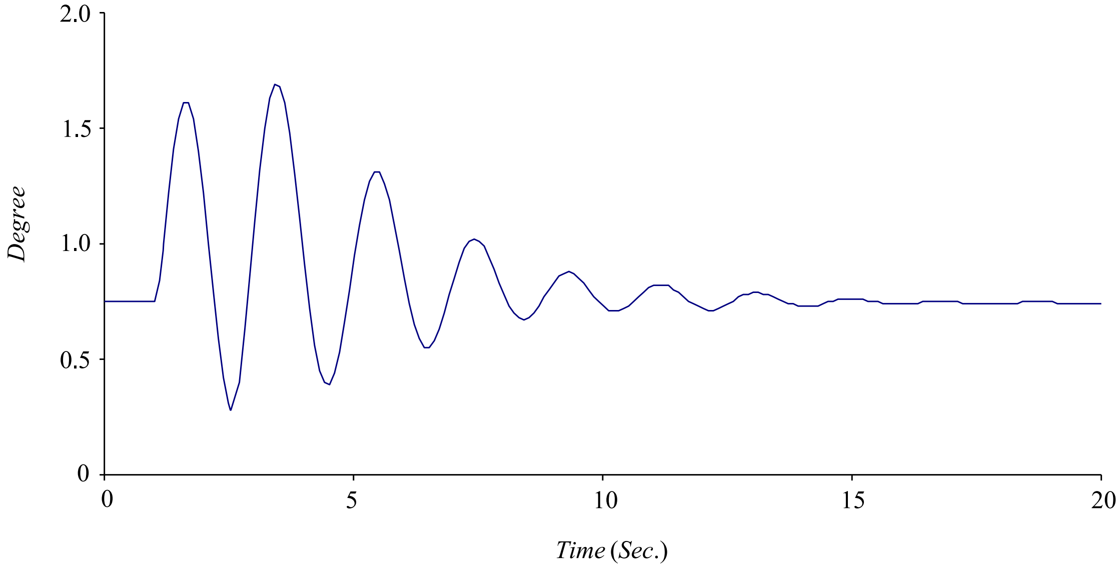
Plot Time Step 10 x dt

TS2

Source: The figure is obtained from ETAP editor.

Figure 2 – The first transient scenario editing window

The time dependence of the relative power angle of generator 6 during the first transient process is shown on Figure 3.



Source: The data of waveform based on the transient stability analysis.

Figure 3 – The first scenario power angle waveform

The graph shows the change in the relative angle during the transient. A short-circuit occurs at half the length of the transit line, which leads to a sharp jump in the angle, but after the short-circuit is turned off, the angle takes its steady-state value. The shape of the graph indicates that the turbine torque exceeds the electromagnetic torque, and, consequently, transient stability is preserved.

At the end of the transient process, the line busbar voltage is restored to 118.6 kV, which distinguishes it from the steady-state voltage by 0.8%. The relative angle of the sixth and seventh generators recovers to 0.74 and 0.73, respectively, which distinguishes them by 1.3% and 2.7% from steady state values.

The active and reactive powers of the generators have recovered to values different from nominal by 0.13%. The current in the adjacent circuit also takes its steady-state value with a difference of 1.7% from the steady-state current.

Experiment 2 – Unsuccessful line reclosure

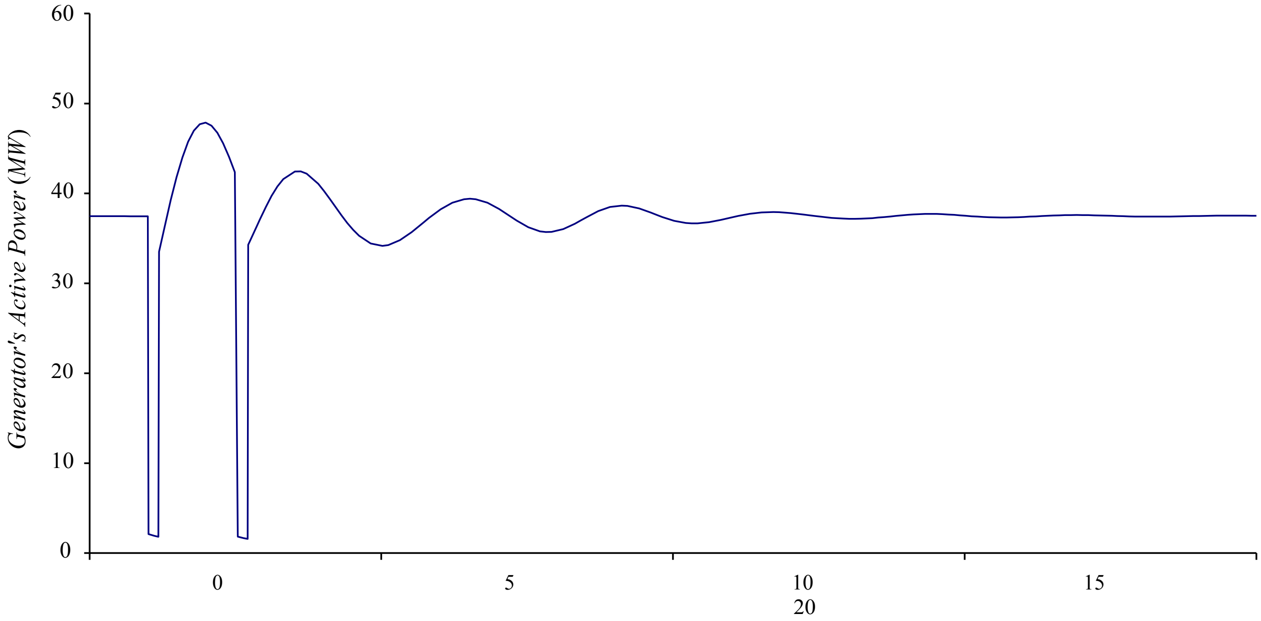
The occurrence of a normative disturbance of the second kind in the 110 kV network – tripping of the network element by the main protection during a three-phase short circuit with unsuccessful reclosure.

Three-phase short-circuit tripping set point – 0.18 sec.

Experience scenario:

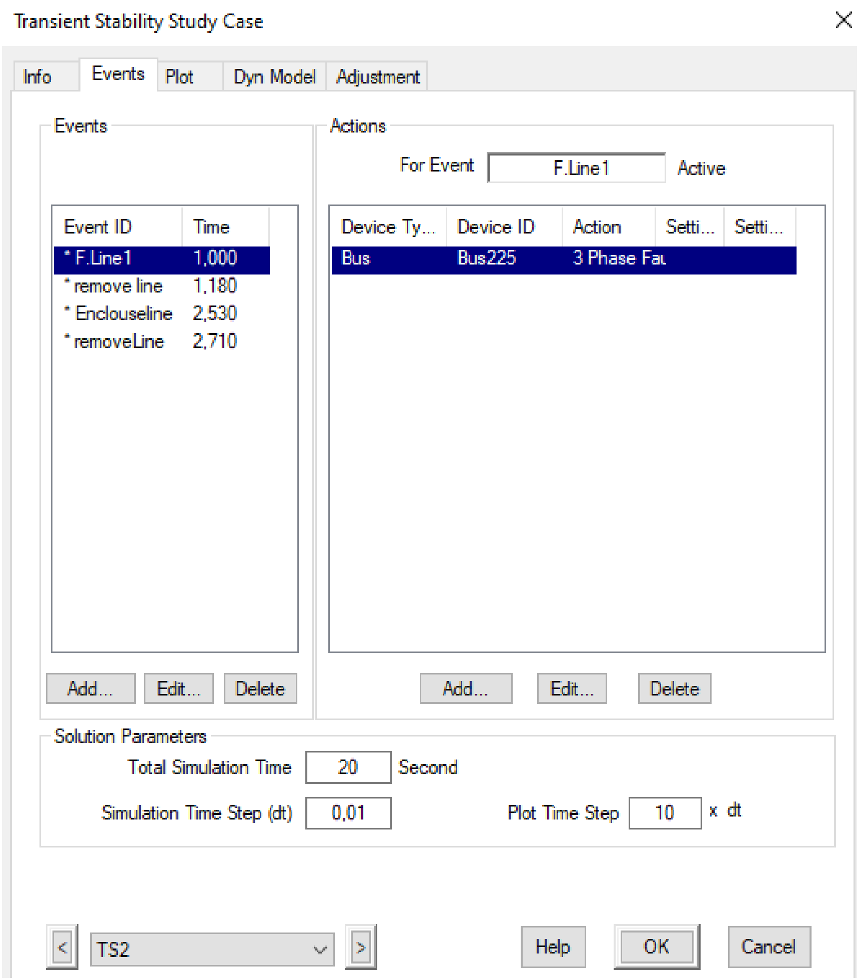
1. The occurrence of a three-phase short circuit in 1 sec;
2. Line disconnection in 0.18 sec after the occurrence of short circuit;
3. Switching the line on the steady-state short circuit in 1.35 sec;
4. Line disconnection after 0.18 sec.

The formation of the scenario in the software package and active power waveform are shown in Figures 4 and 5.



Source: The data of waveform based on the transient stability analysis.

Figure 4 – The second scenario active power waveform



For Event F.Line1 Active

Event ID	Time
* F.Line1	1,000
* remove line	1,180
* Encloseline	2,530
* removeLine	2,710

Device Ty...	Device ID	Action	Setti...	Setti...
Bus	Bus225	3 Phase Fau		

Total Simulation Time 20 Second

Simulation Time Step (dt) 0,01

Plot Time Step 10 x dt

TS2

Source: The figure is obtained from ETAP editor.

Figure 5 – The second transient scenario editing window

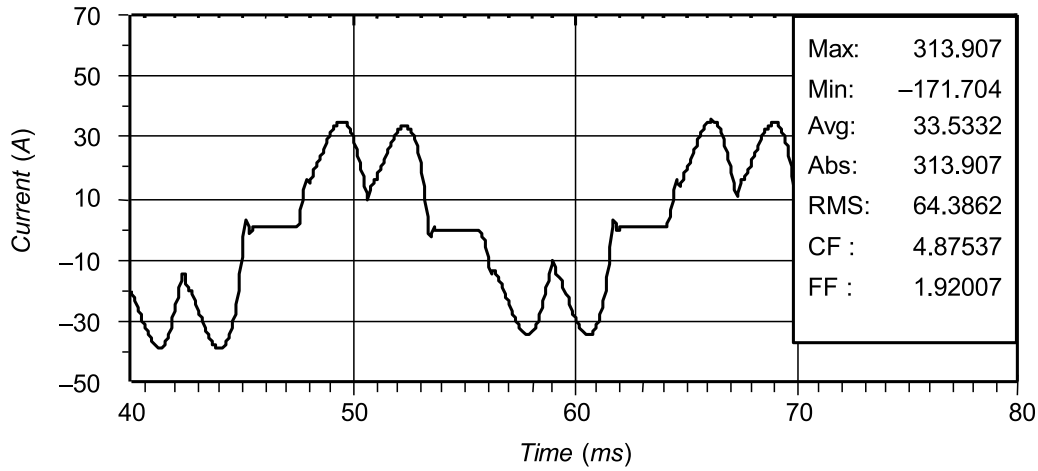
At the end of the transient process, the line bus voltage is restored to 118.6 kV, which distinguishes it from the steady-state voltage by 0.8%. The relative angle of generators six and seven recovers to 0.74 and 0.73, respectively, which distinguishes them by 1.3% and 2.7% from steady state values. The active and reactive powers of the generators have recovered to values different from nominal by 0.13%. The current in the adjacent circuit also takes its steady-state value with a difference of 1.7% from the steady-state current.

3.2 Using of the optimal capacitor placement module

Utilities usually try to keep the operating voltage supplied to the end user within ±5 percent of the rated voltage. Under emergency conditions, for short periods of time, ANSI standard C84.1 allows a voltage range of 6 to 13 percent of rated voltage. Some sensitive loads have more stringent voltage limits for proper operation, and, of course, equipment usually operates more efficiently at voltages close to the rated voltage.

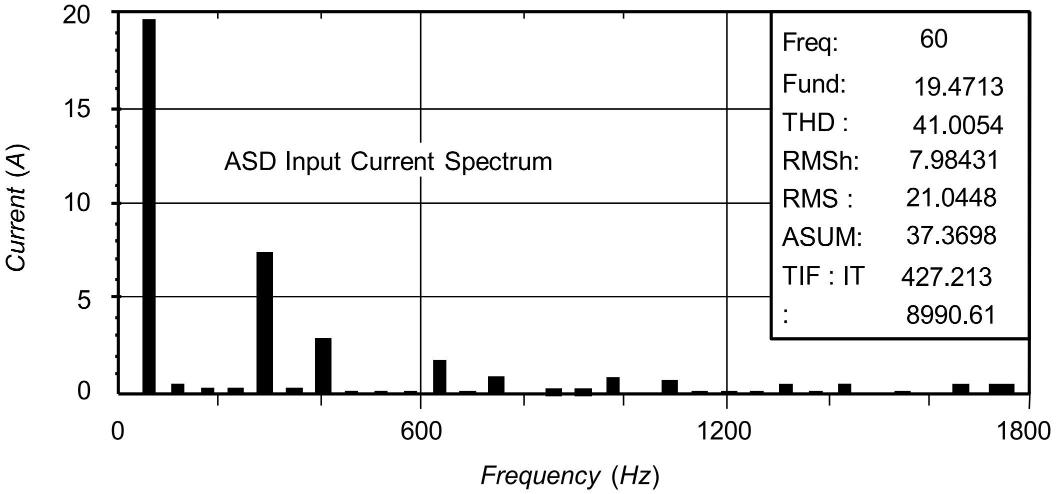
Most power systems operate with a lagged power factor due to inductive loads and transportation devices (lines and transformers).

The main reason for most voltage regulation problems is that the power system has too much resistance to properly supply the load (Figure 6 and 7). Another way to describe this is to say that the power system is too weak for the load. Therefore, when the load is large, the voltage drops too low.



Source: Reproduced from [15].

Figure 6 – The current waveform

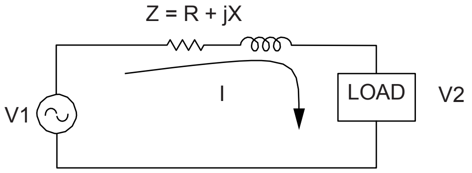


Source: Reproduced from [15].

Figure 7 – The current spectrum

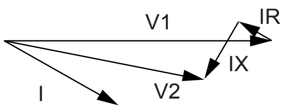
The root cause of most voltage regulation problems is that there is too much impedance in the power system to properly supply the load (Figure 8). Another way of describing this is to say that the power system is too weak for the load. Therefore, the voltage drops too low under heavy load. Conversely, when the source voltage is increased to overcome total resistance, an overvoltage condition can occur when the load drops too low. Corrective measures usually include either Z impedance compensation or IR and jIX voltage drop compensation caused by impedance. Some common options for improving power system voltage regulation, in rough order of priority, that a utility can apply are:

1. Add shunt capacitors to reduce the current I and shift it so that it is more in phase with the voltage.
2. Add voltage regulators that raise the apparent V_1.
3. The conductive lines are larger to reduce impedance Z.
4. Change substation or service transformers to larger sizes to reduce Z resistance.
5. Add some dynamic reactive power compensation (var), which serves the same purpose as capacitors for rapidly changing loads.
6. Add capacitors in series to compensate for the drop in inductive resistance IX.



Source: Reproduced from [15].

Figure 8 – Voltage drop across the system impedance



Source: Reproduced from [15].

Figure 9 – Vector diagram of stresses on the elements

Many voltage regulation devices are used in utility and industrial power systems. There are three main classes:

- Tap-changing transformers
- Isolation devices with separate voltage regulators
- Impedance compensation devices such as capacitors

Capacitors can be used for voltage regulation in the power system in both shunt and series configurations (Figure 10). We will discuss each class of application separately

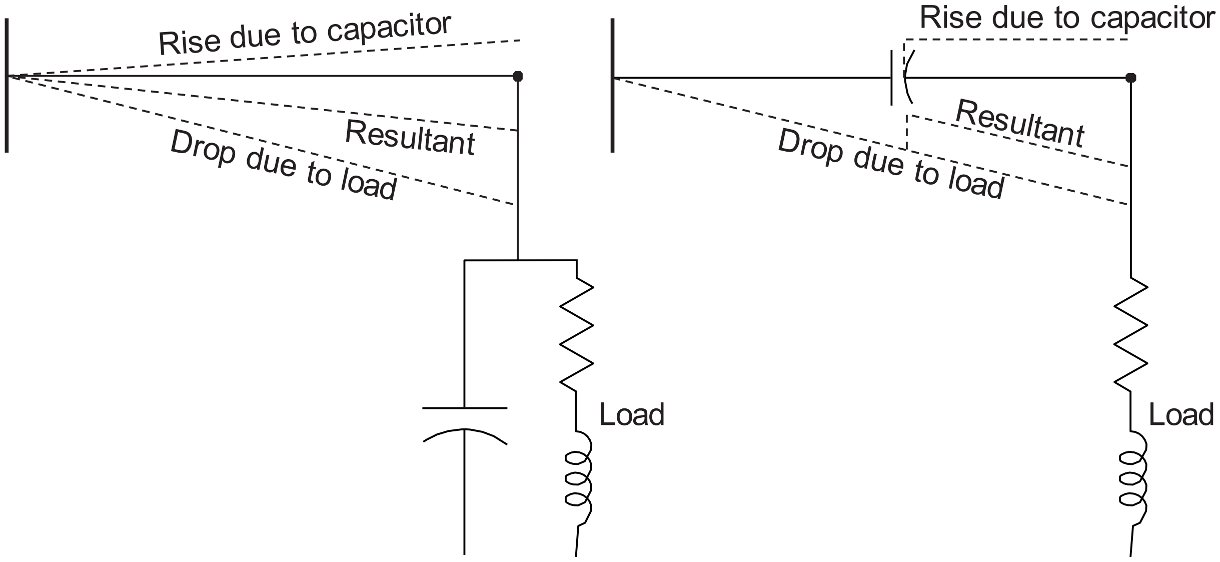


Figure 10 – Feeder voltage rise due to shunt and series capacitors.

As shown in Figure 10, the presence of a shunt capacitor at the end of the feeder causes a gradual change in voltage along the feeder. Ideally, the percentage increase in voltage at the capacitor will be zero at no load and will rise to a maximum at full load. With shunt capacitors, however, the percentage voltage rise is virtually independent of the load. Therefore, automatic switching is often used to provide the desired regulation at high loads, but to prevent excessive voltage at low loads.

In contrast to a shunt capacitor, a capacitor connected in series with the feeder causes a voltage increase at the end of the feeder, which is directly dependent on the load current. The voltage rise is zero at no load and maximum at full load. Therefore, series capacitors do not need to be switched in response to changes in load. Moreover, a series capacitor would require much lower kV and kVAr values than a shunt capacitor providing equivalent regulation. But series capacitors have several disadvantages. First, they cannot provide reactive compensation for feeder loads and do not significantly reduce system losses. Series capacitors can release additional system capacitance only if it is limited by excessive feeder voltage drop.

Shunt capacitors, on the other hand, are effective when system capacity is also limited by high feeder current. Second, series capacitors cannot withstand short-circuit current. This will result in catastrophic overvoltage and must be prevented by bypassing the capacitor through a circuit breaker. An arrester must also be connected to the capacitor to divert current until the switch is not closed.

There are several other problems that need to be evaluated when using a series capacitor. These include resonance and/or resonance with synchronous and induction motors, and ferroresonance with transformers. Because of these problems, the use of series capacitors in distribution systems is very limited. One area where they have proven useful is where feeder reactance must be minimized, for example, to reduce flicker.

Power systems are inductive in nature and require additional reactive power flow from the grid. However, excessive reactive power requirements result in lower system capacity, higher losses and lower voltages, and higher operating costs. Batteries of shunt capacitors can compensate for the current share of reactive power in the power system, but unit size, location, capacitor control method and cost considerations are important issues that need to be optimized during the design phase. A capacitor placement tool capable of weighing all of these factors and considering load levels is proposed as a solution. This tool will determine the capacitor placement measure for voltage support and power factor correction, while minimizing the overall installation and operating cost.

Capacitor size and suitable placement for voltage support and power factor correction can be determined in various ways. One common method applies the rules of “thumb” method and then performs several load flow studies to fine tune the size and location. Unfortunately, this method may not provide an optimal solution. And it can also be very time consuming and impractical for large systems [15].

It is also important to minimize costs when mathematically sizing and locating the condenser. Since this is an optimization problem, an optimization approach should be used. This is the advantage of the ETAP kernel. It allows capacitors to be placed to support voltage and power factor correction while minimizing overall costs. The exact calculation approach automatically determines the best location and size of the capacitor bank. In addition, the module shows capacity utilization in branches and savings during the planning period by reducing reactive power losses. The capabilities of the module are briefly described below:

- Calculates the most economical installation locations and optimal capacitor bank size;
- Minimizes overall installation and operating costs;
- Offers voltage support and power factor correction options;
- Evaluates the way the capacitor is controlled;
- Allows analysis of the impact of the capacitor on the system.

Types of capacitors

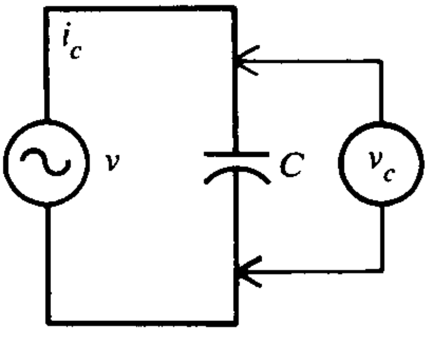
Commercial capacitors are named according to their dielectric. The most common types are air capacitors, mica capacitors, paper capacitors, ceramic capacitors, and electrolytic capacitors. These types are compared in Table 9. Most capacitor types can be connected to an electrical circuit without regard to polarity. But electrolytic capacitors and some ceramic capacitors are labeled to show which side should be connected to the more positive side of the circuit [16].

Table 9. Types of capacitors [16].

Dielectric	Construction	Capacitance
Air	Meshed plates	1–400 pF
Mica	Stacked sheets	10–5000 pF
Paper	Rolled foil	0.001–1 pF
Ceramic	Tubular	0.5–1600 pF
	Disk	0.002–0.1 pF
Electrolytic	Aluminum	5–1000 pF
	Tantalum	0.01–300 pF

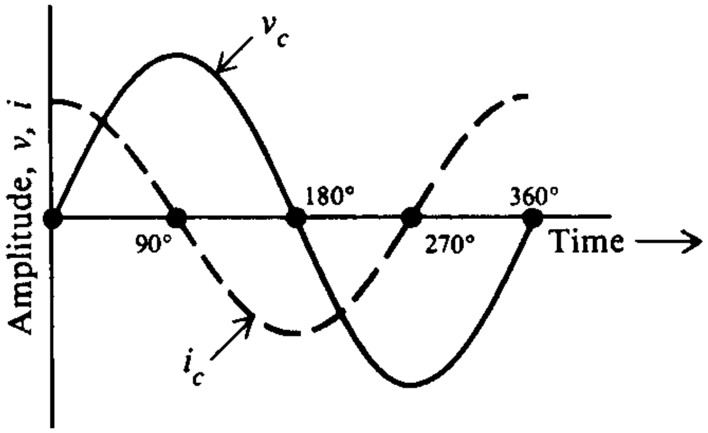
Capacitive circuits

Capacitance only. If an AC voltage v is applied across a circuit having only capacitance (Figure 11), the resulting ac current through the capacitance, i_C, will lead the voltage across the capacitance v_C by 90º (Figure 12 and Figure 13). (Quantities expressed as lowercase letters, i_C and v_C, indicate instantaneous values.) Voltages v and v_C are the same because they are parallel. Both i_C and v_C are sine waves with the same frequency. In series circuits, the current I_C is the horizontal phase angle for reference (Figure 14) so the voltage V_C can be considered to lag I_C by 90º [16].



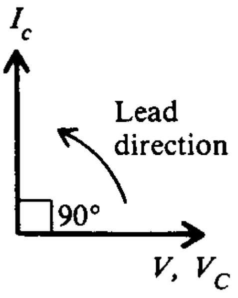
Source: Reproduced from [16].

Figure 11 – Circuit with C only, schematic diagram.



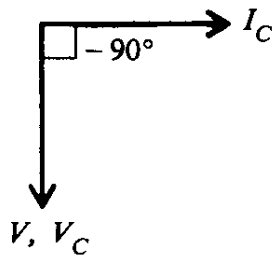
Source: Reproduced from [16].

Figure 12 – Circuit with C only, time diagram, i_C leads v_C by 90°.



Source: Reproduced from [16].

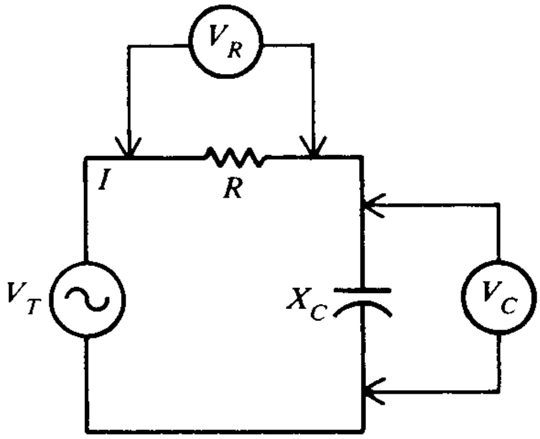
Figure 13 – Phase angle diagram, V reference when circuit with C only.



Source: Reproduced from [16].

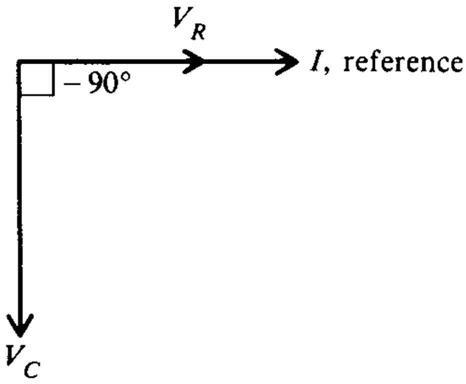
Figure 14 – Phase angle diagram, I_C reference when circuit with C only.

***RC* in series**. As with inductive circuits, the combination of resistance (Figure 15) and capacitive reactance is called impedance. In a series circuit containing R and X_C, the same current I flows in X_C and R. The voltage drop across R is $V_R = I_R$, and the voltage drop across X_C is $V_C = IX_C$. The voltage across X_C lags the current through X_C by 90° (Figure 16). The voltage across R is in phase with I since resistance does not produce a phase shift (Figure 17).



Source: Reproduced from [16].

Figure 15 – R and X_C in series circuit.



Source: Reproduced from [16].

Figure 16 – R and X_C in series, phase angle diagram.

To find the total voltage V_T , we add phase angles V_R and V_C. Since they form a right triangle (Figure 16).

$$V_T = \sqrt{V_R^2 + V_C^2}$$

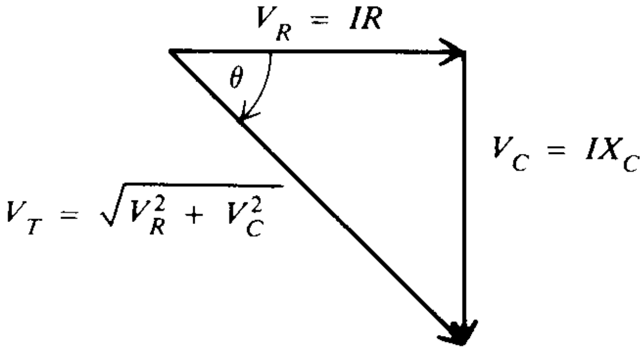


Figure 17 – Voltage-phase angle triangle [16].

Note that the IX_C phase angle is downward, exactly opposite from an IX_L phase angle, because of the opposite phase angle. The phase angle θ between V_T and V_R (Figure 17) is expressed according to the following equation [16]:

$$\tan\theta = -\frac{V_C}{V_R}$$

$$\theta = -\arctan\left(\frac{V_C}{V_R}\right)$$

In a series circuit since I is the same in R and X_C, I is shown as the reference phase angle at 0º. I leads V_T or, equivalently, V_T lags I. For the time diagram, see Figure 18.

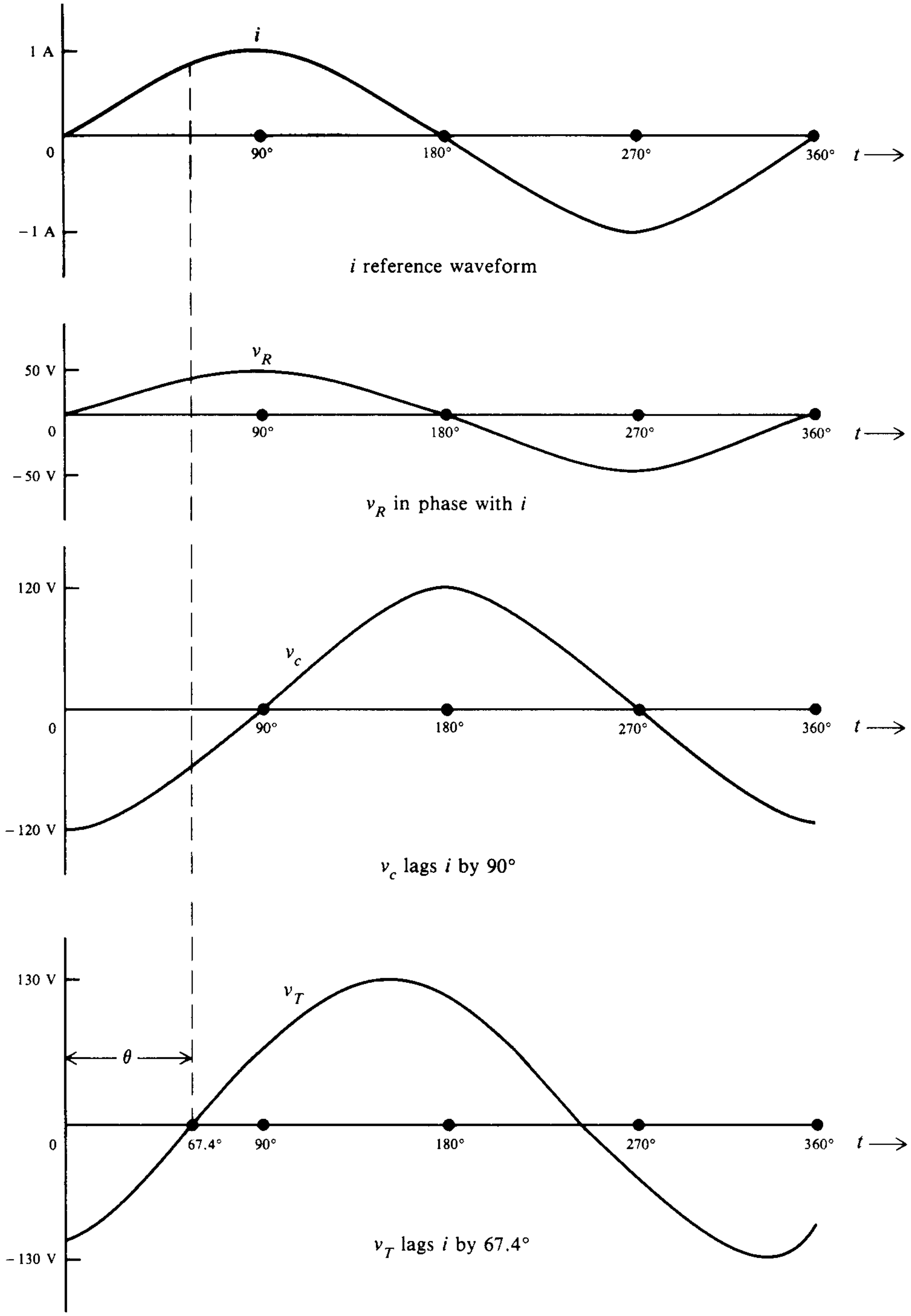


Figure 18 – Time diagram of RC series circuit [16].

Impedance in series *RC*. The voltage triangle (Figure 17) corresponds to the impedance triangle (Figure 19) because the common factor I in V_C and V_R cancels.

$$V_C = IX_C$$
$$V_R = IR$$
$$\tan\theta = -\frac{IX_C}{IR} = -\frac{X_C}{R},$$

Impedance Z is equal to the phase angle sum for R and X_C.

$$Z = \sqrt{R^2 + X_C^2} ,$$

The phase angle θ is

$$\theta = -\arctan\left(\frac{X_C}{R}\right),$$

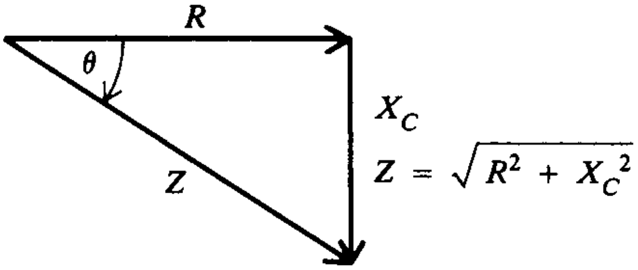
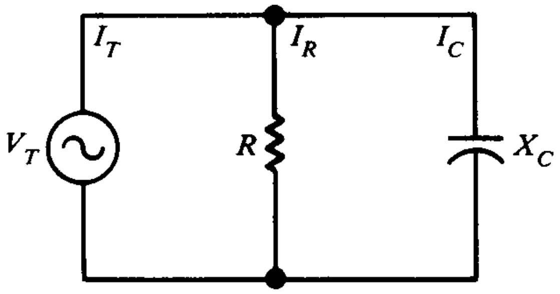


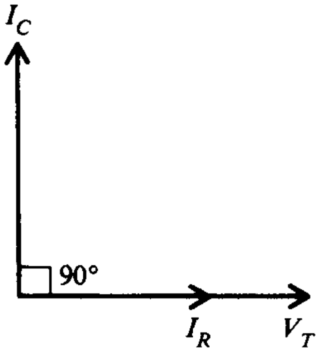
Figure 19 – Series *RC* impedance triangle [16].

***RC* in Parallel.** In the *RC* parallel circuit (Figure 20), the voltage is the same across the source, *R* and X_C since they are in parallel. Each branch has its individual current. The resistive branch current $IR = V_T/R$ is in phase with V_T. The capacitive branch current $I_C = V_T/X_C$ leads V_T by 90º (Figure 21). The phase angle diagram has the source voltage V_T as the reference phase angle because it is the same throughout the circuit. The total line current I_T equals the phase angle sum of I_R and I_C (Figure 22) [16].



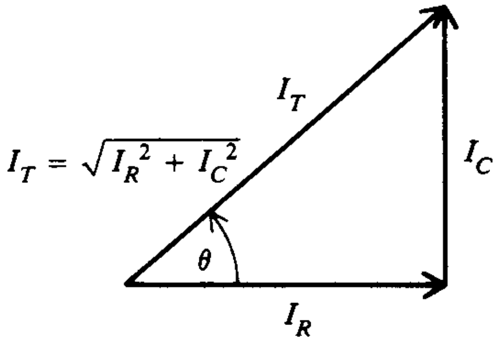
Source: Reproduced from [16].

Figure 20 – X_C and *R* in parallel, circuit.



Source: Reproduced from [16].

Figure 21 – X_C and R in parallel, phase angle diagram.



Source: Reproduced from [16].

Figure 22 – X_C and R in parallel, current-phase angle triangle.

$$I_T = \sqrt{I_R^2 + I_C^2}$$

$$\tan\theta = \frac{I_C}{I_R},$$

$$\theta = \arctan\left(\frac{I_C}{I_R}\right)$$

Impedance in parallel R_C. The impedance of a parallel circuit equals the total voltage V_T divided by the total current I_T [16].

$$Z_T = \frac{V_T}{I_T},$$

ETAP kernel

ETAP currently uses a genetic algorithm for optimal capacitor placement. The genetic algorithm is an optimization method based on the theory of natural selection. The genetic algorithm starts by generating solutions with a wide variety to represent the characteristics of the entire search space. By mutation and cross-over, good characteristics are selected and transferred to the next generation. The optimal solution can be achieved through repeated iterations.

OCP uses the present value method to compare alternatives. It considers initial installation and operating costs, which include maintenance, depreciation, and savings from loss reduction.

The goal of optimal capacitor placement is to minimize system cost. This cost is measured in four ways:

- Fixed cost to install a condenser;
- Cost of purchasing the capacitor;
- Operating costs of the capacitor bank (maintenance and depreciation);
- Cost of actual power losses.

Mathematically the cost function is representable as follows:

$$Objective\ Function = \sum_{i=1}^{Nbus} (x_i C_{0i} + Q_{ci} C_{1i} + B_i C_{2i} T) + C_2 \sum_{l=1}^{Nload} T_l P_L^l \rightarrow MIN,$$

where: N_{bus} – the number of buses to be installed CBs;

x_i – 0/1, 0 means no CBs installed on bus *i*;

C_{0i} – CB installation cost;

Q_{ci} – Cost of CB per one kVAr;

C_{1i} – Capacity of the CB in kVAr;

B_i – Number of capacitor batteries;

C_{2i} – Operating costs for one CB in one year;

T – Planned period of work (in years);

C_2 – Cost of one kW loss in USD/kW;

l – Load level (maximum, average and minimum);

T_l – Load time in hours;

P_L^l – Total losses in the system at each load level.

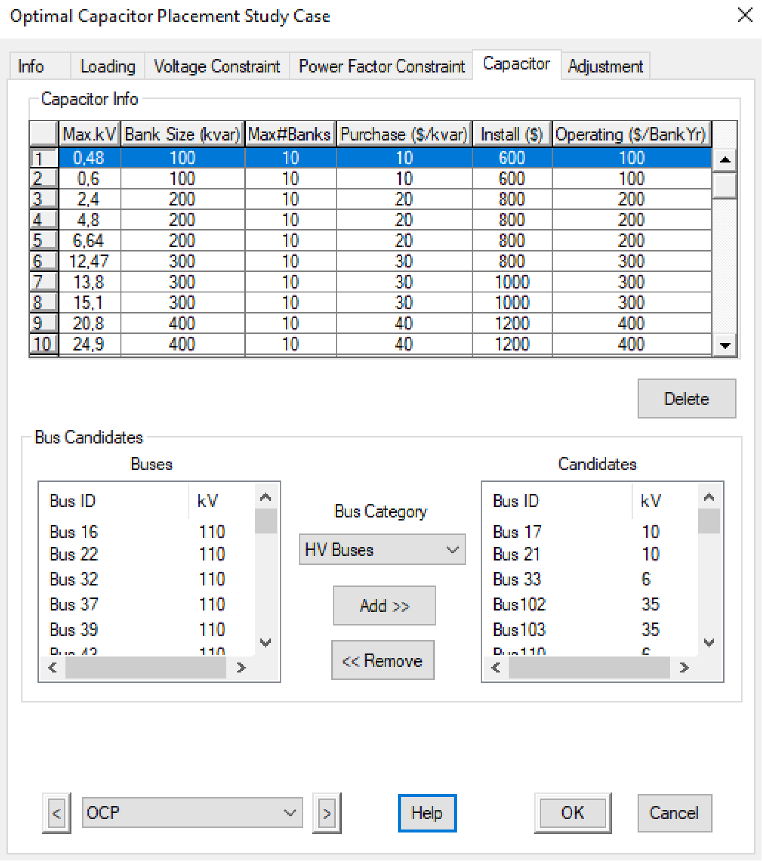
The main constraints for capacitor placement are to observe the load flow limits. In addition, all load bar voltages (*PQ*) must be within the lower and upper bar limits. The load power factor (*PF*) must be greater than the minimum. This may be the maximum power factor at the bus.

The constraints can be represented mathematically as the value of the power flow $F(x,u)=0$; $V_{\min} \le V \le V_{\max}$, $PF_{\min} \le PF \le PF_{\max}$ for all loaded buses [9].

3.2.1 Configuring the optimal placement of static capacitor batteries

To use this kernel, it is necessary to enter the same parameters into the model as for the overflow analysis module. Moreover, it is necessary to proactively enter in the list the intended buses for installation of the CBs and to set the calculation conditions. The conditions may be both the preservation of the voltage on the buses in the specified range and the preservation of the power factor. If necessary, you can also supplement the already existing library of CBs with new batteries, such a need may arise in the absence of batteries with the required voltage rating [1].

In my model, the assumed buses for the installation of CBs will be both the power release buses – 6–10 kV buses, and the 35 kV network buses. The conditions for the calculation will be to keep the voltage on the 6–10 kV buses in the range of ±10%.



	Max.kV	Bank Size (kvar)	Max#Banks	Purchase ($/kvar)	Install ($)	Operating ($/Bank Yr)
1	0,48	100	10	10	600	100
2	0,6	100	10	10	600	100
3	2,4	200	10	20	800	200
4	4,8	200	10	20	800	200
5	6,64	200	10	20	800	200
6	12,47	300	10	30	800	300
7	13,8	300	10	30	1000	300
8	15,1	300	10	30	1000	300
9	20,8	400	10	40	1200	400
10	24,9	400	10	40	1200	400

Buses

Bus ID	kV
Bus 16	110
Bus 22	110
Bus 32	110
Bus 37	110
Bus 39	110

Bus Category: HV Buses

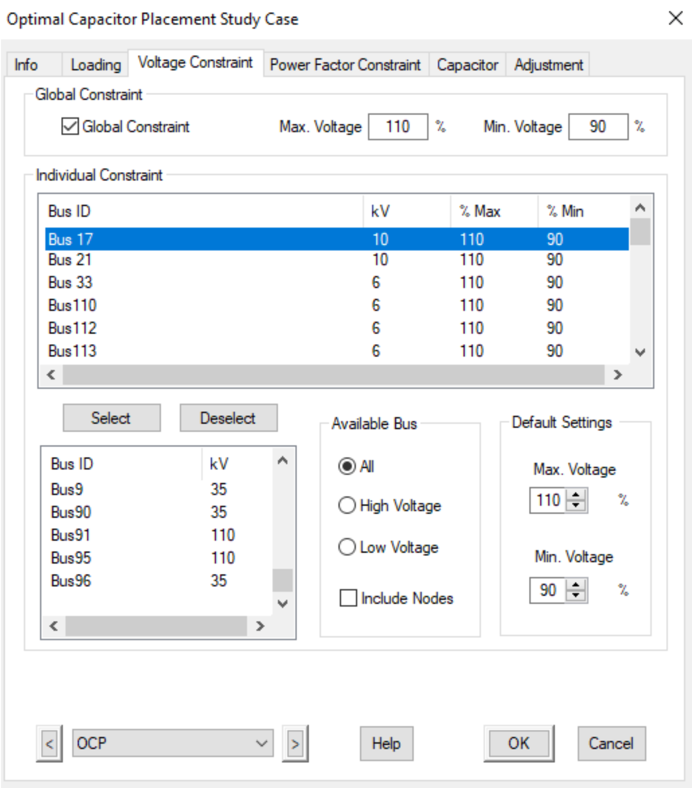
Candidates

Bus ID	kV
Bus 17	10
Bus 21	10
Bus 33	6
Bus102	35
Bus103	35

OCP

Note: The figure is obtained at ETAP editor

Figure 23 – ETAP editing window of CBs



Optimal Capacitor Placement Study Case

Global Constraint

☑ Global Constraint Max. Voltage 110 % Min. Voltage 90 %

Individual Constraint

Bus ID	kV	% Max	% Min
Bus 17	10	110	90
Bus 21	10	110	90
Bus 33	6	110	90
Bus110	6	110	90
Bus112	6	110	90
Bus113	6	110	90

Bus ID	kV
Bus9	35
Bus90	35
Bus91	110
Bus95	110
Bus96	35

Available Bus

● All
○ High Voltage
○ Low Voltage
☐ Include Nodes

Default Settings

Max. Voltage 110 %

Min. Voltage 90 %

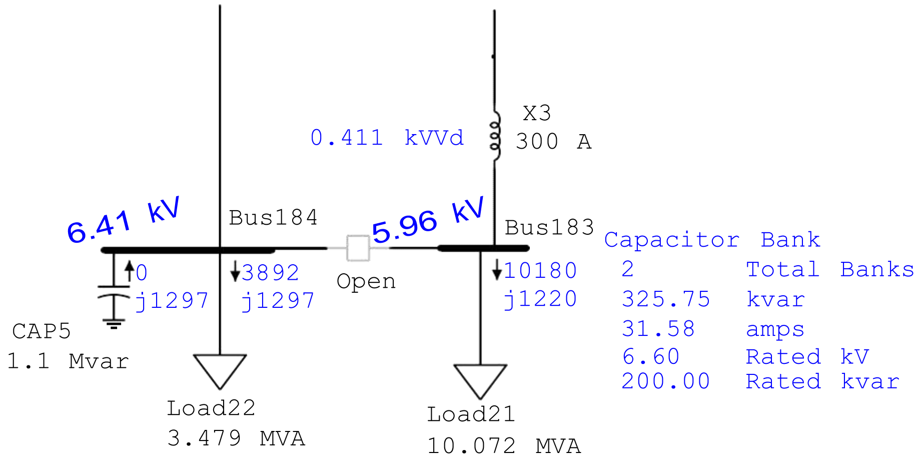
OCP

Note: The figure is obtained at ETAP editor

Figure 24 – Constraints editing window

3.2.2 Results of calculation of optimal capacitor banks placement

According to the calculation results, the optimal location for the capacitor banks would be the 6 kV buses on the 220 kV Yuzhno-Sakhalinskaya substation and on the 110 kV Yuzhnaya substation. Figure 25 shows a graphical representation of the result in the single-line diagram itself.



Note: The figure is obtained at ETAP OCP kernel

Figure 25 – Graphical representation of the calculation result

The parameters of the installed capacitor banks are shown in Table 10

Table 10. The error of power flow through the PLs 110 kV

TS Name	Q_{CB}, kVAr	U_{NOM}, kV	N, pcs	$\sum Q$, kVAr	Cost, USD		
					Installation	Purchasing	Maintenance per year
220 kV Yuzhno-Sakhalinskaya	200	6.640	9	1800	800	36000	1800
110 kV Yuzhnaya	200	6.640	8	1600	800	32000	1600

Source: Data are obtained from the library of ETAP.

Changes in power losses in circuit-mode situations with and without the installation of capacitor banks are shown in Appendix A.1 The document regulating the quality of electricity is IEC 60038, according to it the voltage on the bus bars of the consumer can not exceed and can not be less than 10% of its nominal value with slow changes in voltage. Module of optimal location of capacitor banks carried out a calculation to meet the standard specified in IEC 60038. Implementation of this standard was made possible by installing CBS on consumer buses and reactive power compensation through the issuance of reactive power in the network in the opposite phase to the existing one. Thus, the node voltage and branch currents are shown in Appendices 4 and 5. According to the reports, additional adjustment is required at the transformers of generating nodes G2, G3, G4 by 2.5%, 2.5% and 5%, respectively. The power factor changes its value from 0.81 to 0.97 at all voltage classes. The exception is the bus of the 220 kV Yuzhno-Sakhalinskaya substation, where the power factor is 0.78. The reduction of reactive power losses on the network transits is up to 18.5%. The benefit of using the capacitor banks proposed by the calculation would be $20,000. In the second year of use, and payback of all installations is 5 years. The calculation results in increasing the capacity of transmission lines, preserving the nominal voltage in the specified interval. Economically, the installation of CBs is beneficial due to the ability to deliver more useful power to the consumer. Qualitatively, this can be clearly seen in the graphs in the applications. It is worth noting that capacitor banks were already installed on the selected buses, but according to the normal wiring diagram they were disconnected. Also, the states of the shunt reactors were not specified in the diagram, so when calculating the optimal arrangement of the CBSs, a limit number of reactors was included to allow the calculation iterations to be completed. In this context, the limit number is the number of reactors, exceeding it by at least one number, which leads to a divergence of the mode.

3.3 Using of the harmonic analysis module

Due to the wide and growing use of power electronic devices such as variable speed drives, uninterruptible power supplies (UPS), static power converters, etc., the voltage and current quality of the power system has been seriously affected in some areas. In these areas, you may find that distorted voltage and current waveforms contain components other than the fundamental frequency. These components are usually integer multipliers of the fundamental frequency, called harmonics. In addition to electronic devices, several other nonlinear loads or devices, including saturated transformers, arc furnaces, fluorescent lamps, and cycloconverters, are also responsible for power system degradation.

The presence of harmonics in an power system can lead to many problems, including overheating of equipment, reduced power factors, degraded performance of electrical equipment, improper operation of protective relays, interference in communication devices, and in some cases circuit resonance resulting in dielectric damage to an electrical device and other types of serious damage. Even worse, harmonic currents generated in one area can creep into the power grid and spread to other areas, causing voltage and current distortions throughout the system. This phenomenon has become a serious problem for power quality due to the ever-increasing use of electronic devices and equipment in power systems.

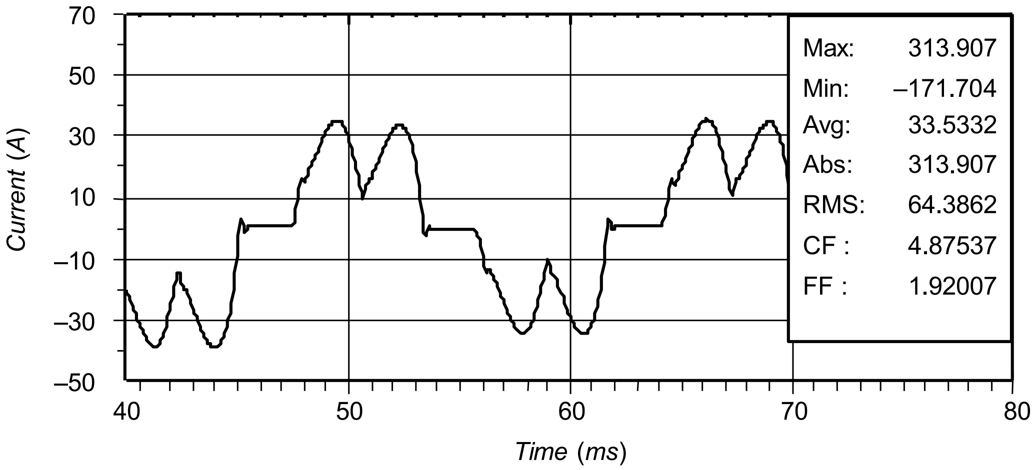
Using computer modeling, power system harmonic phenomena can be modelled and analyzed. The harmonic analysis module ETAP provides a tool for accurately simulating different power system components and devices with respect to their frequency dependence, nonlinearity, and other characteristics in the presence of harmonic sources. This module uses two analytical methods: the harmonic load flux method and the harmonic frequency scanning method. Both methods are the most popular and powerful approaches to harmonic analysis of power systems. Using these two methods in combination, various harmonic indices are computed and compared to industry standard limits, and existing and potential power quality and safety problems related to harmonics can be easily identified. The causes of these problems can be identified, and various mitigation and correction schemes can be tested and finally verified [2].

3.3.1 Harmonic analysis calculation methods

Harmonics are sinusoidal voltages or currents whose frequencies are integer multiples of the frequency at which the power system is intended (called the fundamental frequency; usually 50 or 60 Hz). Periodic distorted signals can be decomposed into a sum of the fundamental frequency and harmonics. Harmonic distortions arise in the nonlinear characteristics of devices and loads in the power system.

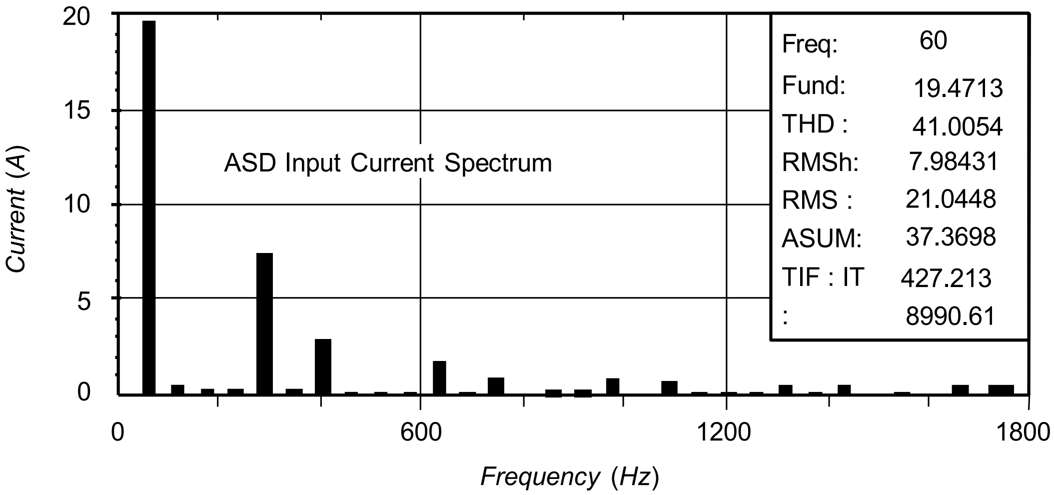
Harmonic distortion levels are described by the full harmonic spectrum with the magnitudes and phase angles of each individual harmonic component. It is also common to use a single quantity, the total harmonic distortion (THD), as a measure of the effective value of harmonic distortion. The Figure 26 and 27 illustrates the waveform and harmonic spectrum for a typical input current of a variable speed drive (ASD).

Current distortion levels can be characterized by the THD value as described earlier, but this can often be misleading. For example, many variable speed drives will exhibit high THD values for input current when they operate at very low loads. This is not necessarily a serious problem because the harmonic current magnitude is small, even if its relative distortion is large [15].



Source: Reproduced from [15].

Figure 26 – Current waveform for an ASD input current



Source: Reproduced from [15].

Figure 27 – Harmonic spectrum for an ASD input current

To solve this problem with the consistent characterization of harmonic currents, IEEE Standard 519-1992 defines another term, total distortion on demand (TDD). This term is the same as total harmonic distortion, except that the distortion is expressed as a percentage of some nominal load current rather than as a percentage of the fundamental current at the time of measurement. IEEE Standard 519-1992 provides guidelines for current and voltage harmonic distortion levels in distribution and transmission circuits.

Power system harmonic analysis includes modelling the frequency response of the various components of power systems, calculating harmonic indices on given buses and branches, identifying problems related to existing harmonics, and providing an environment for modelling and testing any migration methods. This section briefly discusses these topics and prepares you to use the ETAP harmonic analysis module to perform projects or analysis of your systems in the most efficient way.

Interharmonics. Voltages or currents that have frequency components that are not integer multiples of the frequency at which the power system is intended (for example, 50 or 60 Hz) are called interharmonics.

They can be displayed as discrete frequencies or as a broadband spectrum. Interharmonics can be found in all voltage classes. The main sources of interharmonic waveform distortion are static frequency converters, cycloconverters, induction furnaces, and arc-quenching devices.

Transmission line carrier signals can also be considered as interharmonics. Much work has been done on this subject since the first edition of this book. There is now a better understanding of the origin and effects of interharmonic distortion. It is usually the result of frequency conversion and is often not constant; it varies with load. Such interharmonic currents can cause rather strong resonances in a power system because the changing interharmonic frequency becomes coincident with the natural frequencies of the system. They have been shown to affect the transmission of carrier power line signals and to cause visual flicker in fluorescent and other arc lighting, as well as in computer display devices [15].

The ETAP harmonic analysis module is fully compliant with the latest version of the following standards:

- IEEE Standards 519-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Power Systems;
- ANSI/IEEE Standard 399-1997, IEEE Recommended Practices for Industrial and Commercial Power System Analysis;
- IEEE Standard 141-1993, IEEE Recommended Practices for Industrial Power Distribution;
- IEC 61000-4-7, Test and Measurement Methods - General Guide for Harmonic and Interharmonic Measurements and Instrumentation for Electrical Supply Systems and Connected Equipment.

Methods for calculating harmonic analysis [9]:

1. Component simulation;
2. Study of harmonic load flow;
3. Investigation of harmonic frequencies;
4. Harmonic filter;
5. Transformer Phase Shift.

3.3.2 Harmonic analysis indices

The influence of harmonics is usually measured by means of several indicators, which are defined below. The definitions apply to both voltage and current [1].

- Total Harmonic Distortion (THD) - also known as the Harmonic Distortion Factor (HDF) is the most popular measure of harmonic distortion in voltage and current. It is a measure that shows the ratio of the root mean square of all harmonics to the fundamental component. For an ideal system, THD is zero. THD is determined by the formula:

$$THD = \frac{\sqrt{\sum_{i=2}^{\infty} F_i^2}}{F_1},$$

Where F_i – amplitude of the *i*-th harmonic;

F_1 – fundamental amplitude.

- The Telephone Influence Factor (TIF) is the change in THD with a different weight assigned to each of the harmonics depending on the amount of interference for the audio signal in the same frequency range. Typically, the current TIF has a greater effect on adjacent communication systems. TIF is defined by:

$$TIF = \frac{\sqrt{\sum_{i=1}^{\infty}(W_i \cdot F_i)^2}}{\sqrt{\sum_{i=1}^{\infty}F_i^2}},$$

Where W_i - the weighting factor of the TIF.

The values of the weighting factors for the different harmonic frequencies are given in IEEE Standard 519. For harmonic systems other than 50 Hz, the weights are linearly interpolated [9].

- Power Factor (*PF*), which is defined as the ratio of active power P to total power S:

$$PF = \frac{P}{S},$$

In practice, this term is often confused with cosine φ, which can be found by the following formula:

$$\cos\varphi = \frac{P_1}{S_1},$$

where P_1 – base frequency active power;

S_1 – fundamental frequency power.

Thus, cosine φ refers only to the fundamental frequency, and in the presence of harmonics is different from the power factor. If the measured *PF* is not equal to cosine φ, this indicates the presence of significant harmonic distortion in the network (i.e. *PF* is less than cosine φ).

- Amplitude Factor (cross-factor) is the ratio of the peak value of current or voltage to their RMS values:

$$k_a = \frac{I_m}{I_{rms}} \quad or \quad k_a = \frac{U_m}{U_{rms}},$$

where I_m, U_m – current or voltage amplitude;

I_{rms}, U_{rms} – the effective value of the current or voltage.

For a sinusoidal signal this coefficient is $\sqrt{2}$. For a non-sinusoidal signal its value can be either greater or less than $\sqrt{2}$. The amplitude factor is especially useful for identifying large current or voltage peaks.

The amplitude factor of the currents consumed by nonlinear loads is much greater $\sqrt{2}$ and can have values as high as 1.5–2 and up to 5 in critical cases. A very large amplitude coefficient indicates the presence of significant overcurrents. If detected by the protection devices, these overcurrents can cause false tripping.

- Distortion power. The total power S is defined as:

$$S = U_{rms} \cdot I_{rms},$$

where U_{rms} – effective voltage;

I_{rms} – effective current.

In the presence of high harmonics, the formula will be as follows:

$$S^2 = \left(\sum_{n=1}^{\infty} U_{n(rms)}^2 \right) \cdot \left(\sum_{n=1}^{\infty} I_{n(rms)}^2 \right),$$

From this we see that in the presence of harmonics the ratio $S^2 = P^2 + Q^2$ is invalid. The distortion power is determined as follows:

$$D = \sqrt{S^2 - P^2 - Q^2},$$

where $P = \sum_{h=1}^{\infty} U_h \cdot I_h \cdot \cos \varphi_h$ - the active power of a signal containing harmonics, which is the sum of the active powers generated by voltages and currents of the same order;

$Q = U_1 \cdot I_1 \cdot \sin \varphi_1$ – Reactive power, which is determined only for the main frequency [9].

From this you can see that the distortion power is the sum of the individual reactive power harmonics. The frequency spectrum is a histogram showing the amplitude of each harmonic series in relation to its frequency. For example, Figure 28 shows the frequency spectrum of a rectangular signal for voltage *U*(*t*).

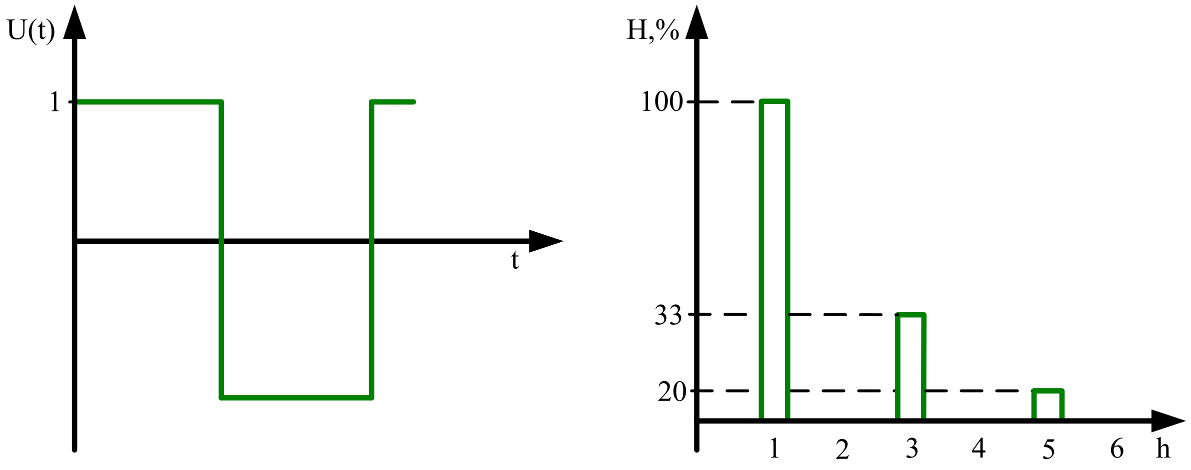


Figure 28 – Frequency spectrum of a rectangular signal [2]

The consequences of current and voltage distortion are different. The following are the consequences of equipment operation in the presence of an appropriate percentage of nonlinear voltage distortion:

- <5% – normal situation, no equipment malfunction;
- 5–7% – significant pollution of the network by harmonics, some malfunctions are possible;
- 8–10% – a high degree of pollution of the network by harmonics, failures in operation of the equipment are possible. Requires a thorough analysis and installation of compensating or filter-compensating devices;
- 10–49% – significant contamination of the network by harmonics with a risk of temperature increase in cables and the resulting need to switch to cables with a larger cross-section and more powerful power supplies;
- 50% – high degree of contamination of the network by harmonics, malfunctions of the equipment are possible. Requires careful analysis and installation of compensating or filter-compensating devices [2].

Harmonic distortion is caused by nonlinear devices in the power system. A nonlinear device is a device in which the current is not proportional to the applied voltage. The Figure 29 illustrates this concept with an example of a sinusoidal voltage applied to a simple nonlinear resistor in which the voltage and current vary according to the curve shown. While the applied voltage is perfectly sinusoidal, the resulting current is distorted. Increasing the voltage by a few percent can double the current and change the waveform. This is the source of most harmonic distortion in the power system.

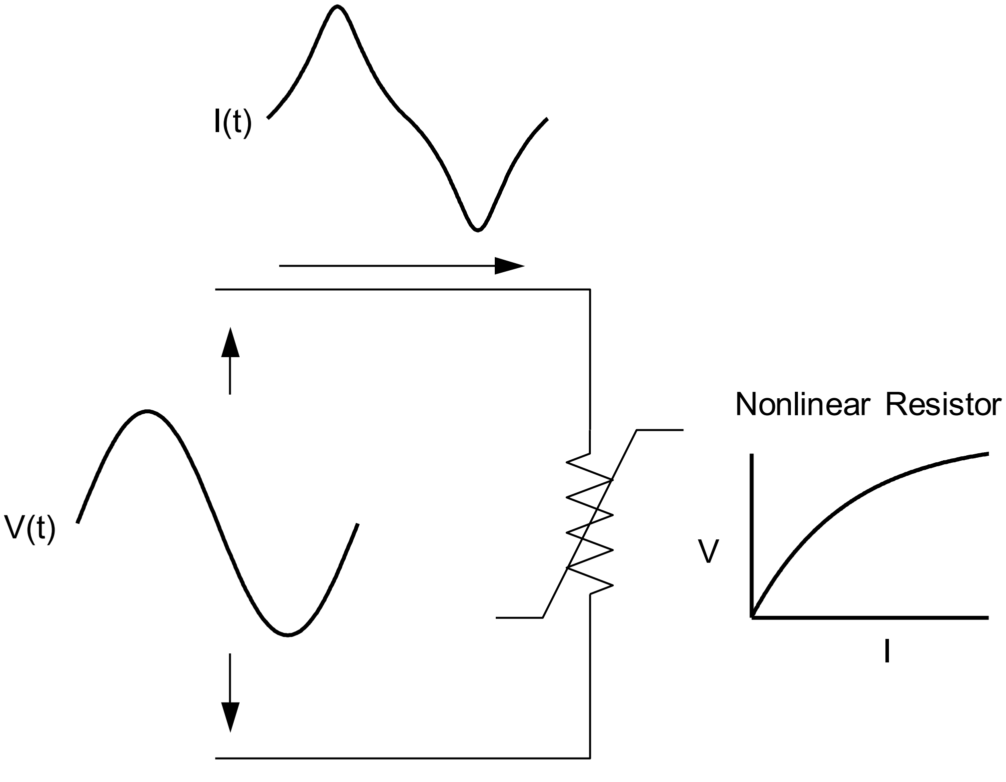


Figure 29 – Current distortion caused by nonlinear resistance [15]

The Figure 30 shows that any periodic distorted waveform can be expressed as a sum of sine waves. When a waveform is identical from one cycle to the next, it can be represented as a sum of pure sine waves in which the frequency of each sine is an integer multiple of the fundamental frequency of the distorted wave. This multiple is called the harmonic of the fundamental, hence the name of this subject [15].

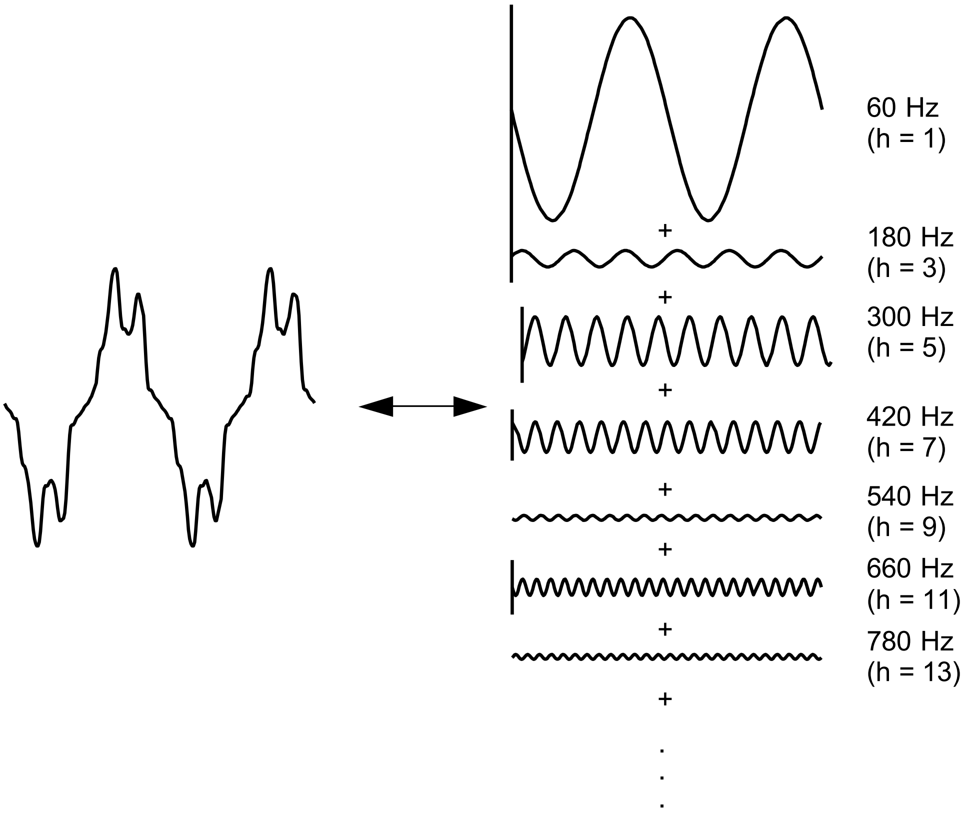


Figure 30 – Fourier series representation of a distorted waveform [15]

The sum of the sinusoids is called the Fourier series, named after the great mathematician who discovered the concept. Because of the above property, the concept of Fourier series is universally applicable in the analysis of harmonic problems. The system can now be analyzed separately at each harmonic. In addition, finding the response of the system sine wave of each harmonic separately is much easier compared to all distorted waveforms.

The output signals at each frequency are then combined to form a new Fourier series from which the output waveform can be calculated if desired. Often only the magnitudes of the harmonics are of interest. When both positive and negative half-periods of the signal have the same shape, the Fourier series contains only the odd harmonics. This provides further simplification for most power system studies, since most common harmonic-generating devices look the same for both polarities. In fact, the presence of even harmonics is often a sign that something is wrong, either with the load equipment or with the sensor used for measurement. There are notable exceptions to this rule, such as half-wave rectifiers and arc furnaces, where the arc is random.

Typically, higher order harmonics (above the 25th to 50th order range, depending on the system) are insignificant for power system analysis. Although they can interfere with low-power electronics, they usually do not damage the power system. It is also difficult to collect sufficiently accurate data to simulate power systems at these frequencies. A common exception to this rule occurs when system resonances exist in the frequency range. These resonances can be excited by nicks or switching transients in electronic power converters. This results in voltage signals with multiple zero-crossings that disrupt synchronization circuits. These resonances usually occur in systems with underground cable, but without power factor correction capacitors. If the power system is depicted as series and shunt elements, as is common practice, the vast majority of nonlinearities in the system are found in the shunt elements (i.e., loads). The series resistance of the supply system (i.e., the short-circuit resistance between the source and the load) is remarkably linear. In transformers, the shunt branch (magnetizing resistance) of the common 'T" model is also a source of harmonics; the leakage resistance is linear. Thus, the main sources of harmonic distortion will ultimately be the end-user loads. This does not mean that all end-users who experience harmonic distortion will themselves have significant sources of harmonics, but harmonic distortion usually occurs with some end-user load or combination of loads [15].

The real characteristics of current and voltage waveforms of a particular network area, taken by the HIOKI PW3198 device, are shown in Figures 31 and 32, respectively [1].

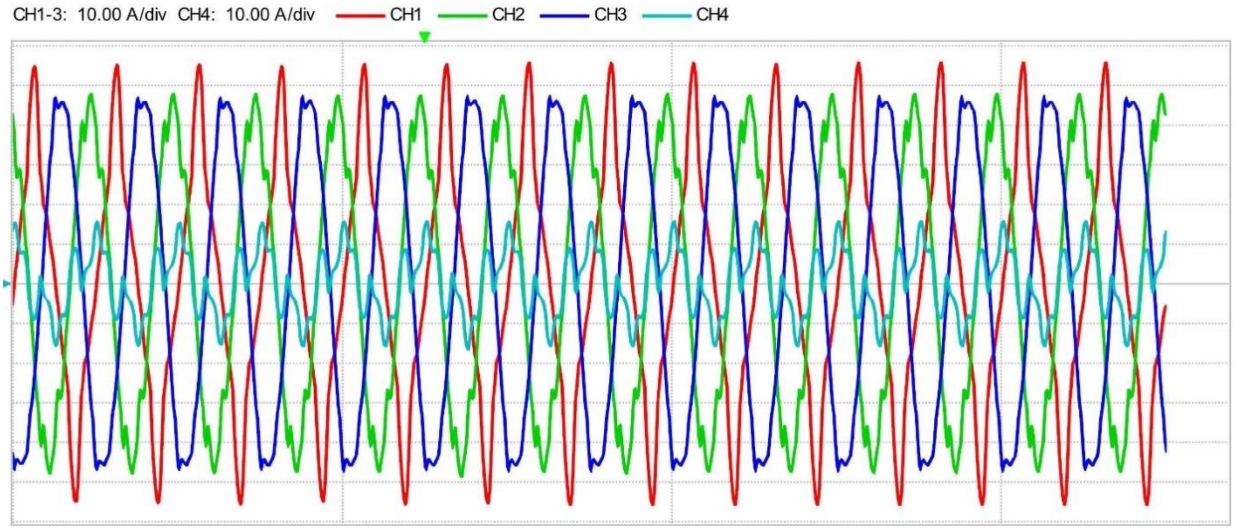


Figure 31 – LV consumer buses currents [1]

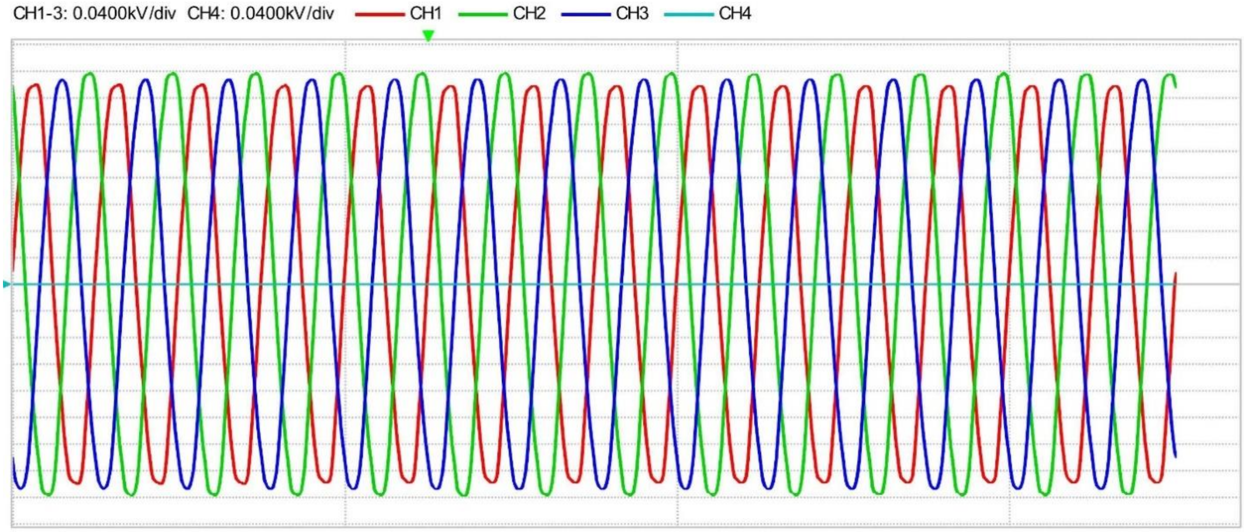


Figure 32 – LV consumer buses voltages [1]

3.3.3 Preparing the model for the harmonic current analysis

To use this module, it is necessary to consider the reverse and zero sequence circuitry. To simplify the calculations, the reverse and zero sequence resistances will be equated to the forward sequence resistances. Moreover, the large number of nodes in the network does not allow the use of adaptive calculation methods and their accelerated methods, so the standard Newton-Raphson method will be specified [9].

Physically the network is modeled harmonic injection from the 220 kV bypass link at the Yuzhno-Sakhalinskaya substation. To do this, it was necessary to replace the cutoff from the rest of the 220 kV network with a static load subject to static load characteristics with the presence of 6-pulse harmonics. The appearance of harmonics in a network other than the main network brings with it distortion power, which reduces the capacity of the lines, oscillating in the transit line. This is shown graphically in Figure 33. The distortion energy oscillates between the transformer secondary and the consumer [2].

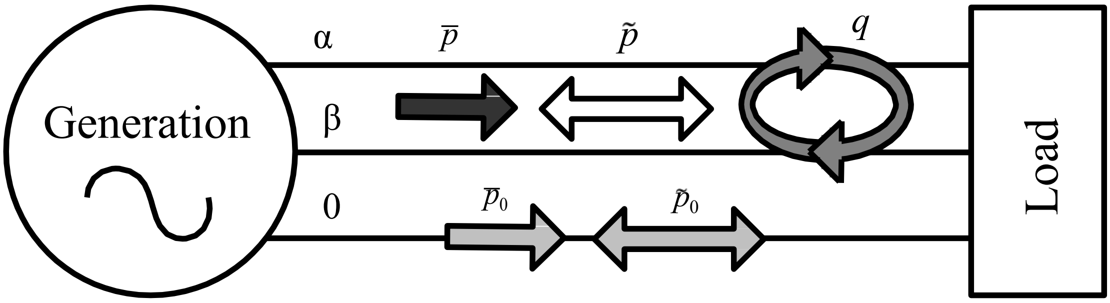


Figure 33 – Constituents of the p-q theory in coordinates α-β-0 [2]

Figure 34 shows the components of the p-q theory in coordinates α-β-0 in the presence of an active filter in the circuit. In this case, the energy is redistributed between the load and the filter-compensating device.

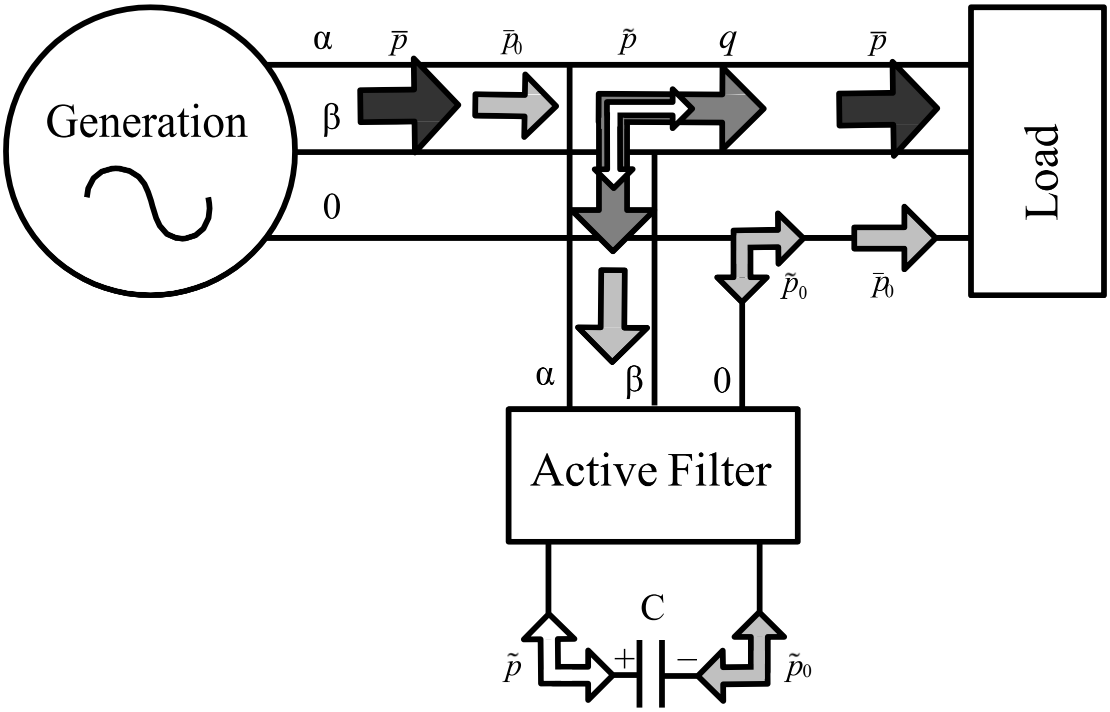


Figure 34 – Components of p-q theory in coordinates α-β-0 in the presence of an active filter [2]

The values of the electrical system shown in Figures 33, 34 represented in coordinates α-β-0, have the following physical meaning:

$\bar{p}_0$ − The average value of the instantaneous zero sequence power, corresponding to the energy per unit time that is transferred from the power supply to the load through the zero sequence voltage and current components;

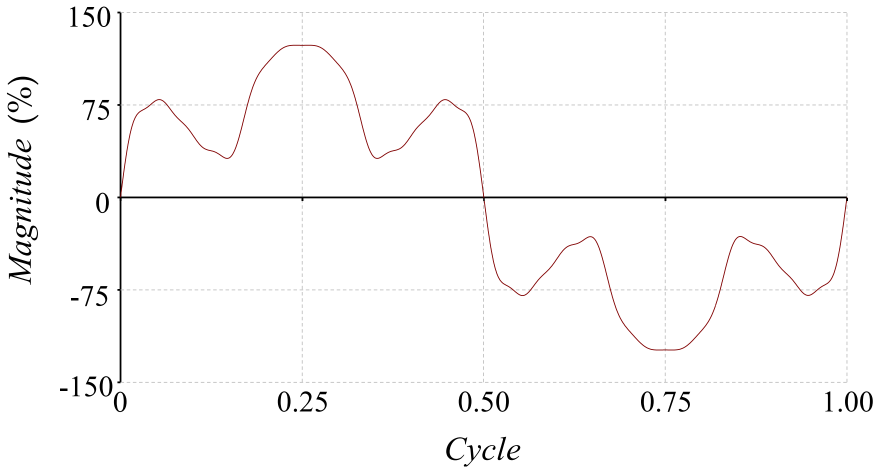
$\tilde{p}_0$ − The variable value of the instantaneous zero sequence power, corresponds to the energy per unit time that is exchanged between the power supply and the load through the zero sequence components. Zero sequence power exists only in three-phase systems with a neutral conductor. In addition, systems must have unbalanced voltages and currents or harmonics for voltage or current;

$\bar{p}$ − The average value of the instantaneous real power, corresponding to the energy per unit time that is transferred from the power supply to the load;

$\tilde{p}$ − The variable value of the instantaneous real power, corresponding to the energy per unit time that is exchanged between the power supply and the load;

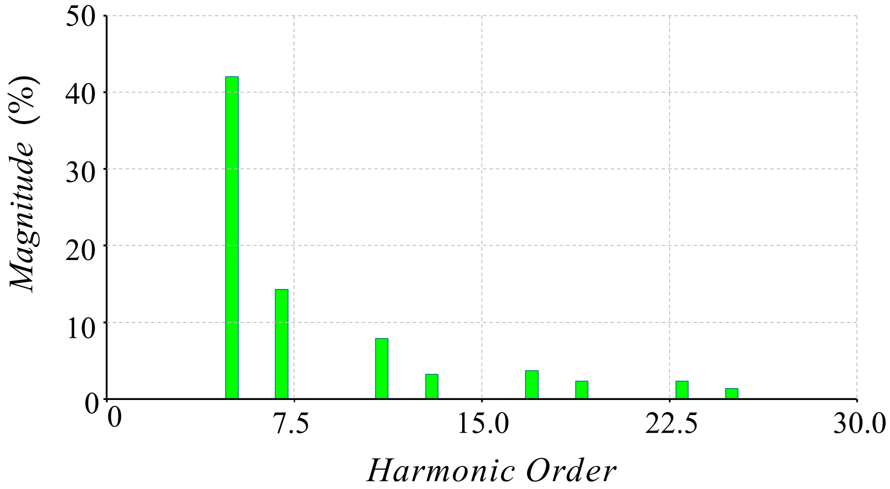
q − The instantaneous imaginary power, corresponds to the power that flows between the phases of the load. This component of the system does not involve energy transfer or exchange between the power supply and the load, but is responsible for the existence of unwanted currents circulating between the phases of the system. In the case of a balanced sinusoidal voltage system and a balanced load with or without harmonics, the average value of the instantaneous imaginary power is equal to the usual reactive power [2].

The waveform loaded into the load node and its spectrum are shown in Figures 35 and 36 [9].



Source: The figure is obtained at ETAP library.

Figure 35 – Waveform of the loaded harmonic



Source: The figure is obtained at ETAP library.

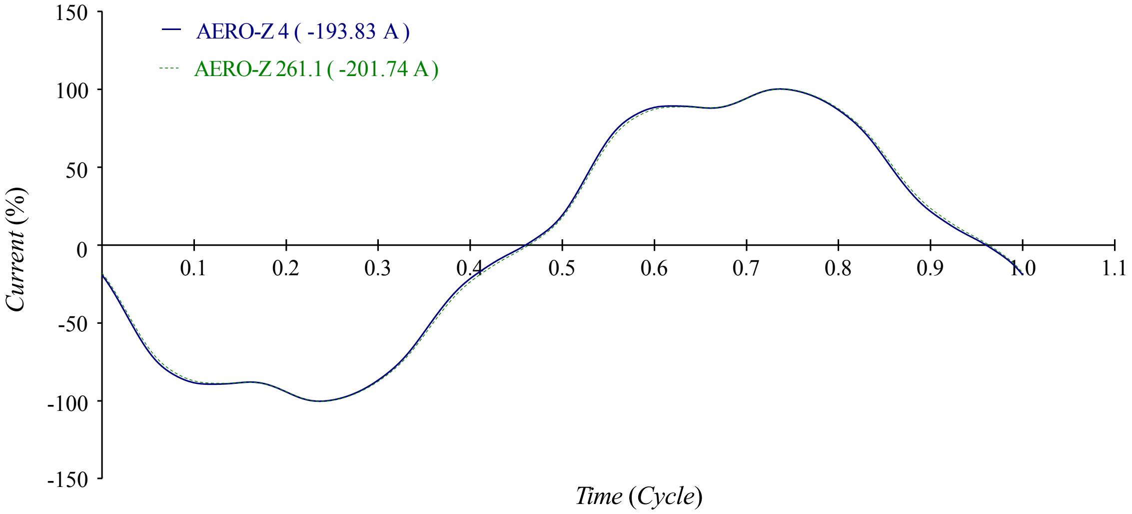
Figure 36 – Loaded harmonic spectrum

Since this section is aimed specifically at determining the degree of influence of harmonic distortion of current composition on the amount of losses on the system elements, the composition of the resulting current in the section will be evaluated only by some indices of harmonic composition estimation.

Thus, exceeding the THD index by voltage is mostly found on the consumer buses of through substations with heavy loads, as well as on the 220 kV Yuzhno-Sakhalinskaya nodal substation. Qualitatively, the excess of this index reports a great influence of high frequency current on the operating frequency current, such influence leads to an increase in the amplitude of the operating current along the transits, and as a consequence, to an increase in losses on these very transits.

TIF coefficient expectedly does not exceed its admissible limits, because the pulse rate of the given harmonic is low enough [2].

The quantitative values of the described coefficients can be found in the Appendix A.2. The influence of the loaded harmonic can be qualitatively estimated in Figure 37.



Source: The figure is obtained at ETAP model results.

Figure 37 – Waveform of the current on the monitored section based on the analysis of harmonic load flow

Since the consequence of the presence of high-frequency current is an increase in the amplitude component of the resultant current, it is inevitable that the losses on the transit lines will increase. The values of overcurrents in the network and voltages in its nodes in three circuit-mode situations are shown in Appendix A.2. The voltages were measured at the generator buses and at the last outlet buses of the last substations in the branch.

The presence of high harmonics in the network has expectedly led to an increase in transmitted power losses in transit lines. This is caused by the "stratification" of current and voltage into basic and higher frequencies, which occupy the transmission capacity of lines with useless power. However, the presence of high-frequency current and voltage did not lead to a significant increase in the voltage on the substation buses.

3.4 Summary

In this section, steady-state calculations were performed using the optimal capacitor bank placement module in the ETAP software.

According to the data obtained, the presence of harmonics, even of small pulses, significantly increases losses in transit lines. So in the monitored section (110 kV Yuzhno-Sakhalinskaya CHPP-1 (the 5th power unit) - Yuzhno-Sakhalinsk) losses increased by 4.10%, which increases the cost of electricity by 12.86 r/hr (according to the tariffs of the Sakhalin region - 7.99 r/kWh). In the adjacent circuits the losses grew by 4.457%, which adds to the final cost of the spent electricity 15.98 r/hr. At the same time the use of CBs compensates 5.32% of reactive power and saves 9.51 r/hr. Also in the adjacent circuits is compensated

4.41% of the reactive power, which reduces the cost of the spent electricity after the harmonics by 3.995 p / h. Taking into account that the balancing zone in general cases ends at the outputs of the low side of the transformer, the costs of the installed CBs will be borne by the consumers, which means that the economic benefit to consumers will be noticeable in 5 years, after the payback period of the CBs. Thus, the installation of CBs can only be considered a half-measure in the issue of compensation of losses from the presence of higher harmonics in the network, rather than a full-fledged solution. Definitely solve the problem of compensation for higher harmonics is possible with the use of passive or active filter-compensating devices. However, the use of the first requires more calculation and the possibility to regulate it is usually not available, and the purchase of the latter will have an extremely large impact on the subsequent tariff for consumers, but its benefit in terms of loss compensation relative to CBs can grow up to tens of times.

4. Selection of electrical equipment

The stage after the initial front-end engineering design of the project, where I checked the feasibility of the project and designed the reactive power compensation system, is its economic evaluation. In this Chapter I will estimate the amount of investment in each configuration of the capacitor bank system. After that I will calculate the net present value and based on the average annual cost I will evaluate the possible feasibility of this project.

Another feature of this solution is that I am going to look at these options from the manager's perspective. In this case, from the manager's point of view, it is necessary to get the maximum NPV value. It should also be understood that in this case reactive power compensation is not an economic benefit, but serves as a means of regulating the parameters in the mode of maximum loads. The only thing that can be done here is to save money by reducing transmission losses.

4.1 Determination of the average mean time to failure of a capacitor unit

According to the results of calculations of paragraph four, I determined that to compensate the reactive power in order to increase the transmitted active power it is necessary to install a block of nine series-connected capacitor banks at the substation Yuzhno-Sakhalinskaya, and eighth capacitor banks at the substation Yuzhnaya.

It is worth noting that if one of the capacitor plant systems is disconnected, then compensation will not be appropriate due to the presence of its own losses on the capacitor plants. Thus, the calculation will be made for the unit with the highest chance of tripping. In our case, the system of nine series-connected capacitor banks at the Yuzhno-Sakhalinskaya substation is such a system.

As noted earlier, the system is nine series-connected capacitor banks in a medium-voltage parallel circuit. The system is connected to the power supply bus via a fuse. The schematic diagram is shown in Figure 38.

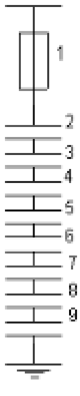


Figure 38 – Schematic diagram of the capacitor unit.

Figure 39 shows the calculated diagram of the reliability of the capacitor plant, where each element is marked with its own reliability parameters. The failure rate of each capacitor bank $\lambda_{2-10} = 0.02\, failure / year$, the failure rate of the fuse $\lambda_1 = 0.03\, failure / year$.

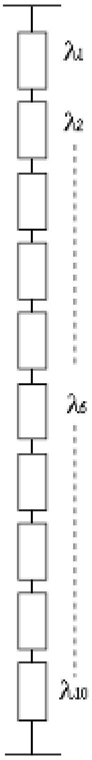


Figure 39 – Calculation scheme of the reliability of a capacitor plant.

The capacitor also fails when the fuse 1 blows. Consequently, if any one element fails, the system consisting of 10 elements will fail.

Failure rate of the capacitor battery will be:

$$\lambda_0 = \sum_{i=1}^{10} \lambda_i = 0.02 \cdot 9 + 0.03 = 0.21\, failure / year$$

The probability of failure-free operation of the battery in one year is:

$$P(t) = e^{-\lambda_0 \cdot t} = e^{-0.21 \cdot 1} = 0.811$$

The average MTF is:

$$T_0 = \frac{1}{\lambda_0} = \frac{1}{0.21} = 4.762 \approx 5\, years$$

Thus, the economic assessment will be carried out for the mean time until the failure of the equipment, which is five years.

5. Methodology of economic evaluation

To implement the project, it is necessary to estimate the volume of investments and expected expenditures, as well as analyze the options with Net Present Value and Annual Payments.

The Net Present Value (NPV) is the criterion that allows to decide whether it is reasonable to invest in a project. NPV estimate the difference between the present value of cash inflows and the present value of cash outflows. However, there are no cash flows in the current project, so the net present value for each measure will be estimated on the basis of electricity bills, taking into account annual inflation and the expected life of the project. Because the NPV calculation is purely cost-based, the NPV for all measures will be negative, and a closed to zero NPV would be more desirable [18].

The NPV is calculated according to following formula [18]:

$$NPV = C_0 + \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} ,$$

where:

C_0 – Initial investment in the project (usually a negative number);

T – Service lifetime of the equipment;

t – Number of time periods;

C_t – Summary cash flow in the period t;

r – Discount rate.

The NPV approach properly considers the time value of money and adjusts for project's risk using the opportunity cost of capital as the discount rate. Thus, it clearly measures the increase in market value or wealth created by the project. NPV is the only metric that provides a theoretically correct measure of project cost [18].

Once the NPV has been calculated, the annual payments to operate must be calculated. The amount of the annuity payment with a given present or future value is calculated using the following formula [18]:

$$PMT = \frac{-NPV}{T\ annuity\ factor}$$

$$T\ annuity\ factor = \frac{1}{r} - \frac{1}{r \cdot (1+r)^T} ,$$

where:

PMT – Annual payment;

$T\ annuity\ factor$ – annuity factor for period T.

5.1 General economic parameters

For project implementation it is necessary to know the various economic parameters of the country where the project will be realized. So I will evaluate some basic parameters, which will be the same for illumination system and regulators, such as inflation rate, corporate tax and discount rate.

1. Inflation

Inflation is an increase in the general price level of goods and services. In inflation, the price of identical goods increases over time. In effect, the purchasing power of money is reduced and money becomes worthless [18]. It is only possible to estimate the future rate of inflation by analyzing inflation in previous years. Therefore, for this project I have taken the average geometric inflation rate for the last 10 years. The data is presented in Table 11.

Table 11. Historic inflation in Russia [19]

Year	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Inflation, %	6.58	6.45	11.36	12.91	5.38	2.52	4.27	3.05	4.91	8.39
Average inflation, %	6.53									

According to Table 11, I have plotted a graphical chart to better representation of inflation level.

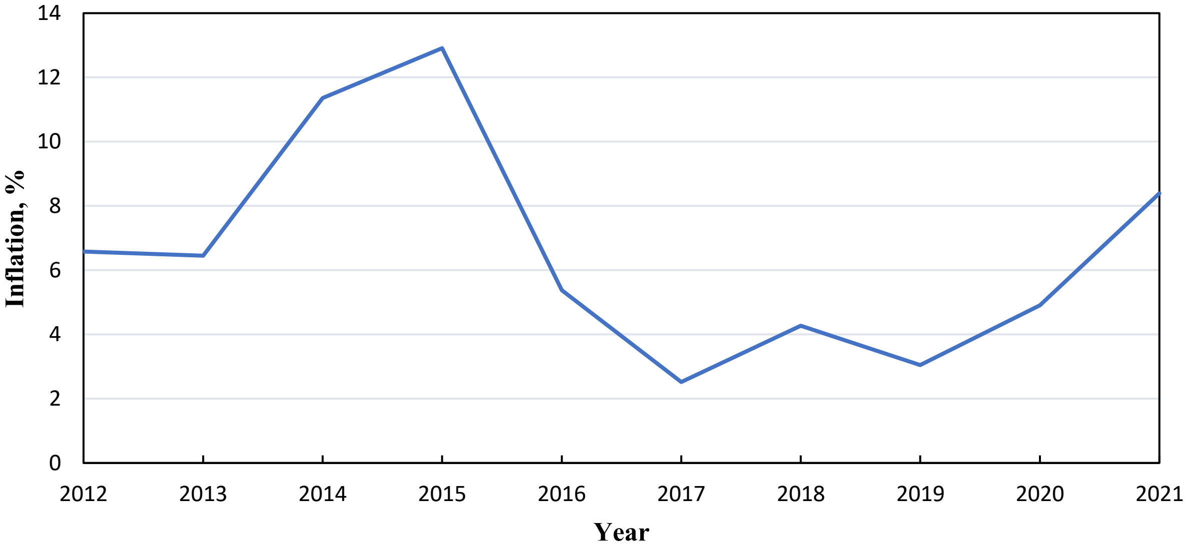


Figure 40 – Annual inflation in Russia (illustration based on data from [19])

2. Corporate tax

Corporate tax is a direct tax levied on the profits of an organization. Profit for the purposes of this tax is generally defined as income from a company's activities reduced by the amount of statutory deductions and exemptions [20].

According to the tax law of Russia, corporate tax rate is equal to 20% [20].

3. Discount rate

The discount rate is the ratio of return used to discount future cash flows to their present value. According to Capital Asset Pricing Model (CAPM), the discount rate can be calculated using followed formula [18]:

$$r = r_f + \beta \cdot (r_m - r_f) = 7.42 + 0.5 \cdot 8.1 = 11.47\%,$$

where:

$r_f = 7.42\%$ – Risk free rate equals to 10 years federal bond ratio [21];

$\beta = 0.5$ - The average volatility of stocks in this sector (construction and production of reinforced concrete) in Russia's market [22].

$r_m - r_f$ – Average risk premium rate on market for 10 years [23].

4. Depreciation

Depreciation is the process of transferring the cost of fixed and tangible assets by instalments as they are technically or morally depreciated to the cost of products (works, services) produced [18].

Accelerated depreciation has been adopted to reduce taxes faster as money is worth more now [18]. When calculating depreciation for tax reducing purposes, I used the variable declining balance method, the essence of which is to use two methods of calculating double-declining balance and straight-line depreciation. The point is that this VDB is better than the DDB method, as the second does not always achieve the full depreciation amount by the end of service life [39].

An example of a comparison between two types of accelerated depreciation is shown below in Table 12. See Chapter 4.3.2 for more details about estimation of these values. All calculations have been done using functions in Excel.

As Table 12 shows, the final result of using double-declining balance depreciation does not cover the amount of initial investments in the project, so the variable-declining balance method will be used for further depreciation calculations.

Table 12. Comparison of DDB and VDB methods

Year	1	2	3	4	5	Total amount, RUB
Double-declining balance method, RUB	22,929,581	13,757,748	8,254,649	4,952,789	2,971,674	52,866,441
Variable-declining balance method, RUB	15,286,387	9,171,832	5,503,099	4,127,325	4,127,325	38,215,968

5.2 Economic estimation

According to Tables 11 and 12, I will calculate NPV and estimate average yearly payments for the system of the capacitor batteries. In order to calculate all necessary costs, I will use some general economic indicators from Chapter 5.3, as well as to specific economic indicators such as:

- Initial investment in the project;
- Energy consumption cost;
- Cost of maintenance;

5.2.1 Specific economic parameters

1. Initial investment in the project

To determine the initial cost it is necessary to multiply the price of one capacitor bank by the recommended number of capacitor banks. The following formula is used:

$$C_0 = (C_1 \cdot n_1 + C_2 \cdot n_2) \cdot ER\,,$$

where:

n_1 – Required number of capacitor banks on substation Yuzhno-Sakhalinskaya;

n_2 – Required number of capacitor banks on substation Yuzhnaya;

C_1 – Price of one capacitor bank on substation Yuzhno-Sakhalinskaya;

C_2 – Price of one capacitor bank on substation Yuzhnaya;

ER – dollar-ruble exchange rate.

This formula does not take into account the inflation rate because the purchase is being made at the present time.

2. Energy consumption cost

According to the calculations in Chapter 4, the amount of compensated reactive power can be determined using the following formula:

$$P_t^{en} = E \cdot \Delta P \cdot h \cdot (1 - INF)^t\,,$$

where:

C_t^{en} – Reactive consumption profit;

$E = 64.38\ RUB\ per\ kW \cdot h$ - Cost of kWh in Sakhalin, Russia [38];

ΔP – Power losses, kW;

$h = 43800\ h$ - Mean lifetime;

$INF = 6.53\%$ - Geometric average inflation in Russia for 10 years' period.

3. Cost of maintenance

The payback period was taken from the ETAP capacitor battery library (Table 10). Which is \$1,800 per battery per year at the 220 kV Yuzhno-Sakhalinskaya substation and \$1,600 per battery per year at the 110 kV Yuzhnaya substation

4. Purchasing new equipment

The cost of purchasing a capacitor bank was taken from the ETAP capacitor bank library (Table 10), which is \$36,000 per unit for the 220 kV Yuzhno-Sakhalinskaya substation and \$32,000 per unit for the 110 kV Yuzhnaya substation. Also worth considering is the installation cost, which is \$800 per unit at both substations.

5.2.2 Economic model

So I created an economic model for each capacitor bank, using the parameters I described above. To calculate the NPV I took a base period of 5 years, which corresponds to the payback period of one capacitor battery.

At the end of the sub-will be a general Table with final calculations for all luminaire types. Calculation example for 220 kV Yuzhno-Sakhalinskaya substation:

- Initial investments in the project

$$C_0 = (C_1 \cdot n_1 + C_2 \cdot n_2) \cdot Ex.Rate = (9 \cdot 36800 + 8 \cdot 32800) \cdot 64.38 = 38,215,968\ RUB$$

The purchase is made at time t=0, so inflation rate is not taken into account.

- Profit for the power losses decreasing

$$C_t^{en} = E \cdot \Delta P \cdot h \cdot (1 + INF)^t$$

$$C_1^{en} = 64.38 \cdot 17.5 \cdot 43800 \cdot (1 + 0.0653)^1 = 1,800,932\ RUB$$

Thus, adjusted for inflation, the profit for electricity sale in second year would be 1,918,533 RUB, etc.

- Depreciation

The depreciation method used for tax purposes does have monetary consequences that need to be taken into account when calculating NPV. Thus, accounting for depreciation will reduce the payment of taxes over the operating time of the equipment [18].

The VDB depreciation method and the depreciation values for fluorescent light bulbs are presented in Table 7.

- Tax saved

Since loss reduction cannot inherently generate a profit, but only increases the lifetime of the equipment, this means that, from an economic point of view, the project only generates a cost. If the project generates a loss, this loss can be used to reduce the tax on the rest of the company's activities. In this case, the project generates tax savings - the tax outflow is negative [18].

When calculating tax savings, only operating expenses are taken into account, the initial investment and further purchase of equipment are counted as a cash outflow.

$$Tax\,saved_t = Corp.tax \cdot Operational\ \ expenses$$

So, for example, in the 1st year of use it was possible to save taxes by:

$$Tax\,saved_1 = 0.2 \cdot \left(1{,}988{,}936 + 15{,}286{,}387\right) = 3{,}455{,}065\ RUB$$

- Cash flow

To calculate cash flow for NPV, account for capital costs when they are incurred, not later when they show up as depreciation. To go from accounting income to cash flow, you need to add depreciation (which is not a cash outflow) and subtract expenses (which are cash outflows) [18].

So, in this case summary cash flow in the first year will be:

$$C_1 = -\left(1{,}988{,}936 - 1{,}800{,}932\right) = -188{,}004\ RUB$$

Next, I calculated the discounted cash flow for each and summed all these values and got the total NPV for 5 years for this project. Then, I calculated the average annual cost for maintaining this project. Table 13 shows all the indicators needed to calculate NPV for a given type of CBs over a project period.

Table 13. Economic model for CBs, RUB

Year	0	1	2	3	4	5
Initial Investment	38,215,968					
Energy saved		-1,800,932	-1,918,533	-2,043,813	-2,177,274	-2,319,450
Maintenance of equipment		1,988,936	2,118,814	2,257,173	2,404,566	2,561,584
CBs` Depreciation		15,286,387	9,171,832	5,503,099	4,127,325	4,127,325
Tax saved		3,455,065	2,258,129	1,552,054	1,306,378	1,337,782
Cash flow	-38,215,968	3,267,060	2,057,848	1,338,695	1,079,086	1,095,648
Discounted CF	-38,215,968	2,930,888	1,656,141	966,513	698915	636,621
Net Present Value	-31,326,891					
Annual payments	-4,598,814					

The NPV value of project equals to -31,326,891 RUB. The average annual payments (PMT) equals 4,598,814 RUB.

In accordance with the above described economic model, I have calculated the NPV and the average annual payments for the equipment.

As shown in Table 13, the NPV of this project is negative and far from zero. However, as stated earlier, the project is aimed at maintaining the parameters of the power system at the level established by GOST.

5.2.3 Sensitivity analysis

Project sensitivity analysis determines how different sources of uncertainty in a mathematical model contribute to the overall uncertainty of the economic model. In other words, sensitivity analysis examines the impact of input parameters such as investments, operating expenses, discount rate and so on final NPV result. Finally, it is possible to identify the impact of each parameter and each degree of influence on final result and make decision.

The first step is to identify the baseline parameters that can have the greatest possible impact on the project cost. After, I have made a change to each selected parameter and assess its impact.

Here is a list of parameters which will be used in sensitivity analysis of NPV:

- Electricity price

- Inflation rate
- Discount rate

Results are represented on Figures 41 – 43.

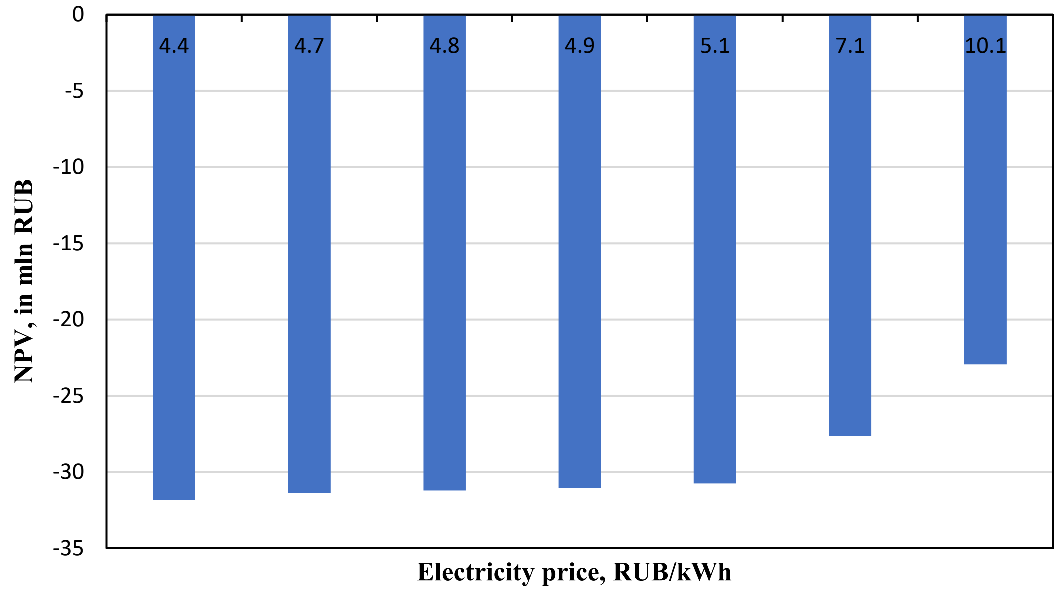


Figure 41 – Dependence of NPV on electricity price

I have used column chart to display the results better. The graph in Figure 41 has exponential characteristic. From the graph, it can be seen that when the cost of electricity increases, NPV also increases.

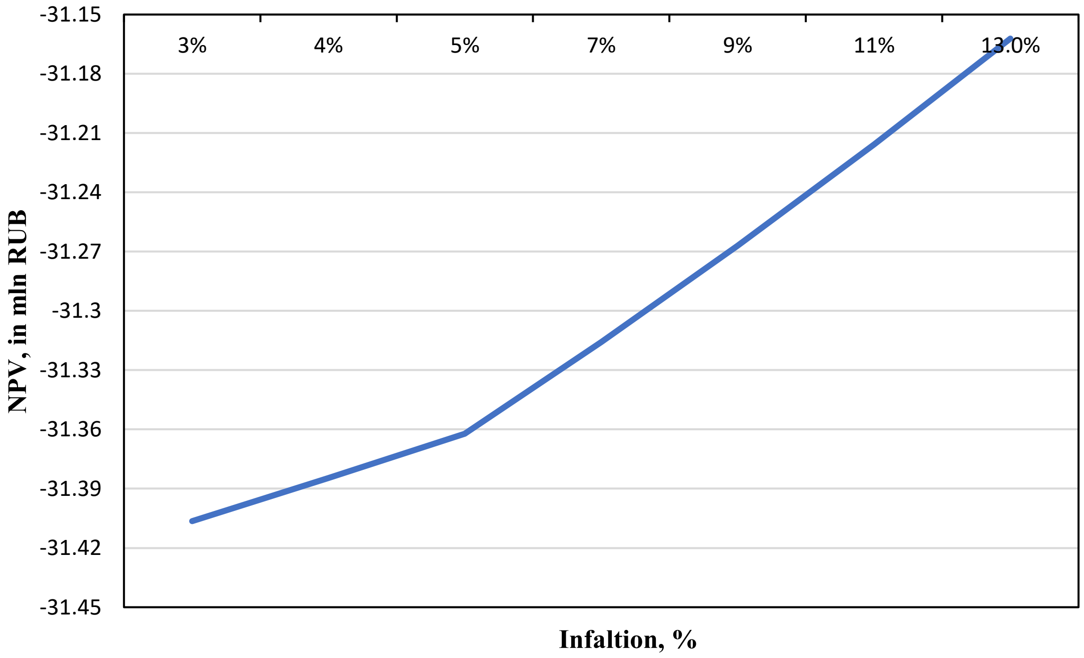


Figure 42 – Dependence of NPV on inflation rate

Figure 42 shows that as the interest rate increases, the cost of project implementation also increases. These calculations are based on the assumption that inflation rate should be less than the calculated discount rate (11.47%).

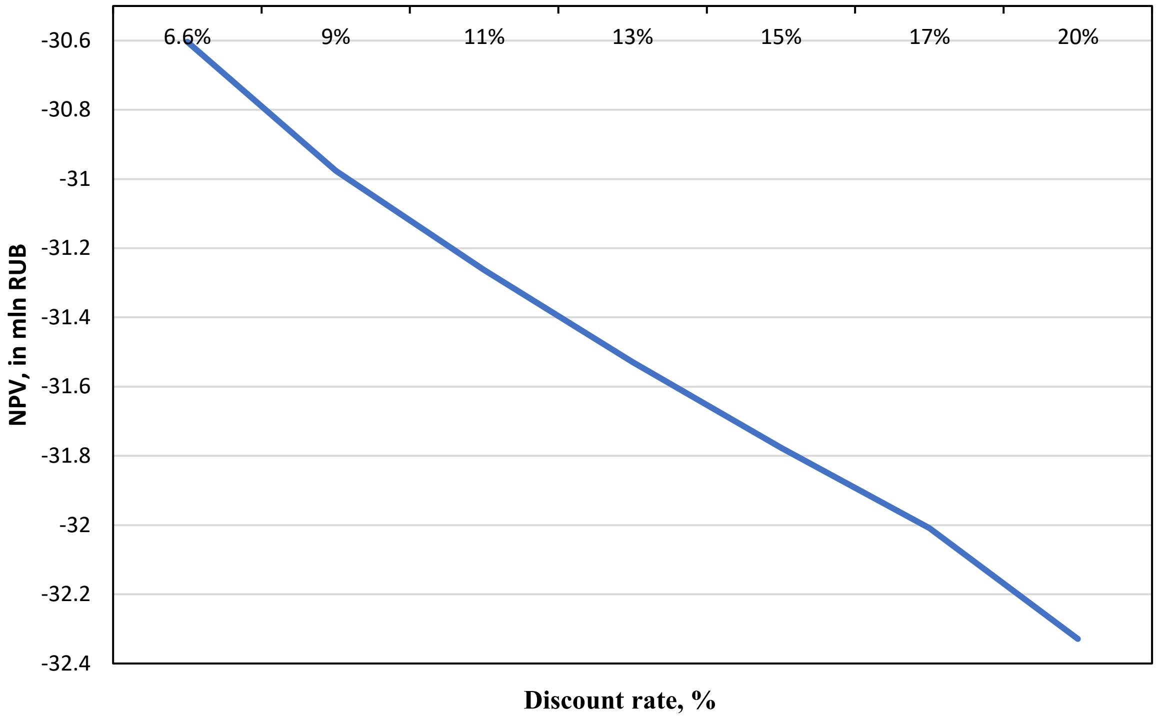


Figure 43 – Dependence of NPV on discount rate

The graph in Figure 43 has exponential characteristic for each configuration. The greater the discount rate the less NPV. These calculations are based on the assumption that discount rate should cover the inflation rate (6.53%).

5.3 Summary

In this section, an economic evaluation of my project was given. Thus, it can be concluded from the findings that the project is unprofitable, but it is worth bearing in mind that this is only a rough economic assessment. It is rather difficult to conclude unambiguously about the economic viability, as reduced power losses do not lead to more power transmission to the consumer. Reduced losses have an economic benefit by increasing the quality of electricity transmitted and consequently increasing the lifetime of the consumer's equipment. However, it is not possible to assess the increase economically, as there is insufficient data on the installed equipment at the customer and its current condition. It is estimated that the lifetime of the equipment can be increased by up to 30% of the nominal lifetime. In any case, the project was aimed solely at keeping the system parameters of the power system within the stated GOST limits.

Sensitvity analyses show a strong NPV dependence on the electricity tariff, as the only income that can be roughly estimated comes from the sale of compensated losses.

Conclusion

In this paper the existing power system of the Sakhalin region has been considered. A model simulating the actual behavior of the power system was generated in the ETAP software package. The model was then verified using data from winter peak load measurements. The verification was carried out with respect to system parameters such as voltage at consumer buses and power flows through transit power lines.

The section on international experience of isolated power systems gave an insight into how governments support the maintenance and maintenance of system parameters. Since isolated power systems are susceptible to various kinds of disturbances, their automatic systems and relay protection systems are given special attention to avoid blackouts. International experience shows considerable financial assistance from both private investors and governments. The most common investments are in the form of grants and subsidies aimed at maintaining stable and sustainable operation of power systems.

Transient stability of the power system has also been established in two experiments. The first experiment simulated the occurrence of a three-phase fault on a transit line, the tripping of the line by the relay protection systems and the subsequent successful automatic reclosure of the line. The second, in turn, also simulated the occurrence of a three-phase short-circuit, the tripping of the line by the protection relay systems, the line closing into a continuing short-circuit and the reclosure of the line. In other words, the second experiment simulated the unsuccessful automatic reclosure of the line during a three phase short-circuit.

In the following section, the optimal capacitor bank placement software kernel was applied. It is worth noting that the main purpose of the capacitor banks is to increase the voltage on the consumer busbars. The software kernel has defined the locations of the capacitor banks according to specified parameters such as voltage control within 10% of the nominal bus voltage and power factor control over the transmission lines, the latter in turn leads to a reduction in losses and also to an increase in power quality. Thus, by selecting the number and nominal parameters of the capacitor banks by the software kernel, the declared GOST parameters of the consumer bus voltage were achieved.

In the section on current and voltage harmonics, the influence of higher harmonics on the current and voltage amplitude was discussed. The presence of such harmonics in the network is due to equipment operating at high frequencies, such as communication lines. The increase in the amplitude value of current and voltage can be a cause of false operation of relay protection systems and automation equipment and therefore it is necessary to filter them to prevent their entry into the network from the consumer. The occurrence of six-pulse harmonics from the consumer was simulated in the software package by including the spectrum of higher harmonics in the load model. The ability to filter harmonics by installing capacitor banks was then evaluated. Thus, the harmonic filtering provided by the capacitor banks is insignificant and most of the harmonics somehow get into the rest of the network. For more filtering, active or passive filters should be installed, but their cost must be evaluated in relation to the filtering effect.

The final section gave an economic evaluation of the project in question. However, it is too early to draw a clear conclusion about its profitability. A rough estimate of the profit due to loss compensation makes it clear that the project is not economically viable. Also keep in mind that this project is aimed only at technical compliance of system parameters to GOST, and profits from it can be used to increase the cash flow in other projects, which will be directly aimed at profit. The main thing to note is that the reduction of losses in transmission lines is not in itself a direct increase in the volume of electricity transmitted, but only an indication of an increase in the quality of electricity transmitted. In turn, an increase in the quality of electricity increases the service life of electricity equipment, but this effect has not been assessed in this paper due to the lack of necessary data on the installed electrical equipment at the customer.

This project therefore requires a more detailed economic evaluation in order to make an unambiguous decision on its economic feasibility. However, it can already be concluded that the initial objective of the project, namely to keep the system parameters within the limits set by GOST, has been fully achieved. Moreover, the assumption has been made that the capacitor banks may be effective in filtering higher harmonics, but this possibility needs to be analysed in more detail.

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Appendices

Appendix A – Tables

Table A.1 – Changing power losses in circuit-mode situations

Name of branch		U. kV	ϕ. deg	P. kW	Q. kVAr	S. kVA
In the absence of CBs						
Yuzhno-Sakhalinskaya	CHPP-1 (G1) – TS	6.1	-3.09	3.99	-84	84.09
	CHPP-1 (G2) – TS	6.24	-2.98	70.8	51.7	87.67
	CHPP-1 (G3) – TS	10.4	-2.96	105.1	165.8	196.30
	CHPP-1 (Power Unit 4) – TS 1st chain	10.4	-3.02	33.1	18.4	37.87
	CHPP-1 (Power Unit 4) – TS 2nd chain	10.22	-3.02	30.6	14.32	33.78
	CHPP-1 (Power Unit 5) – TS	10.4	-3.04	41.01	39.4	56.87
	TS – Centr 1st chain	5.64	-14.9	23.98	-168.4	170.1
	TS – Centr 2nd chain	5.35	-25.6	273.4	110.3	294.44
	TS – Centr with branch on Promouzel 2nd chain	6.02	-6.93	10.7	-14.7	18.18
	TS – Korsakovskaya	9.76	-8.76	536	-501.6	734.1
	TS – Lugovaya 1st chain	9.96	-6.23	3.82	-36.2	36.4
	TS – Lugovaya 2nd chain	10.05	-7.72	2.14	-38.1	38.16
	TS – Yuzhnaya 1st chain	5.99	-7.75	390.5	534	661.55
	TS – Yuzhnaya 2nd chain	5.91	-8	240.78	98.4	259.79
Centr – Promouzel with branch on Yugo-Zapadnaya		5.94	-7.84	18.8	-306.8	307.38
Khomutovo-2 – Korsakovskaya		9.96	-4.96	3.66	-1162	1162.01
Yuzhnaya –Khomutovo-2		9.63	-7.88	165.6	-4.75	165.67
In the presence of CBs						
Yuzhno-Sakhalinskaya	CHPP-1 (G1) – TS	6.13	-3.46	3.96	-84.8	84.89
	CHPP-1 (G2) – TS	6.24	-2.97	76.3	57.6	95.60
	CHPP-1 (G3) – TS	10.4	-2.95	101	157.5	187.10
	CHPP-1 (Power Unit 4) – TS 1st chain	10.4	-3.01	31.7	16	35.51
	CHPP-1 (Power Unit 4) – TS 2nd chain	10.4	-3.12	29.4	12.08	31.79
	CHPP-1 (Power Unit 5) – TS	10.4	-3.15	38	33.8	50.86
	TS – Centr 1st chain	6.12	-4.91	20.7	174	175.23
	TS – Centr 2nd chain	6.07	-6.86	221	49.9	226.56
	TS – Centr with branch on Promouzel 2nd chain	6.05	-6.94	10.6	-15.2	18.53
	TS – Korsakovskaya	10.01	-4.94	530.9	-522.6	744.96
	TS – Lugovaya 1st chain	10.1	-6.2	3.8	-36.6	36.8
	TS – Lugovaya 2nd chain	10.01	-7.67	2.13	-38.5	38.56
	TS – Yuzhnaya 1st chain	6.01	-7.7	386.8	520.6	648.57
	TS – Yuzhnaya 2nd chain	5.97	-7.94	238.52	92	255.65
Centr – Promouzel with branch on Yugo-Zapadnaya		5.98	-7.84	18.6	-310.9	311.46
Khomutovo-2 – Korsakovskaya		9.81	-8.7	3.63	1172	1172.01
Yuzhnaya –Khomutovo-2		9.69	-7.83	163.9	-9.96	164.2

Table A.2 – Quantitative indicators of the harmonic composition of current and voltage

Name of branch		**U. kV**	**ϕ. deg**	**P. kW**	**Q. kVAr**	**S. kVA**	**THD$_U$. %**	**THD$_I$. %**	**D. kVA (%)**
The case without the installation of CBs and without taking into account the higher harmonics									
Yuzhno-Sakhalinskaya	CHPP-1 (G1) – TS	6.1	-3.09	3.99	-84	84.09	–	–	–
	CHPP-1 (G2) – TS	6.24	-2.98	70.8	51.7	87.67	–	–	–
	CHPP-1 (G3) – TS	10.4	-2.96	105.1	165.8	196.30	–	–	–
	CHPP-1 (Power Unit 4) – TS 1st chain	10.4	-3.02	33.1	18.4	37.87	–	–	–
	CHPP-1 (Power Unit 4) – TS 2nd chain	10.22	-3.02	30.6	14.32	33.78	–	–	–
	CHPP-1 (Power Unit 5) – TS	10.4	-3.04	41.01	39.4	56.87	–	–	–
	TS – Centr 1st chain	9.96	-4.96	3.66	-1162	116.01	–	–	–
	TS – Centr 2nd chain	9.76	-8.76	536	-501.6	73.1	–	–	–
	TS – Centr with branch on Promouzel 2nd chain	5.64	-14.9	23.98	-168.4	170.1	–	–	–
	TS – Korsakovskaya	9.63	-7.88	165.6	-4.75	165.67	–	–	–
	TS – Lugovaya 1st chain	9.96	-6.23	3.82	-36.2	36.4	–	–	–
	TS – Lugovaya 2nd chain	10.05	-7.72	2.14	-38.1	38.16	–	–	–
	TS – Yuzhnaya 1st chain	5.99	-7.75	390.5	534	661.55	–	–	–
	TS – Yuzhnaya 2nd chain	5.91	-8	240.78	98.4	259.79	–	–	–
Centr – Promouzel with branch on Yugo-Zapadnaya		5.94	-7.84	18.8	-306.8	307.38	–	–	–
Khomutovo-2 – Korsakovskaya		6.02	-6.93	10.7	-14.7	18.18	–	–	–
Yuzhnaya –Khomutovo-2		5.35	-25.6	273.4	110.3	294.44	–	–	–
The case without the installation of the CBs and taking into account the higher harmonics									
Yuzhno-Sakhalinskaya	CHPP-1 (G1) – TS	6.11	-3.16	3.99	-84	84.09	7.45	6.58	0.00
	CHPP-1 (G2) – TS	6.24	-3.05	73.6	54.8	91.76	4.9	7.6	18.17
	CHPP-1 (G3) – TS	10.4	-3.03	109.1	173.2	204.70	4.92	8.73	50.09
	CHPP-1 (Power Unit 4) – TS 1st chain	10.4	-3.09	34.3	20.4	39.91	4.68	9.56	8.81
	CHPP-1 (Power Unit 4) – TS 2nd chain	10.23	-3.09	31.8	16.28	35.73	7.4	6.54	7.74
	CHPP-1 (Power Unit 5) – TS	10.23	-3.1	41.98	41.01	58.69	7.4	8.03	11.38
	TS – Centr 1st chain	5.36	-14.9	23.97	-168.6	170.3	7.29	7.25	8.21
	TS – Centr 2nd chain	5.64	-25.4	273.2	109.8	294.81	7.25	7.3	10.49
	TS – Centr with branch on Promouzel 2nd chain	6.02	-7	10.7	-14.8	18.26	6.9	7.34	1.72
	TS – Korsakovskaya	9.96	-5.02	535.7	-503.3	735.04	6.74	8.3	41.33
	TS – Lugovaya 1st chain	9.96	-7.78	3.82	-36.2	36.4	7.05	7.4	0
	TS – Lugovaya 2nd chain	10.06	-6.3	2.14	-38.1	38.16	6.76	7.03	0
	TS – Yuzhnaya 1st chain	5.99	-7.81	395.9	547.3	675.48	7.72	9.93	119.92
	TS – Yuzhnaya 2nd chain	5.92	-8.06	240.68	97.8	260.11	6.88	6.62	10.85
Centr – Promouzel with branch on Yugo-Zapadnaya		5.95	-7.9	18.8	-307	307.58	6.7	7.12	11.08
Khomutovo-2 – Korsakovskaya		9.76	-8.82	3.66	-1162	1162.01	7.58	6.95	0
Yuzhnaya –Khomutovo-2		9.64	-7.94	165.6	-4.75	165.67	6.27	6.63	0
In the case when installing the CBs and taking into account the higher harmonics									
Yuzhno-Sakhalinskaya	CHPP-1 (G1) – TS	6.12	-3.16	3.98	-84.4	84.49	7.76	6.88	8.21
	CHPP-1 (G2) – TS	6.24	-3.04	75.9	57.3	95.10	5.12	7.89	24.71
	CHPP-1 (G3) – TS	10.4	-3.03	107.5	170.1	201.22	5.14	9.26	38.00
	CHPP-1 (Power Unit 4) – TS 1st chain	10.4	-3.09	33.8	19.5	39.02	4.89	10.13	6.46
	CHPP-1 (Power Unit 4) – TS 2nd chain	10.4	-3.09	31.4	15.42	34.98	7.17	6.84	5.72
	CHPP-1 (Power Unit 5) – TS	10.4	-3.1	40.79	38.83	56.32	7.71	8.58	6.68
	TS – Centr 1st chain	6.03	-14.2	21.54	-172.1	173.44	9.41	24.15	35.49
	TS – Centr 2nd chain	6.01	-23.3	250.1	83.4	263.64	8.72	16.09	72.18
	TS – Centr with branch on Promouzel 2nd chain	6.04	-7	10.7	-14.9	18.34	7.26	7.77	2.43
	TS – Korsakovskaya	9.98	-5.02	533.5	-511.9	739.37	7.05	7.3	102.17
	TS – Lugovaya 1st chain	9.98	-7.77	3.81	-36.4	36.6	7.37	7.39	3.81
	TS – Lugovaya 2nd chain	10.08	-6.29	2.13	-38.3	38.36	7.07	7.76	3.91
	TS – Yuzhnaya 1st chain	6	-7.8	388.7	527.4	655.16	8.05	10.23	83.7
	TS – Yuzhnaya 2nd chain	5.95	-8.04	239.65	95.2	257.87	8.01	9.41	24.89

Name of branch	U. kV	ϕ. deg	P. kW	Q. kVAr	S. kVA	THD_U. %	THD_I. %	D. kVA (%)
Centr – Promouzel with branch on Yugo-Zapadnaya	5.96	-7.9	18.7	-308.7	309.27	7.07	7.54	34.2
Khomutovo-2 – Korsakovskaya	9.78	-8.8	3.65	-1167	1167.01	7.9	8.68	107.91
Yuzhnaya –Khomutovo-2	9.66	-7.93	164.8	-7.31	164.96	6.6	7.37	5.56