LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
LUT School of Energy Systems
Master Degree Program in Electricity Markets and Power Systems

Andrei Bolshakov

INVESTIGATION OF THE APPLICABILITY OF LVDC MICROGRIDS IN UTILITY DISTRIBUTION IN RUSSIA

Examiners: Prof. Jarmo Partanen

M.Sc. (Tech.) Tero Kaipia

ABSTRACT

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Investigation of the applicability of LVDC microgrids in utility distribution in Russia

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Keywords: LVDC distribution, LVDC microgrids, Russian electric power industry, economic potential analysis.

The research towards efficient, reliable and environmental-friendly power supply solutions is producing growing interest to the “Smart Grid” approach for the development of the electricity networks and managing the increasing energy consumption. One of the novel approaches is an LVDC microgrid.

The purpose of the research is to analyze the possibilities for the implementation of LVDC microgrids in public distribution networks in Russia. The research contains the analysis of the modern Russian electric power industry, electricity market, electricity distribution business, regulatory framework and standardization, related to the implementation of LVDC microgrid concept. For the purpose of the economic feasibility estimation, a theoretical case study for comparing low voltage AC and medium voltage AC with LVDC microgrid solutions for a small settlement in Russia is presented.

The results of the market and regulatory framework analysis along with the economic comparison of AC and DC solutions show that implementation of the LVDC microgrid concept in Russia is possible and can be economically feasible. From the electric power industry and regulatory framework point of view, there are no serious obstacles for the LVDC microgrids in Russian distribution networks. However, the most suitable use cases at the moment are expected to be found in the electrification of remote settlements, which are isolated from the Unified Energy System of Russia.

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LIST OF SYMBOLS AND ABBREVIATIONS

AC	Alternating Current
CAIDI	Customer Average Interruption Duration Index
CHP	Combined Heat and Power Plant (cogeneration plant)
DC	Direct Current
EC	European Commission
EIC	Electrical Installations Code
ES	Energy System
FAS	Federal Anti-Monopoly Service
FC	Fuel Cells
HVDC	High-Voltage Direct Current
ICT	Information and Communications Technology
IEC	International Electro-technical Commission
IT	Grounding system with isolated or impandance-grounded neutral
JSC	Joint Stock Company
LC	Load Controllers
LLC	Limited Liability Company
LVDC	Low-Voltage Direct Current
MC	Micro Source Controller
MGCC	Microgrid System Central Controller
MVAC	Medium-Voltage Alternating Current
NP	Non-profit Partnership
OJSC	Open Joint Stock Company
OPEX	Operations Expenses (costs)
PJSC	Public Joint Stock Company
PV	Photo Voltaic
RAB	Regulatory Asset Base
RAO	Russian joint stock power engineering and electrification company
RD	Ruling Document
RDC	Regional Distribution Company
R.E.	Revised Edition
RES	Renewable Energy Sources
SAIFI	System Average Interruption Frequency Index

SFS	The Finnish Standards Association SFS
SG	Smart Grid
TDC	Territorial Distribution Company
THD	Total Harmonic Distortion
TN	Grounding system with exposed conductive parts connected to the neutral
TN-C	TN grounding system with combined protective earth and neutral conductors.
TN-C-S	TN grounding system with partly separated and partly combined protective earth and neutral conductors.
TN-S	TN grounding system with separate protective earth and neutral conductors.
TS	Technical Specifications – type of standards for different products in Russia, which are obligatory to follow.
TT	Grounding system with earthed neutral
UES	United Energy System
USSR	Union Of Soviet Socialist Republics
СИП-х	Self-supporting insulated wire - aerial bundled cable types in Russia
ТМГ	Oil-filled waterproofed transformer

Symbols

C_{EL}	costs of energy losses
C_{PL}	costs of power losses
C_{price}	component price
C_{cons}	construction costs
C_{inv}	investment costs of the network component
C_{loss}	loss costs of the network component
C_{main}	maintenance costs of the network component
C_{out}	outage costs of the network component
C_{tot}	total cost of the network component
K_{u}	total harmonic distortion index
p	interest rate
r	load growth rate
ΔV_{AC}	voltage drop in a AC line
ΔV_{DC-}	voltage drop in the negative pole of a DC line
ΔV_{DC+}	voltage drop in the positive pole of a DC line
V_{nom}	nominal voltage

Greek symbols

η	efficiency of a rectifier/inverter
κ	capitalization coefficient
ψ	the present value

Units

GW	gigawatt
Hz	Hertz
kV	kilovolt
kVA	kilovolt ampere
kW	kilowatt
mA	milliampere
MW	megawatt
rub.	rubles
VAC	volts of alternating current
VDC	volts of direct current

1. INTRODUCTION

Investigators all over the world have recently turned to the Smart Grids (SG) concept. The term Smart Grid can be defined as a “smart” approach to the development of the electricity networks in order to increase the efficiency, reliability and sustainability of the power supply (Shahnia et al., 2013). The origins of this concept are coming from the problem of increasing energy consumption and climate changes. Today’s global environmental policy dictates new rules for the electricity generation industry. The groundbreaking Paris Agreement sets ambitious goals for the future and limits the conventional energy production even more. Renewable energy sources are being implemented more frequently. As an example, in the year 2015, nearly 1.3 GW of new PV capacity was installed in Germany (Wirth ed., 2015). Unfortunately, a majority of renewable energy sources (RES) have one main disadvantage: intermittent operation. A large amount of renewable energy based electricity production units, connected to an existing energy system, can destabilize it.

Microgrid is a novel approach to an electric power supply system, which is aimed at better adoption of distributed generation with RES into an energy system and increase of electricity distribution reliability. Furthermore, the microgrid technology can provide economic benefit in certain cases. Microgrid system combines distributed generation, manageable loads, energy storage system and can be applied as an isolated energy system (island operation mode) or along with the main grid (grid-connected mode). (Narayanan, 2013) While operating in the grid-connected mode, microgrid system can store a surplus of energy from its own generating units and the main grid to cover consumption peaks subsequently or serve as back up for the main grid in fault cases. Islanded mode means totally independent operation based on small-scale power generation and energy storage. (Fedorov, 2007)

Small-scale power generation technologies applied in microgrids can be more cost-effective when compared to conventional power sources (Fedorov, 2007). In addition, small-scale generation units can be placed closer to consumers, therefore reducing transmission power losses and increasing power supply reliability by offering a reserve power source. From the main grid perspective, a microgrid can be considered as a single adaptive energy system, which can operate in a master-slave mode when required and produce heat along with electricity (Lasseter, 2002). A Microgrid system can control itself by means of microprocessor-based control center and high-speed power electronic devices, which are utilized for fast switching of loads and power generation units (Fedorov, 2007; Narayanan, 2013).

The majority of the distribution networks utilize 3-phase AC. However, AC systems are experiencing such problems as power losses, reliability decrease due to long transmission distances and aging of the equipment. Furthermore, there is a need for synchronization of the generators with the system. In terms of microgrid, such problems as harmonic distortion from power electronic devices, power losses due to numerous power conversions are typical for AC systems (Narayanan, 2013).

Low Voltage Direct Current (LVDC) distribution was introduced as a feasible alternative to an AC system in certain cases, which eliminates underlined problems (Nuutinen et al., 2014). Instead of synchronization of each generator, a whole microgrid system is synchronized with the main grid by means of single power converter. In addition, suitable small-scale RES-based electricity generation units as Photovoltaic Panels (PV) or Fuel Cells (FC) and energy storage systems are operating on DC. With appropriately designed control system, it is easier to control the DC system than AC system. However, the control system for DC microgrid is more dependent on ICT.

1.1. Research objectives and questions

The main objective of the thesis is to analyze the possibilities, drivers and challenges for the implementation, recognize the potential and estimate the economic benefit of LVDC microgrids in Russian public electricity distribution networks. The main research questions have been defined as follows:

- Does the regulatory framework in Russia provide an opportunity for implementation of distributed generation and LVDC microgrids?
- Does the present structure of Russian electricity market and distribution system configuration encourage the implementation of distributed generation and LVDC microgrids?
- What are the main drivers for distribution system development in Russia and what are the possible drivers for adopting LVDC microgrids?

- What are the challenges for using LVDC networks and microgrids in public electricity distribution in Russia?

- In what conditions LVDC microgrids can be implemented in Russian distribution grids (what are the suitable use cases) and how much potential applications there can be estimated to exist?

- What are the technical properties (voltages, earthing, line types etc.) of an LVDC distribution system suitable for typical Russian distribution system?

For the purposes of the research, the analysis of the following topics is carried out:

- The current state of the Russian electric power industry
- The organization of the Russian electricity market and business environment related to distribution networks;
- The regulatory framework and standardization related to the use of LVDC distribution, electrical energy storages and small-scale renewables in public distribution networks;
- The electrical safety legislation and standardization.

1.2. Outline of the thesis

The thesis is structured in the following manner:

Chapter 2 describes the LVDC microgrid concept, a basic structure of LVDC microgrids, defines possible implementation cases and benefits of the implementation of such technology in existing distribution networks.

Chapter 3 provides the results of Russian electric power industry’s analysis. The current state of the industry is presented with respect to the implementation of the LVDC microgrid concept and renewable energy sources.

Chapter 4 provides the description of current standardization and the analysis of the regulatory framework related to the use of distributed generation, LVDC and energy storage systems in Russian electricity distribution networks. Furthermore, challenges for the implementation of LVDC microgrids are defined.

Chapter 5 defines the potential drivers for the adaptation of the LVDC microgrids along with the determination of potential use cases. Suitable properties of an LVDC microgrid system, which can be implemented in Russia, are defined in this chapter. A description and results of economical estimation in addition to a description of the calculation model are presented.

Chapter 6 concludes the results of performed research and gives suggestions for further development of the Russian electric power industry and legislation/standardization related to the implementation of the introduced LVDC microgrid concept.

2. LVDC MICROGRID CONCEPT

LVDC distribution brings new prospects for the development and improvement of distribution networks. The quality and reliability of the supply can be increased at relatively low cost. As an example, in an LVDC system voltage fluctuations visible to the end users can be mostly eliminated with the controls of the active power electronics, which can operate within a wide range of DC voltages. Furthermore, higher transmission capacities can be achieved in LVDC, when compared to a typical LVAC system. (Kaipia et al., 2006) LVDC technology enables application of DC-based storage systems without conversion, thus reducing power losses (Kaipia et al., 2009). For isolated energy systems without connection to the main energy system, LVDC networks with distributed generation based on RES are already often considered the first choice prior to the other solutions (Rodriguez-Diaz et al., 2015).

LVDC microgrids can be utilized as small independent energy systems, which can be interconnected with each other to create even more stable and reliable electricity supply system. By means of this interconnection, microgrids will be able to support each other, when power shortfall occurs. Furthermore, there is no need for interconnected systems to utilize same voltage levels and have equal capacity. (Konar and Ghosh, 2015) An example of the system, which comprises of interconnected microgrids, is depicted in Figure 1.

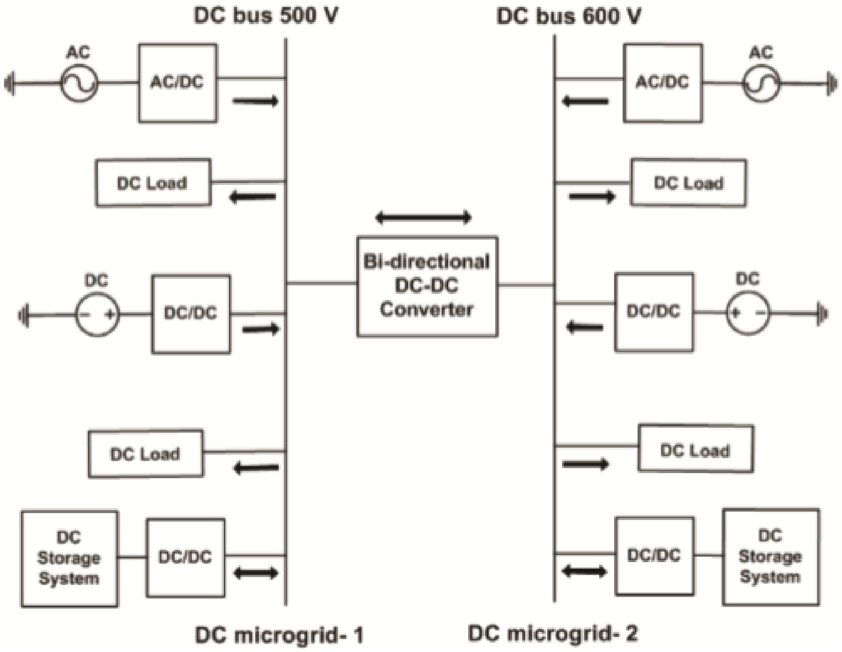

Figure 1. Interconnected DC microgrids (Konar and Ghosh, 2015)

As it can be seen in Figure 1, the power flow between two interconnected DC microgrids in this case is managed by means of bi-directional DC-DC converter. However, there is a disadvantage. Although there are no synchronization problems, the voltage conversion in the interconnection point causes extra losses.

2.1. Configuration of LVDC microgrid system

Although, the voltage level utilized by an LVDC microgrid system depends on a case, a requirement of as sufficient transmission capacity with the lowest price as possible must be met and always within the framework of LV range and respective standardizations. The voltage level is also affected by the prices on power electronic converters (Narayanan, 2013).

Common topology for an LVDC distribution system is a rectifier (AC/DC conversion) located near MV/LV transformer (medium voltage to low voltage distribution transformer), DC-link from the rectifier to the consumers and inverters (DC/AC conversion) on the customers site. The two main circuit configurations of LVDC system are unipolar and bipolar. The unipolar configuration utilizes only one voltage level to which all the loads, distributed generation and storage systems are connected. (Kaipia et al., 2006) An example of a unipolar LVDC network is presented in Figure 2.

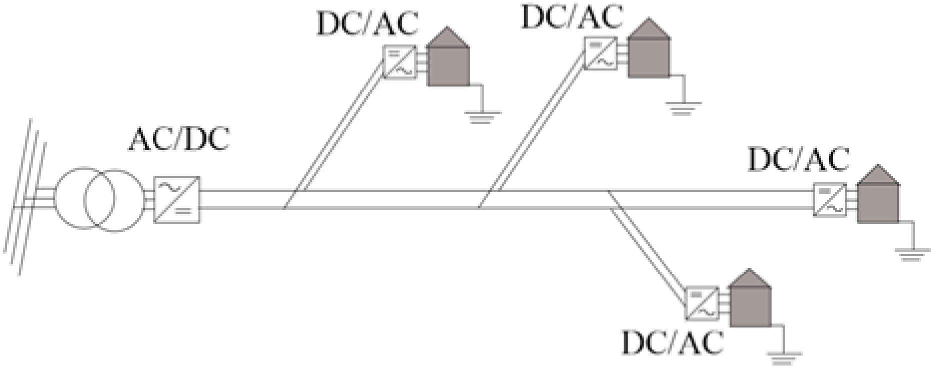

Figure 2. Possible topology of a unipolar LVDC distribution system. (Salonen et al., 2008a)

Two unipolar systems, connected in series are forming a bipolar system, where all of the microgrid’s components can be connected using four different schemes. The connection schemes are: 1 - between positive pole and middle conductor, 2 - between negative pole and middle conductor, 3 – between two poles and 4 – using all three conductors. (Salonen et al., 2008a) An example of a bipolar LVDC networks is depicted in Figure 3.

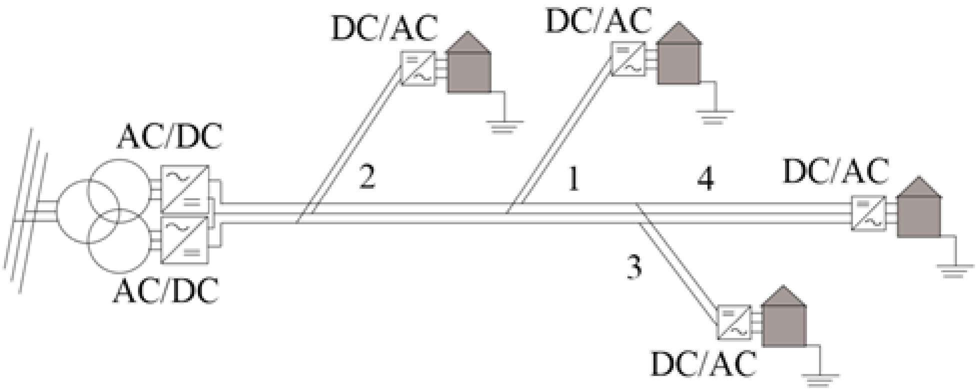

Figure 3. Possible topology of a bipolar LVDC distribution system with different connection schemes (Salonen et al., 2008a)

An LVDC distribution system can be realized as grounded TN (Figure 4.1) or ungrounded IT (Figure 4.2) installation. It is possible to choose, which conductor is grounded. An example of grounding arrangements, adapted from the earlier version of the Finnish standard SFS 6000-1 (based on IEC 60364), is depicted in Figure 4. (Salonen et al., 2008b)

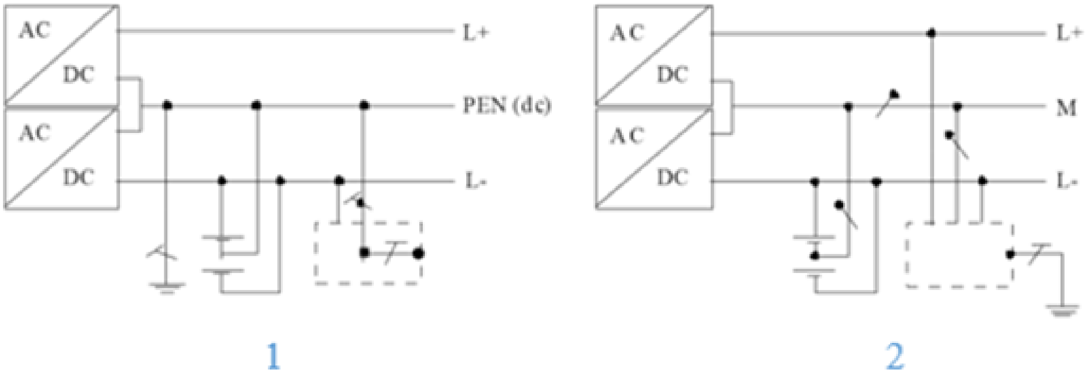

Figure 4. Possible grounding methods for a bipolar LVDC system in Finland: 1 - grounded TN, 2 – ungrounded IT. (Salonen et al., 2008b)

In case of grounded TN system, galvanic isolation between DC network and customer's network should be provided. Otherwise, there will be short circuits via the groundings. Galvanic isolation can be provided by means of an isolation transformer, which can be a part of customer-end inverter. (Salonen et al., 2008b) Galvanic isolation is always required in connection points of installations with different grounding systems. This is the case when the LVDC network is realized as IT system and the customer-end installations as TN systems. In pure IT system, the galvanic isolation is needed to separate the fault circuits of the public network and customers' installations, and thus, disabling a flow of DC fault currents through a simultaneous fault in a customer's installation. Galvanic isolation is also needed for cutting the circuit of common mode interference currents flowing through the EMI-filters of the customers' appliances. (Partanen et al., 2010; Nuutinen, 2015)

An LVDC distribution system comprises of power converters, which are interconnected by means of low-voltage DC network (Narayanan, 2013). Sources and loads are connected to the network through these converters. Distributed generation based on renewable energy sources of DC-nature and energy storage systems can be connected to the DC grid without conversion. An example of the LVDC microgrid's configuration typical for the USA is presented in Figure 5.

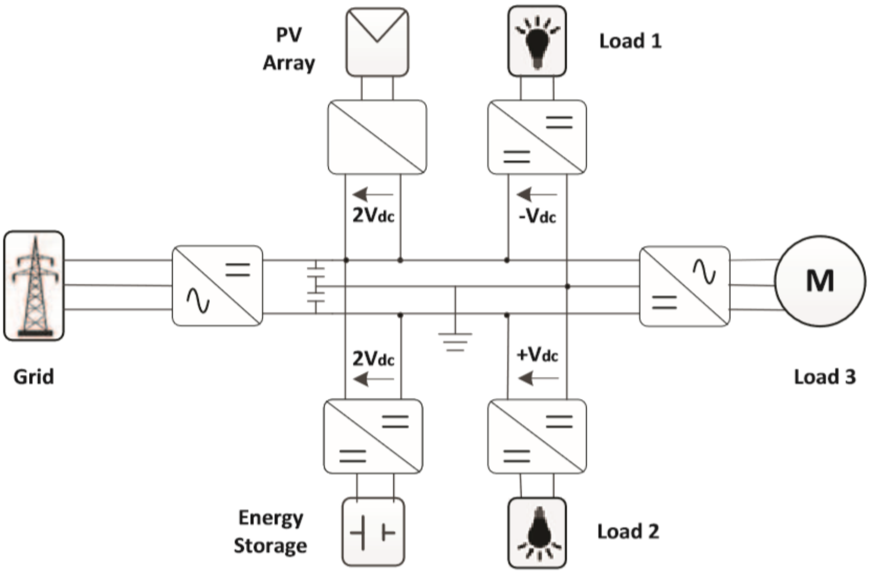

Figure 5. Configuration of an LVDC microgrid typical for the USA. (Rodriguez-Diaz et al., 2015)

One of the possible ways to manage the operation of the LVDC microgrid can be as follows. Each load, micro-scale generator or energy storage perform under management provided by a control system, based on power electronics. These control systems regulate power flow within the system. As an example, control system of a micro-scale generator (Micro source controller or MC) regulates its power generation according to the needs of a microgrid system. Uninterruptible supply of loads is ensured by Load Controllers (LC). Microgrid System Central Controller (MGCC) executes operation of the whole microgrid system. Therefore, the overall control system of a microgrid can be divided on two control levels: local control level (LC and MC) and central control level (MGCC). There can be the third control level represented by Distribution Management System (DMS), which is responsible for the integration of a microgrid into the main grid. The MGCC can be considered as a simple coordinator of local controllers (LC and MC) or, on the other hand, as a powerful
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optimization tool for a microgrid. However, a microgrid system is able to operate without MGCC and DMS systems, if there are no requirements for the operation of the grid according to the open market prices and there is no DMS in the main grid respectively. (Fedorov, 2007)

2.2. Benefits of an implementation of LVDC microgrids in utility distribution

Such controllable system as LVDC microgrid provides manageable loads and generation units in order to eliminate power peaks and decrease the volume of required power production, thus reducing losses in distribution networks. Furthermore, distributed energy generation close to consumers is reducing transmission distances and, as a consequence, power losses (Hatziargyriou et al., 2006).

Effective utilization of energy storage units, which are mainly of DC nature and DC renewable energy generation units such as PV-panels, can push the efficiency of the microgrid to the new better level (Moreno and Mojica-Nava, 2014). DC-based electricity distribution system has greater transmission capacity compared to AC system, which also reduces voltage and power losses (Kaipia et al., 2006). It should be mentioned that there is no reactive power in DC distribution (Rodriguez-Diaz et al., 2015).

Reliability increase is another advantage of LVDC microgrid provided by its self-healing possibilities. From the perspective of supply reliability, it reduces the amount of non-supplied energy and the total number of affected consumers, which can be considered beneficial for distribution grid companies. (Shahnia et al., 2013) The reliability of an LVDC-based distribution system has been proved by the results of a research setup's operation in public network in Finland. This research setup was built by the energy company "Suur-Savon Sähkö Oy" in cooperation with Lappeenranta University of Technology (LUT). (Nuutinen et al., 2014)

From the main network perspective, since LVDC microgrid can be considered as a single adaptive energy system, it is easier to control its operation and interaction with rest of the grid. In addition, LVDC microgrid is able to feed energy back to the main grid, thus acting as a generator. It can be economically beneficial for the companies that are allowed to combine such business activities as electricity distribution and sales. (Hatziargyriou et al.,

2006) Finally, as combined result of the above mentioned, LVDC microgrids can bring cost savings in comparison to alternative AC solutions. (Partanen et al., 2010)

2.3. Limits for techno-economic application of LVDC distribution

In order to define possible use cases for an LVDC microgrid concept, possible technical and economical limits should be summarized. The main technical constraint of an LVDC microgrid is a power transmission distance. Although the transmission distances for LVDC distribution are higher compared to LVAC, it is no match for the capacity of the medium-voltage distribution systems. Thus, an LVDC distribution is in between low-voltage AC and medium-voltage AC distribution. An example of the limits for application of a ±750 V LVDC system with respect to economic feasibility are presented in Figure 6.

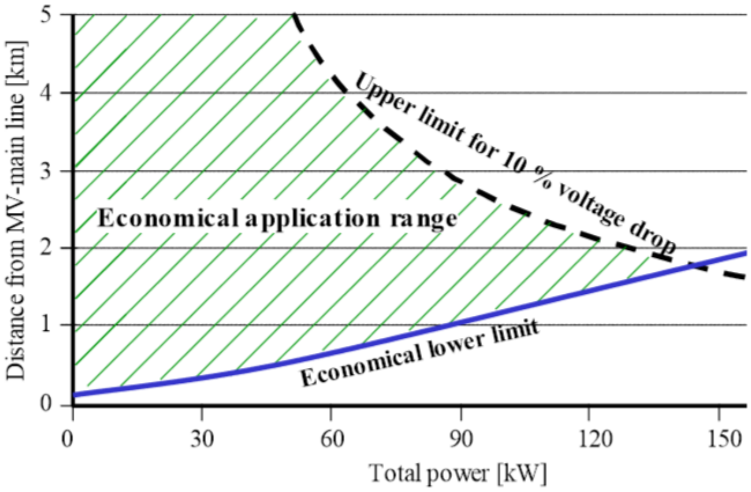

Figure 6. Example of the definition of a techno-economic range for the application of the ±750 LVDC network compared to MVAC network, located in a typical Finnish rural area. (Kaipia et al., 2008)

The figure describes economical application range of the LVDC solution as a replacement for an existing 20/0.4 kV medium voltage AC branch in a typical Finnish rural district (Kaipia et al., 2008). Economic feasibility is shown with respect to the transmitted power and the length of an existing MVAC branch. With a relatively small load, which is typical for rural areas, the LVDC solution can be feasible on a wide range of distances from 0.5 to 5 km and more. As the voltage supplied to the customers is controlled with active converters that tolerate a wide variation of input DC voltage, the voltage drop does not set as strict limit as in the traditional AC system (Partanen et al., 2010).

From the perspective of a conductor selection, DC-systems are more cost effective, since they have better transmission capacity compared to AC-systems utilizing the same conductors. The comparison of the transmission capacities of AC and DC solutions is presented in Figure 7.

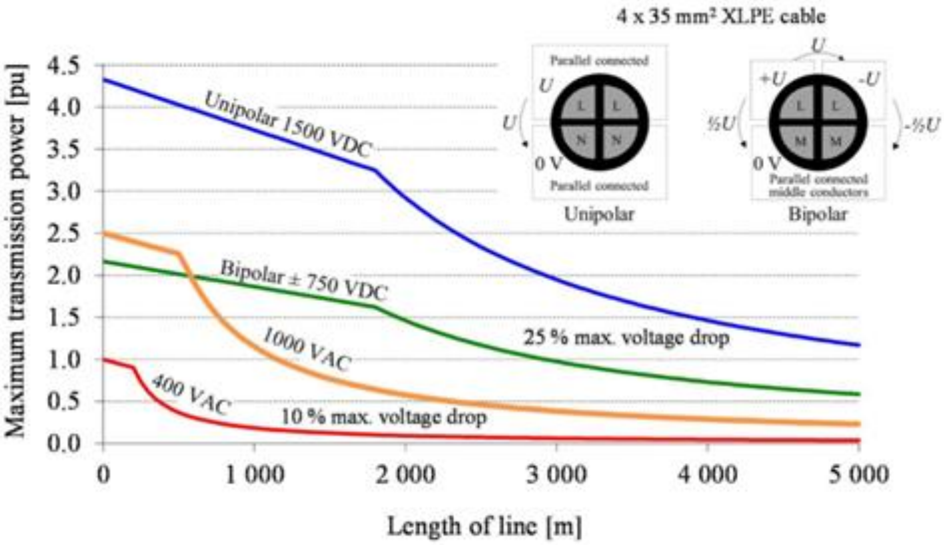

Figure 7. Comparison of maximum permissible transmission capacities of 4x35 mm^2 XLPE cable in AC and DC solutions (Kaipia, 2014)

Furthermore, there is no strong need to replace existing components of a network to implement LVDC distribution technology, as the majority of them are suitable for the DC. (Kaipia et al., 2006)

From the operational conditions' point of view, an LVDC microgrid system can be utilized within outdoor temperature limits of minimum - 40 and maximum + 60 ºC, which are mainly determined by power electronics' operational conditions. (Salonen et al., 2008) Possible voltage levels are determined by legislation of a region where an LVDC microgrid is implemented. As an example, in the countries of the European Union, voltage levels for DC distribution are defined between 75-1500 VDC by The European Union Directive (LVD 2006/95/EC, 2006).

According to the review of LVDC microgrid's typical grounding arrangements, both TN and IT systems can be used. Furthermore, an IT grounding arrangement is the only possible solution for a region with difficult grounding conditions, since in a TN system dangerous touch voltages occur during fault situations.

Summarizing the review of an LVDC microgrid concept, a small settlement or a city district can be considered as a suitable case for the implementation of such system. In addition, climate and environmental conditions should be taken into account for the proper design of an LVDC microgrid system and determination of suitable energy sources.

3. RUSSIAN ELECTRICITY MARKETS

The Unified Energy System of Russia (Unified ES) consists of 69 regional energy systems, which in their turn form seven united energy systems (UES): Eastern, Siberian, Ural, Middle Volga, Southern, Central and Northwestern. All energy systems (excl. Eastern UES) are in parallel operation and interconnected by 220-500 kV high voltage transmission lines (Ministry of Energy, 2015). It should be noted, that the majority of the energy systems included in the Eastern united energy system are isolated and work separately from the Unified Energy System, the rest few are having a weak connection with the Unified ES. The division of Russian Unified Energy system on United ES with their electricity production volumes is presented in Figure 8.

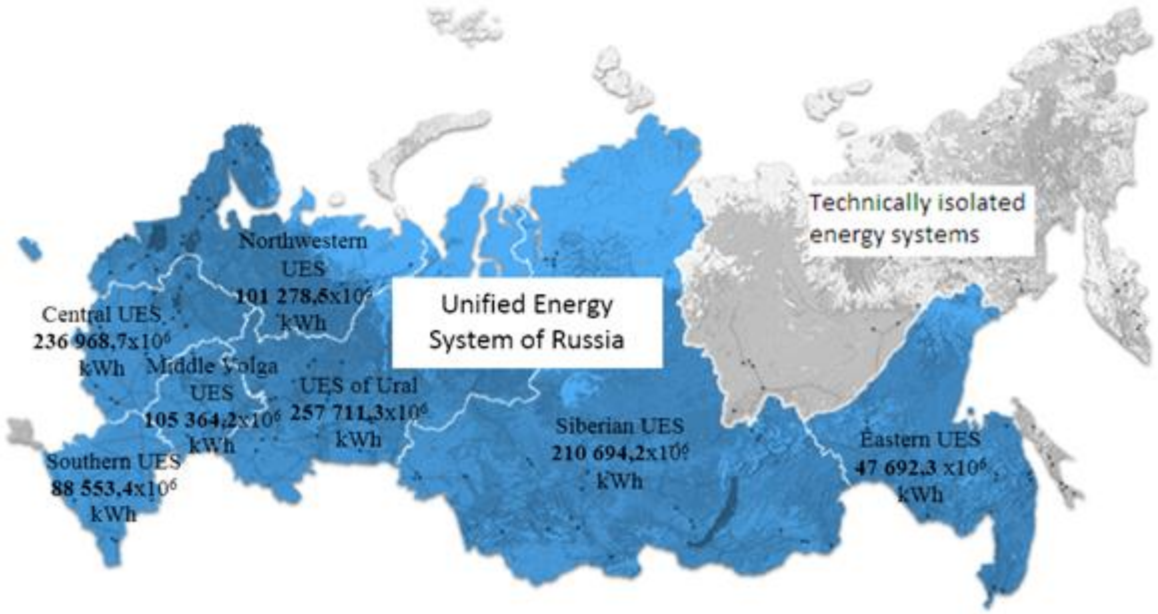

Figure 8. Energy systems of Russia with the energy volumes produced in 2015 (System operator of the Unified Energy System, 2016)

As it can be seen from Figure 8, technically isolated areas are a significant part of the Russian territory. Although, these territories are sparsely populated, the challenge of their electrification rate is of high interest due to the development plan of the country.

The real-time operation of the Russian Unified Energy System (excl. technically isolated energy systems) is executed by OJSC “System operator of the Unified Energy System”, which is 100% controlled by the state. Operators of isolated energy systems are defined by the government (Federal Power Act, 26 March 2003).

Power generation is mainly based on fossil fuel based thermal power plants. A distinctive feature of the Russian energy system is a prevalence of the CHP plants, which are in addition, the main heat providers in the cities (Hubert et al. 2003). Other large-scale electricity generators are hydropower and nuclear power plants. Hydropower provides system services such as frequency and power control and appears as a primary Unified ES’s reliability service. Nuclear power is most common in the Central and Northwestern parts of Russia. (Ministry of Energy, 2016) Such inexhaustible renewable energy sources as solar, wind and hydropower are becoming more common. Distribution of conventional and renewable energy sources is presented in Table 1.

Table 1. Installed capacity structure of power plants in Unified ES of Russia at the beginning of the year 2016. (Ministry of Energy, 2016)

	Total, MW	CHP		Hydro power		Wind power		Solar power		Nuclear power	
		MW	%	MW	%	MW	%	MW	%	MW	%
Unified ES of Russia	235305.6	160233.28	68.1	47855.18	20.34	10.9	-	60.2	0.03	27146	11.53
Central United ES	53306.92	38684.07	72.6	1788.85	3.4	-	-	-	-	12834	24.2
Middle Volga United ES	27040.22	16078.22	56.60	6890	25.40	-	-	-	-	4072	15
United ES of Ural	50707.82	47327.08	93.33	1853.54	3.66	2.2	-	45	0.09	1480	2.92
Northwestern United ES	23142.97	14427.08	62.3	2950.34	12.8	5.3	-	-	-	5760	24.9
Southern United ES	20116.80	11357.35	56.3	5756.05	28.6	3.4	-	-	-	3000	14.9
Siberian United ES	51808.33	26516.73	51.18	25276.4	48.79	-	-	15.2	0.03	-	-
Eastern United ES	9182.50	5842.5	63.6	3340	36.4	-	-	-	-	-	-

The isolated united energy system of the Far East (Eastern united energy system) is controlled by the Holding JSC "RAO Energy System of East". Energy generation, electricity distribution and sales are executed by the companies, which are included in the Holding company. The main stockholder of the Holding is a wholesale generating company JSC “RusHydro”. (RAO Energy System of East, 2016) The map of the Eastern United ES and a part of Siberian United ES (Figure 9) presents location of main power generation centers and technically isolated energy systems.

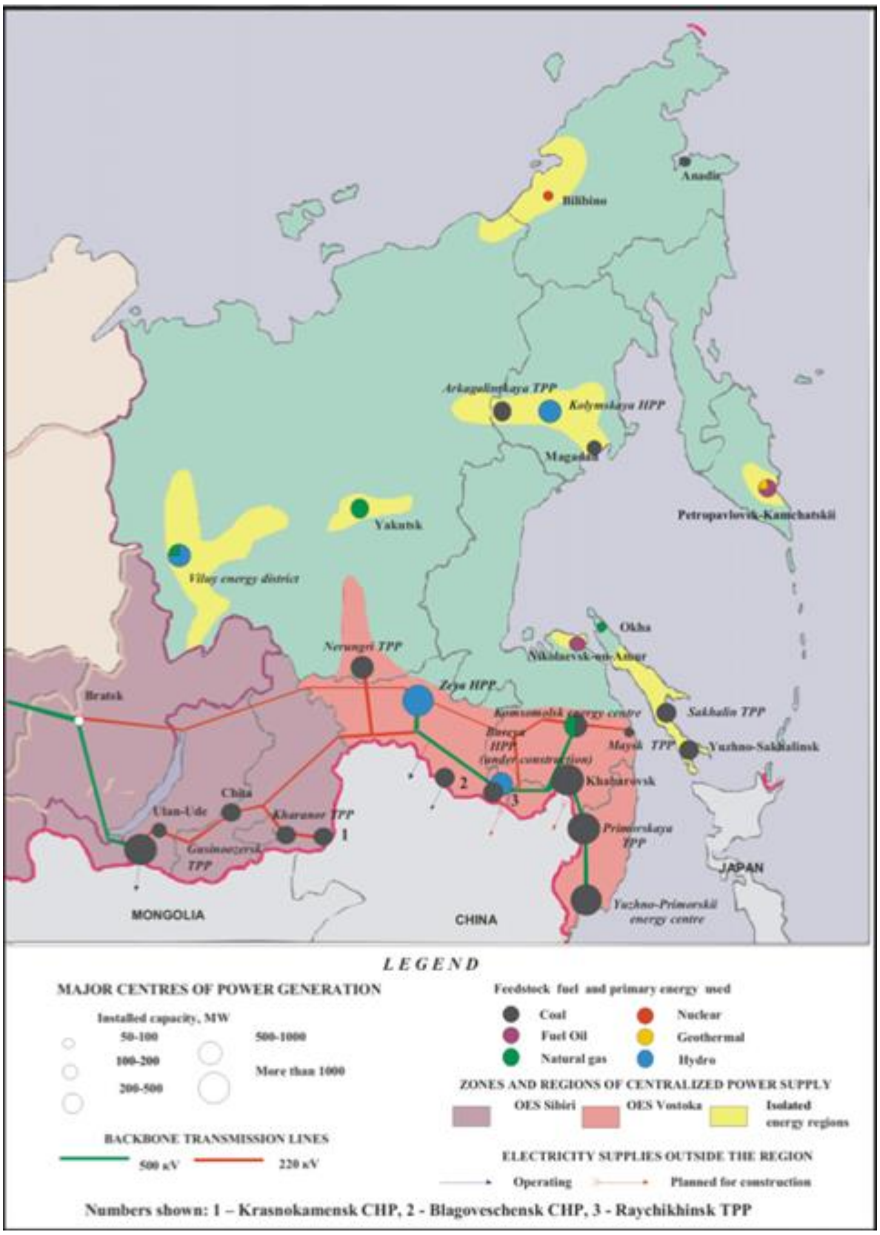

Figure 9. Energy system of Russian Far East (Kalashnikov et al., 2009) (OES Vostoka/Sibiri – Eastern/Siberian UES)

3.1. Basic market structure

Present-day Russian electric power industry (Figure 10) is based on a combination of state regulation and free competition. Natural monopoly and competitive sectors of electric power industry were separated as a part of the reform of electric power industry, which started in 2001. Nevertheless, the energy markets of the isolated areas remain completely monopolized.

Electricity transmission and distribution is a state-regulated monopoly business. PJSC "ROSSETI" is the energy grid operator. The main stockholder (85.3%) is the state represented by the Federal Agency for State Property Management of the Russian Federation. "ROSSETI" controls transmission system operator (80.13%) and distribution system operators. The function of transmission system operator is executed by JSC "Federal Grid Company". Distribution system operators are represented by 14 interregional distribution grid companies, which are in turn divided into regional distribution companies. (ROSSETI, 2016)

Energy trading takes place on wholesale and retail markets (Figure 10). Power generation is represented by seven wholesale generating companies, 14 territorial generating companies, nuclear energy operator "ROSATOM", import/export operator "Inter RAO Unified ES" and generators which are not included in the wholesale market. Wholesale and retail markets are both controlled and operated by a self-regulated organization non-profit partnership "Market Council". A distinctive feature of Russian electricity market is a division on "price" and "non-price" zones. "Price" zones have no price regulation, whereas "non-price" zones have regulated electricity prices. (NP Market Council, 2016)

Russian wholesale market is a closed type market. Only generators that are included in a trade system are able to participate in the wholesale market trading. Renewable energy based electricity generators were introduced to the wholesale market in 2013 with the implementation of (Government decree № 449, 28 May 2013). The new wholesale market includes day-ahead market, bilateral trading, power and balancing markets. Wholesale energy trading for "non-price" zones has state-regulated prices and marginal pricing principle is applied only for "price" zones. Market members buy/sell derivations from planned volume of supply on the balancing market. Power as a product was introduced to the new wholesale market. Power market is an alternative for capacity mechanisms used for encouragement of investments in capacity and long-term reliability increase.

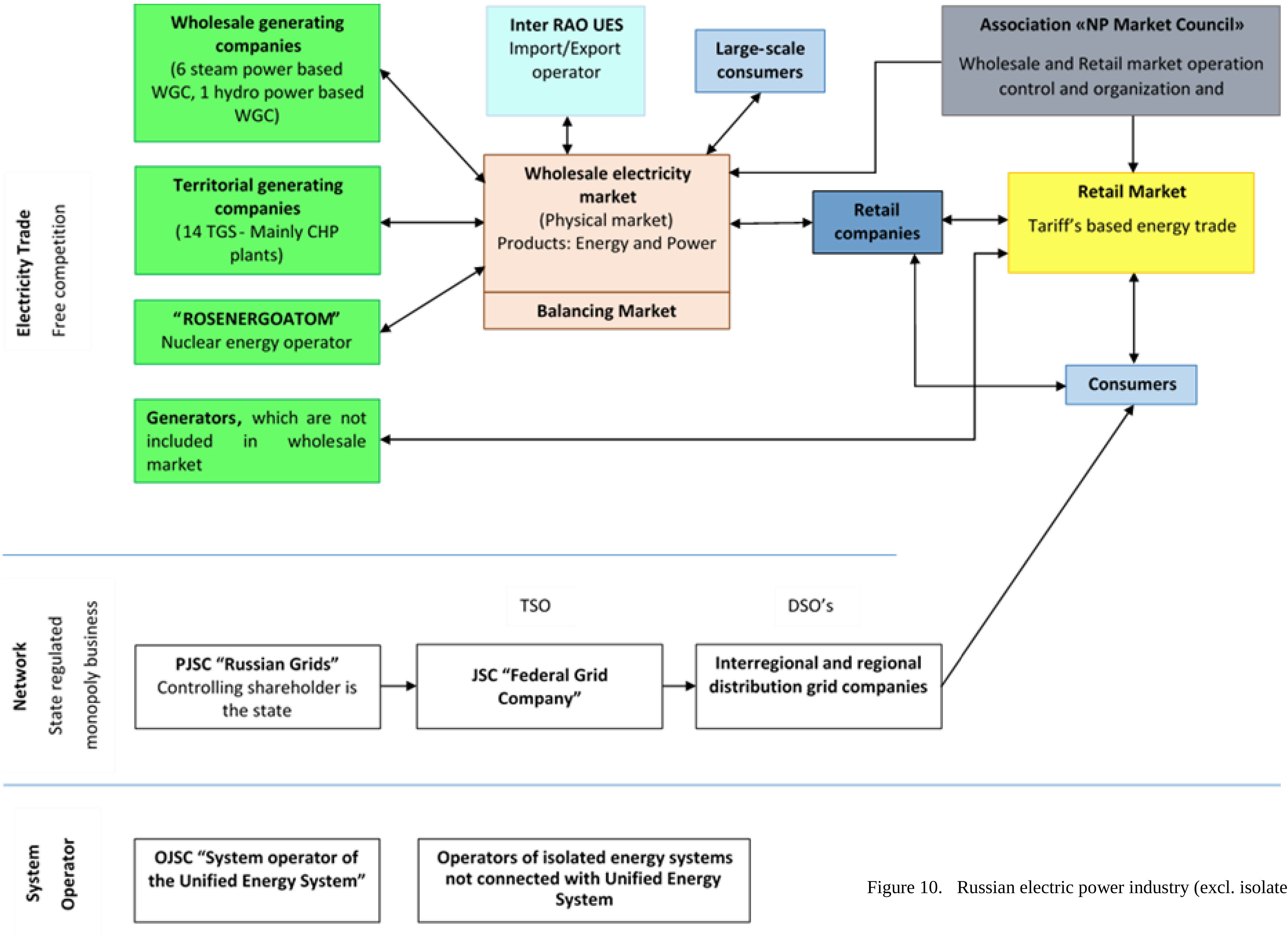

Figure 10. Russian electric power industry (excl. isolated areas)

Energy purchased on the wholesale market and energy generated by producers, which are not included in a trade system and/or have installed capacity under 25 MW, is realized on the retail market (Government decree № 442, 4 May 2012). Energy trading for consumers referred to a public category is based on the tariffs, which are determined by Department for Regulation over Electric Power Industry of Federal Anti-Monopoly Service (FAS). For other categories of consumers retail market is divided on "price" and "non-price" zones similar to the wholesale electricity market. Retail market participants are distribution grid companies, end customers, electricity retailers and supervisory control parties headed by OJSC "System operator of the Unified Energy System".

Electricity sales for public consumers are executed mainly by electricity retailers or retail companies. Retail companies of two types execute sales of electrical energy to consumers: suppliers of last resort (or guaranteed supply companies) and energy providers. The suppliers of last resort are obliged to make a contract with every individual or juridical person within its operational area, whereas energy providers are available to choose their customers (consumers). (Government decree № 442, 4 May 2012)

3.2. Electricity distribution business

Distribution system is divided on 220/110 kV high-voltage distribution network, 35/10/6 kV medium-voltage distribution network and 0.4 kV low-voltage network. An interregional distribution company receives energy from national transmission grid and distributes it to its regional distribution companies. The interregional company operates the 220/110 kV high-voltage distribution network. Territorial primary substations serve as connection points for centralized power generation and territorial power plants, which are considered as distributed generation in Russia. Territorial power plants (mainly CHP) are connected to the distribution grid by means of 110 (220) kV lines. Distribution networks utilize three-phase AC energy transmission. Currently, there are no LVDC distribution networks owned by distribution companies. DC is mainly used in other public systems, such as tramway and trolleybus overhead lines, and in HVDC transmission.

A regional distribution company (RDC) provides transmission and distribution of electrical energy within its boundaries of responsibility, which are mainly corresponding to the boundaries of constituent entities. Regional distribution companies own the network within the boundaries of a region and hold responsibility for its technical conditions and development. However, a regional distribution company may rent its network to a number of smaller distribution companies, which are called territorial distribution companies (TDC).

3.2.1. Interaction between retail market entities

There are two ways for a distribution company to receive payments for its services: “pot from above” model and “pot from below” model. In the “pot from above” model, an interregional distribution company usually acts as a “pot holder”. In that case, electricity retail companies make a contract on electricity supply with an interregional distribution company. In its turn, “pot holder” distribute received profit between regional distribution companies based on individual tariffs for each region. End-consumers make contracts only with an electricity retail company. An advantage of “pot from above” model is a single point of responsibility for a whole region and assurance of financial stability. This model is presented in Figure 11.

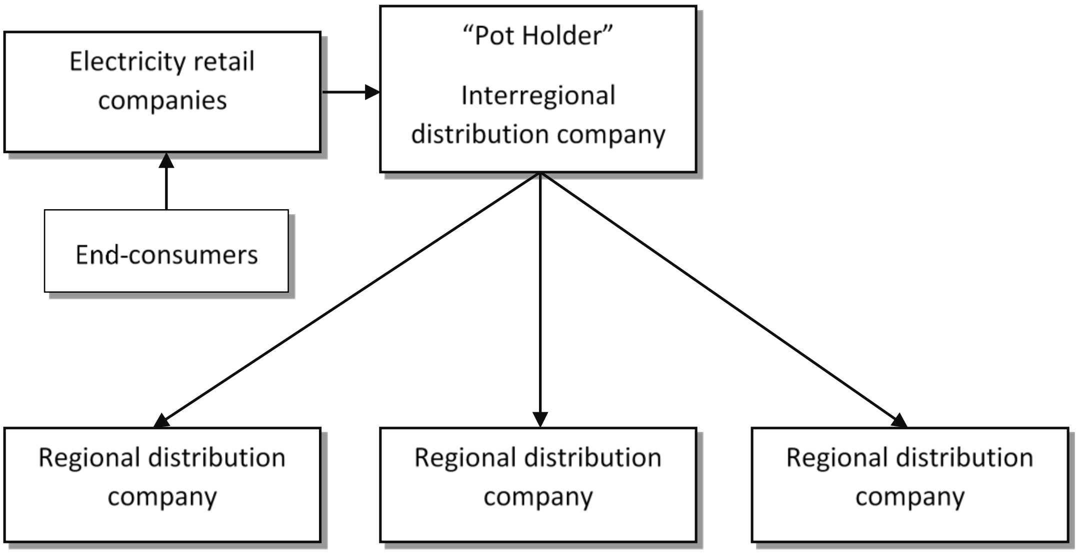

Figure 11. “Pot from above” contract relations model.

In the “pot from below” model (Figure 12), an end-consumer contacts with a regional or territorial network company directly, what can be considered as an advantage of this model, as it increases the responsibility of the network company over the quality of electricity supply. Electricity transmission services are paid according to the unified “pot” tariffs. There is no “pot holder” and consumers pay only for the services of a distribution company, a network of which they are connected to.

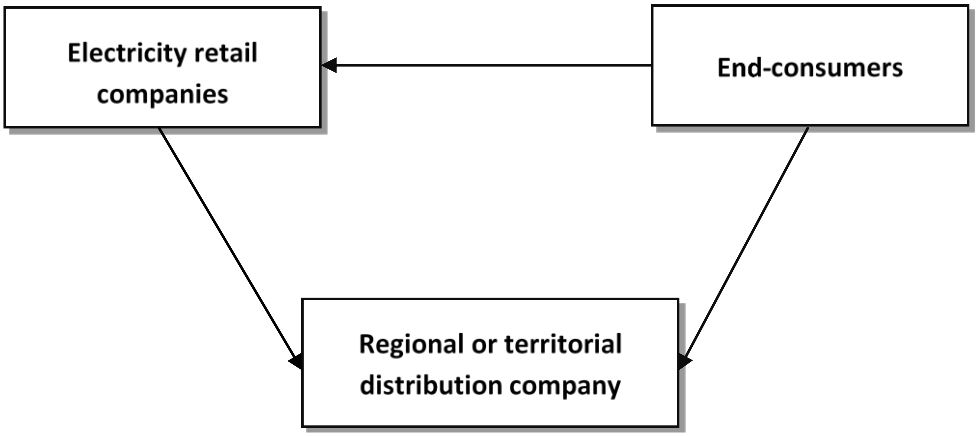

Figure 12. “Pot from below” contract relations model.

3.2.2. Electricity distribution tariffs

Currently, tariffs in electricity power industry are divided on wholesale market electricity tariffs, retail market electricity tariffs and tariffs of wholesale and retail market services. Electricity tariffs for the end-consumers are comprised of electricity generation costs and electricity transmission costs. Tariffs on electricity transmission via the unified national transmission grid and distribution grids are defined by a ratio of gross revenue requirement of a grid company to total connected load of consumers for a calculation period and are determined by the State. Each region of Russia has its own Regional Energy Commission or a Fuel and Energy Industry Committee. (Mironenko, 2012)

For easier understanding, the mechanism of tariff regulation can be explained on the example of a single region. A regional or a territorial distribution company makes a tariff proposal to the Regional Energy Commission/Fuel and Energy Industry Committee of a region annually, based on its gross revenue requirement. The Commission/Committee coordinates tariff proposals from regional distribution companies and territorial distribution companies with the Federal Anti-Monopoly Service of Russia (FAS). Federal Anti-Monopoly Service defines minimum and maximum value of electricity transmission tariff and approves or disapproves tariff regulation decisions of the regional committees. (Government decree №1178, revised 31 December 2015)

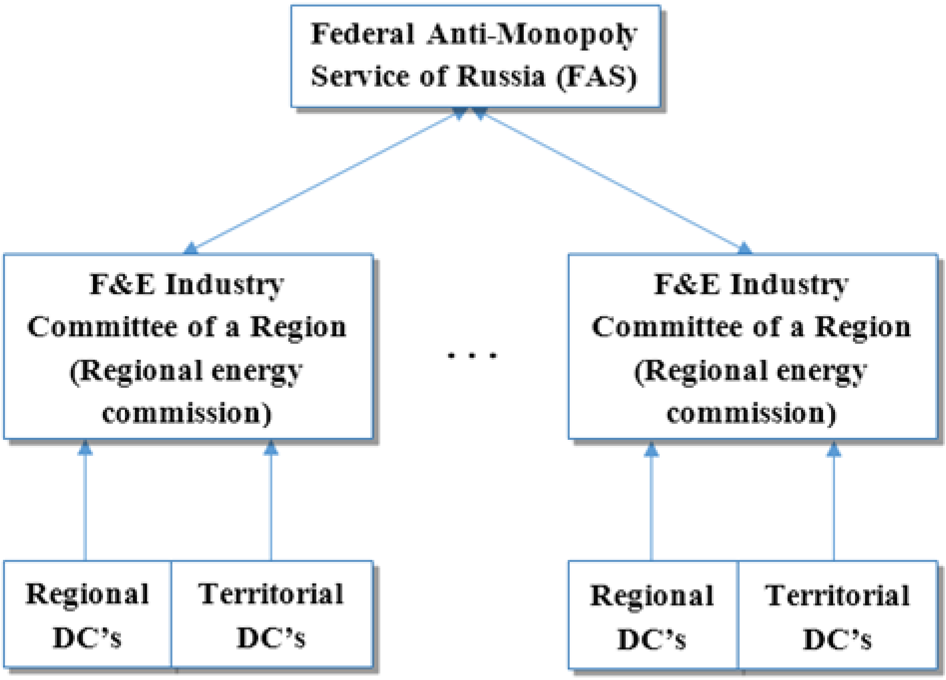

Figure 13. The hierarchy of the tariff regulation process for regional and territorial electricity distribution companies.

Electricity transmission tariff is defined as a so-called unified "pot" tariff. The main idea of "pot" tariff is a redistribution of financial resources between network organizations in order to ensure that each one of them received required gross revenue. Unified "pot" tariffs are of two types: one-part and two-part tariff. Two-part tariff considers unified electricity network's maintenance costs and power losses costs.

Tariffs on energy transmission are differentiated by four voltage levels:

- High voltage level
- First medium voltage level
- Second medium voltage level
- Low voltage level

There are three tariff formation methods: "cost plus" method, "indexation" method and "Regulatory Asset Base" (RAB-regulation) method. However, "cost plus" method is not used anymore.

The "Indexation" method is applied only in Russia. Electricity transmission tariff is calculated for a regulatory period (5 years) based on costs, which are included in gross revenue requirement of a grid company (controlled and non-controlled costs). Gross revenue requirement is adjusted annually. The tariff includes operational costs. According to this method, if a grid company reduces the operational costs, it automatically receives all the revenue less costs under the base tariff value.

Unfortunately, “indexation” method provided weak incentives to reduce costs (Mironenko, 2012). The State enacted the end of the transition to RAB-regulation method for all electricity network companies by 2011 (Government decree №30-р, 19 January 2010). RAB stands for “Regulatory Asset Base” and means a tariff formation method, which aims on attraction of investments into electricity power industry. The main principle of this method is to ensure a return of investments in the fund assets. In case of RAB method, gross revenue requirement comprises of operational costs (OPEX), recovery value of money invested and return on investments. Costs related to service implementation are divided on controlled (salaries, repairs of fixed assets) and non-controlled (rent, payment of services from other organizations) costs. Rate of return and a period of payment are set by the State (Federal Tariff Service Decree № 98/1-э, 17 February 2012). Controlled costs are determined for the regulatory period by the Ministry of Economic Development of the Russian Federation.

In terms of RAB-regulation method, electricity transmission tariffs are determined for each year of a regulatory period, which is at least five years, and are adjusted annually during this period. Since the State guarantees the defined rate of return on investments, distribution companies will have an additional source of financing for the development of the network. Controlled costs are determined for the long-run period by the Ministry of Economic Development and Trade. Non-controlled costs are determined by an executive authority of a region, to which a grid company belongs, based on the development program of the region. In addition, since the tariffs are set for at least five years, distribution companies are able to forecast their long-term costs and profit. As opposed to “indexation” method, amount of capital investments is unlimited in RAB-regulation method. (Mironenko, 2012)

Tariff formation method based on regulatory asset base allows distribution companies to benefit from operational efficiency increase. Since the stockholders of network companies earn from the company’s capitalization growth, they force management to reduce costs. Therefore, they are more motivated to develop their network and to increase quality of services.

3.3. Distributed generation

Modern Russian energy system combines centralized large-scale power production and distributed generation, which is represented mainly by thermal power plants. As it was mentioned earlier, territorial power plants, connected to the distribution grid, are considered as a distributed generation. Although distributed generation for the most part is oriented on combustion of fossil fuels, renewable energy sources are becoming more common. Consistent trend in building new small-scale power plants is observed.

There are no current plans on the transition from centralized to a fully decentralized energy system. Although, there are proposals to reorganize individual segments of Russian energy system. According to (Government decree №1715-p, 13 November 2009) the goal for the period until the year 2020 is to increase the volume of power production and consumption, based on RES (except for hydropower plants with installed capacity more than 25 MW) from 0.5 to 4.5%.

One of the main drivers for the implementation of distributed generation in Russia is a problem of significant power losses (up to 11.4% in the year 2003) in distribution lines. Depending on the region, electricity transmission tariff can reach 40-60% of electricity price. (Khabachev and Plotkina, 2014). Hence, it is economically feasible to implement distributed energy generation in order to reduce energy transmission costs and power losses since they have significant influence on the electricity price for end consumers. In addition, price for connection to the national grid is significantly high, due to the possible reconstruction of existing network or building a new one (Bessmertnykh and Zaichenko, 2012).

Due to regulated retail tariffs, there are weak incentives for the end customers to invest in their own production. Diesel generators are applied as the main source of energy mainly in technically isolated energy systems, where their application is more economically feasible than the connection to the main grid (even considering the high prices on fuel). The owners of the cottages rarely apply PV panels. The average individual cannot afford to buy a PV panel or small wind turbine with the capacity that is enough to provide electric power supply for the house.

Russia has a great potential for small-scale and distributed generation substantially in isolated energy systems located on the East. Due to separate from Unified ES operation eastern energy systems are considered to be suitable for distributed power generation. Analysis of the regulatory framework related to distributed generation and use of renewable energy is presented further in Chapter 4.

3.4. Challenges and development prospects

Long-term orientation on the centralized energy production made Russian energy system unable to react properly to such changes as growth of energy consumption. Centralized energy system was feasible in the context of the state-planned economy of USSR. After the breakup of the Soviet Union and the following transition from state-regulated to electricity market based electric power industry, advisability of the centralized system model became questionable. High electric power losses occur in the network due to long transmission distances, incorrect load growth forecasts used in network planning and the inability to renovate the network to meet with modern requirements. The share of overaged distribution networks has reached 50%. Lifetime for 7% of the network has exceeded the standard lifetime twice. Overall deterioration of distribution networks reached 70% (Government decree “on approval of the Strategy for Development of the Russian power grid”, 3 April 2013).

Implementation of the competitive electricity market model, which was introduced in the early 2000s, can be considered unsuccessful. Slavish adherence to the experience of Western countries without taking into a consideration peculiarities of Russian electric power industry has led to a number of problems. Technically electricity market has free competition between a number of generating companies, although in fact, a significant part of these companies are controlled by the same owners, which are not interested in a competition. Power producers located close to fuel extraction spots have excess profit due to low fuel costs, while a majority of CHP power plants remains unprofitable.

Electricity distribution tariff have nearly run out of growth potential. For many industrial consumers it is already cheaper to have their own energy generation (Moskvichev, 2013). Electricity prices controlled by the state, force distribution companies to reduce investments in the development of the networks due to lack of funds.

According to the Russian government decree №511-р, one of the main directions for the development of modern Russian electric power industry is an implementation of distributed generation. Therefore, regulatory framework and technical conditions for an effective and economically feasible integration of distributed generation into Unified ES of Russia will be provided.

In foreseeable future, the responsibility (incl. financial responsibility) of distribution grid companies for quality and reliability of electricity supply will be increased. By the year 2017, all distribution companies will be providing quality and reliability data acquisition. In addition, such indices as System Average Interruption Frequency Index (SAIFI) and Customer Average Interruption Duration Index (CAIDI) will be implemented for assessment of reliability of the network. Integral performance index reflecting consumer experience along with quality of electricity transmission services will be implemented in order to estimate quality of provided services. Outlined indices will be used as main criterions for optimal balance between tariff level and reliability level. (Government decree “on approval of the Strategy for Development of the Russian power grid”, 3 April 2013)

4. TECHNICAL REGULATIONS

In order to estimate the potential and possibilities of LVDC microgrids in Russian electricity distribution networks, regulatory framework, related specifically to this technology should be analyzed. The chapter presents the main aspects of standardization regulation related to the LVDC and distributed energy sources.

4.1. LVDC related standardization

The main regulatory document for the design of electricity networks is the Electrical Installations Code (EIC). It is based on the different national standards. Reconstruction of the existing and building of new the electricity networks should be done in accordance with EIC, which determines three categories of consumers:

1. ***Consumers of the I-category*** – interruption of power supply may be dangerous for human; may cause a threat to the security of the state, considerable financial or physical damage, malfunction of critical elements of public utilities, communications facilities and television. Power supply of these consumers during normal operation must be provided by two independent power supply sources, which act as a backup for each other.

Critical consumers, uninterruptible supply of which must be provided for safe shutdown of the production process in order to prevent a threat of explosions and fire, are distinguished into the special category. For this category of consumers a third independent power supply source must be provided. The time of power supply interruption should not exceed the time of automatic power supply recovery.

2. ***Consumers of the II-category*** – interruption of power supply may lead to a massive reduction in production volumes, continuous interruption in the work of personnel, industrial transport or dysfunction of a significant number of citizens and country-people. Although, similar to the first category power supply of these consumers during normal operation must be provided by two independent power sources, the allowed time of supply interruption is greater. It should not exceed the time for the supply recovery by on-duty personnel or a service crew.
3. ***Consumers of the III-category*** – the rest of consumers, which are not referred to the first and the second category. Power supply of these consumers can be provided by a single power supply source, if the time of interruption will not exceed a day.

Standardization related to electric power supply is mainly defined by National State Standards. Currently, standardization in low-voltage electricity distribution is represented by adaptations of IEC standards. Voltage levels for DC networks in distribution utility are defined in (National State Standard 32966, 2014), which is based on the standard (IEC 60449:1973, amd.1:1979, MOD). The allowed ranges of voltage levels in the low-voltage DC network for both grounded and ungrounded systems are presented in Table 2.

Table 2. Allowed voltages for LVDC distribution networks.

Grounded systems		Ungrounded systems
Voltage between pole and ground, V	Voltage between poles, V	Voltage between poles, V
$120 < V \leq 900$	$120 < V \leq 1500$	$120 < V \leq 1500$

Furthermore, according to the National State Standard № 30331.1-2013 “Low-voltage electrical installations” (based on IEC 60364-1:2005) DC voltage level up to 1500 V is defined as low-voltage. The above-mentioned standard defines general characteristics of AC and DC low-voltage distribution networks.

There is a new set of National State Standards P 56124.x-2014 adopted from IEC/TS 62257-x: 2005, which is devoted to power supply of remote rural areas without centralized electricity distribution based on small renewable energy sources and hybrid systems. It will be enacted on 1 July 2016. The standard applies to power systems with voltage levels up to 500 VAC and 750 VDC. (National State Standard P 56124.1, 2014)

4.1.1. Quality of power supply

The quality of power supply in public power supply systems is defined by indices from National State Standard 32144-2013. This document is based on IEC 61000 standard series. (National State Standard 32144, 2013) The main power supply quality indices are frequency deviation, steady-state voltage deviation, voltage waveform distortion factor or total harmonic distortion (THD).

Steady-state voltage deviation in supply terminal should not exceed 10% of nominal voltage value within a week. Voltage value under 90% V_{nom} is considered as a voltage dip and starting threshold level for a voltage interruption is 10% V_{nom}. Voltage waveform distortion is defined by total harmonic distortion. THD is presented in standard as K_{u}. Total harmonic distortion index K_{u} should not exceed 12% for a low-voltage network.

Nominal frequency value in the network is 50 Hz. Frequency deviation is considered normal, if it does not exceed ± 0.2 Hz within 0.95t, where **t** – measurement interval, which equals a week. Within **t**, frequency deviation should not exceed 0.4 Hz. It should be noted, that for isolated energy systems with autonomous power generating units, which are not connected to synchronized electricity transmission systems, ± 1 Hz frequency deviation within 0.95t and ± 5 Hz – within **t** is considered normal.

The requirements for supply security are defined for different kinds of customers, as was introduced before in the first paragraph of the section 4.1.

4.1.2. Grounding and protection

Electrical safety issues in LVDC distribution systems are defined by National State Standard № 30331.1-2013. Possible grounding arrangements for two-wire and three-wire DC supply systems are determined and presented in the standard. TN-S, TN-C, TN-C-S, TT and IT grounding systems can be implemented in DC networks. The following examples of TN and

IT grounding arrangements are presented, since based on the analysis of the LVDC microgrid concept they are the most suitable and typical.

- *TN-S grounding arrangements:*

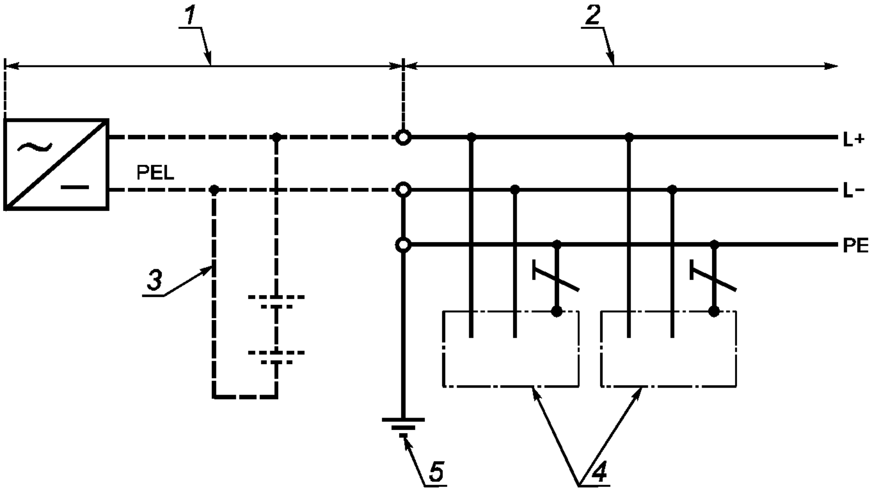

Figure 14. TN-S grounding arrangement in a two-wire LVDC system. (1 – power source; 2 – electric installation; 3 – energy storage unit, which is not compulsory; 4 - exposed conductive parts; 5 – grounding of the system) (National State Standard № 30331.1-2013)

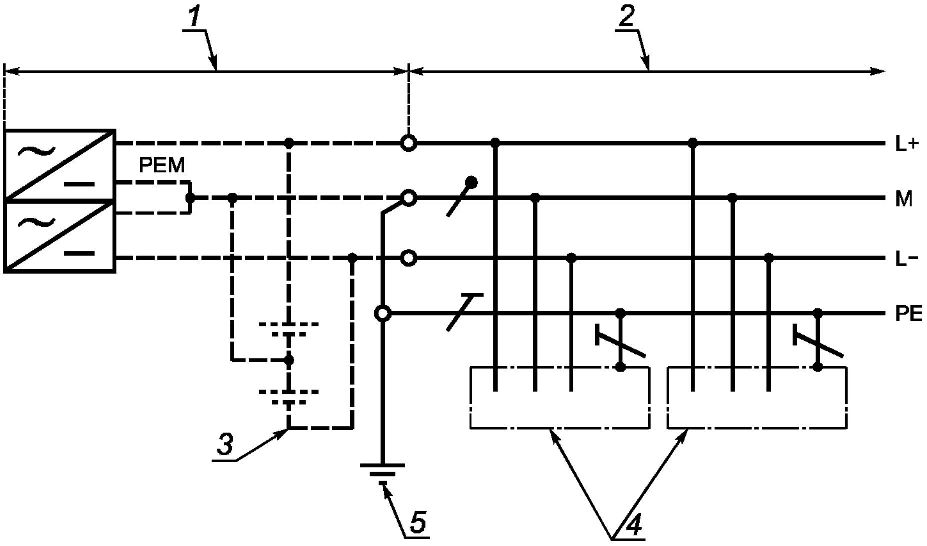

Figure 15. TN-S grounding arrangement in a three-wire LVDC system. (1 – power source; 2 – electric installation; 3 – energy storage unit, which is not compulsory; 4 - exposed conductive parts; 5 – grounding of the system) (National State Standard № 30331.1-2013)

- *TN-C grounding arrangements:*

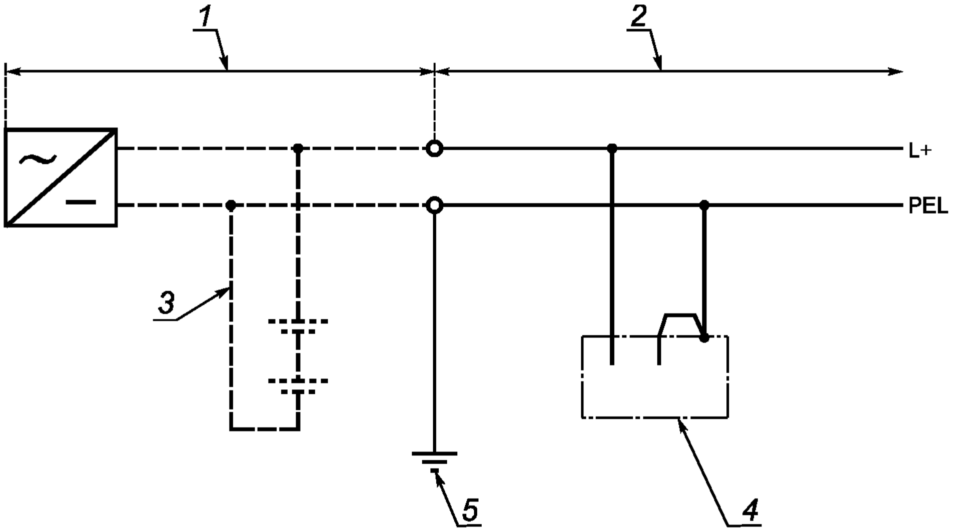

Figure 16. TN-C grounding arrangement in a two-wire LVDC system. (1 – power source; 2 – electric installation; 3 – energy storage unit, which is not compulsory; 4 - exposed conductive parts; 5 – grounding of the system) (National State Standard № 30331.1-2013)

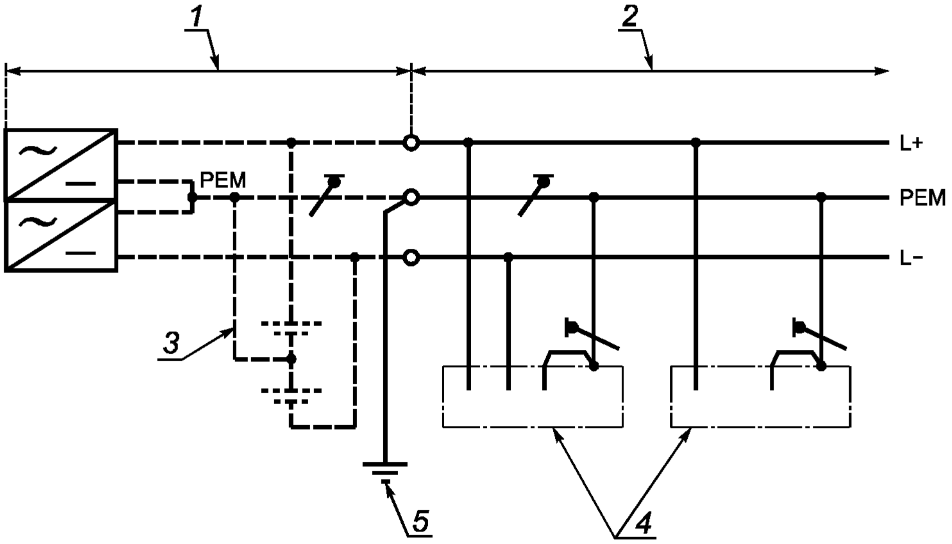

Figure 17. TN-C grounding arrangement in a three-wire LVDC system. (1 – power source; 2 – electric installation; 3 – energy storage unit, which is not compulsory; 4 - exposed conductive parts; 5 – grounding of the system) (National State Standard № 30331.1-2013)

- *TN-C-S grounding arrangements:*

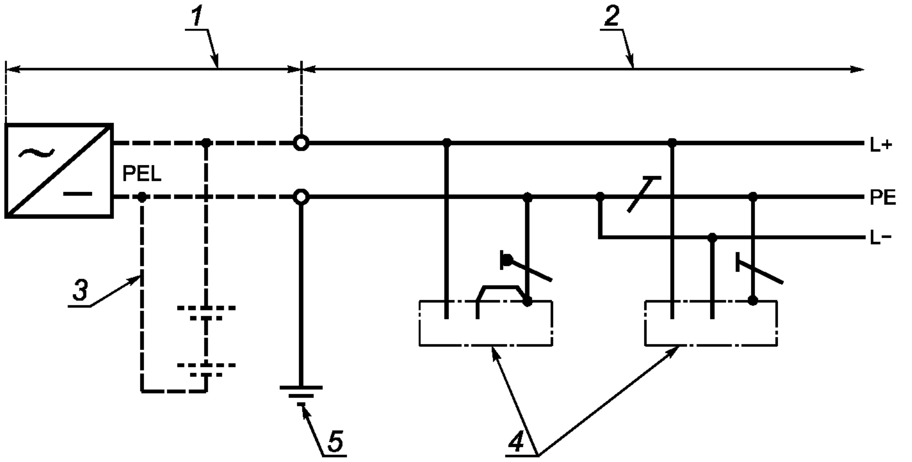

Figure 18. TN-C-S grounding arrangement in a two-wire LVDC system. (1 – power source; 2 – electric installation; 3 – energy storage unit, which is not compulsory; 4 - exposed conductive parts; 5 – grounding of the system) (National State Standard № 30331.1-2013)

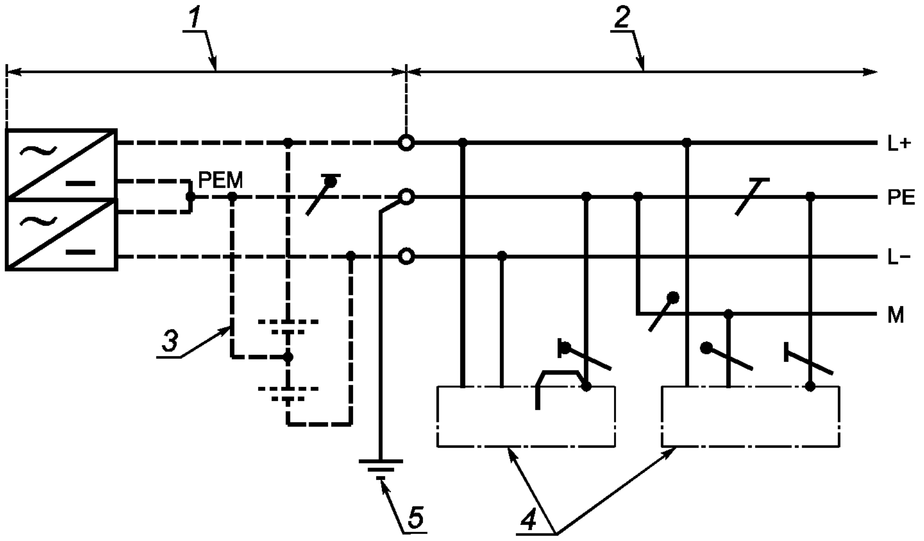

Figure 19. TN-C-S grounding arrangement in a three-wire LVDC system. (1 – power source; 2 – electric installation; 3 – energy storage unit, which is not compulsory; 4 - exposed conductive parts; 5 – grounding of the system) (National State Standard № 30331.1-2013)

- *IT grounding arrangements:*

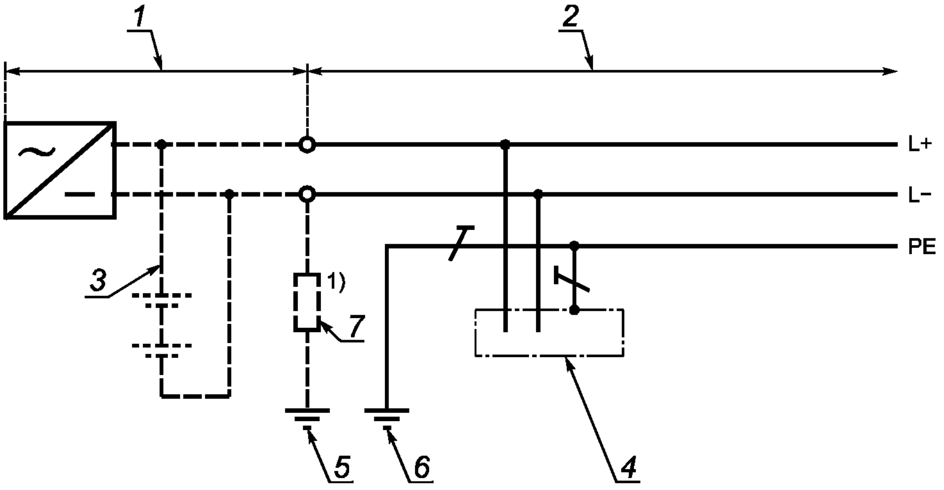

Figure 20. IT grounding arrangement in a two-wire LVDC system. (1 – power source; 2 – electric installation; 3 – energy storage unit, which is not compulsory; 4 - exposed conductive parts; 5 – grounding of the system; 6 –grounding of exposed conductive parts; 7 - optional apparent resistance) (National State Standard № 30331.1-2013)

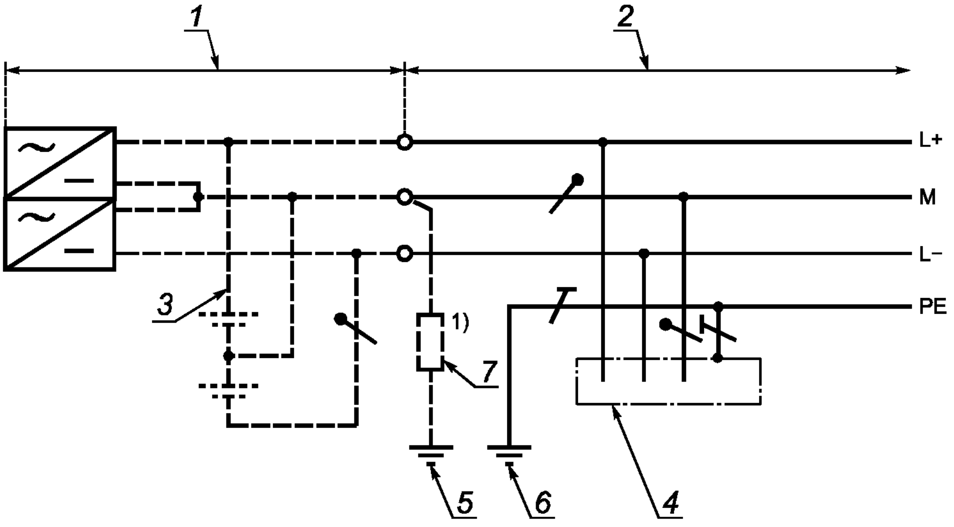

Figure 21. IT grounding arrangement in a three-wire LVDC system. (1 – power source; 2 – electric installation; 3 – energy storage unit, which is not compulsory; 4 - exposed conductive parts; 5 – grounding of the system; 6 –grounding of exposed conductive parts; 7 - optional apparent resistance) (National State Standard № 30331.1-2013)

There is a National State Standard №56124.5-2014, which is a part of new set of standards that was mentioned earlier. This standard defines the principles of protection against electric shock and grounding arrangements for low-voltage distribution networks in remote rural areas. Only TN and TT systems are considered, since, according to the standard, IT systems are not generally used in decentralized electricity supply systems. However, this standard is not enacted yet.

Allowed touch voltage levels are defined by National State Standard №12.1.038 for current paths from one hand to other hand and from hand to legs. During normal operation of a network, touch voltage should not exceed 2 VAC and 8 VDC. In fault cases in low-voltage distribution networks (under 1000 V) touch voltage should not exceed 220 V with duration of exposure 0.01-0.08 sec. Value of current should not exceed 220 mA in this case. With duration of exposure over 1 sec. touch voltage should not exceed 12 V and current should not exceed 2 mA. (National State Standard №12.1.038)

4.2. Regulations for distributed energy resources

First steps towards development of renewable energy sources were made in 2007 with the introduction of the term "renewable energy sources" to the Federal Power Act, determination of energy sources, which are considered as RES by the Russian Government and definition of main principles and method of support. The new energy strategy of Russia for the period until the year 2035 defines the development of RES-based power industry as one of the main strategic development directions. However, the project of new energy strategy does not stipulate for the establishment of Federal Act on RES. Unfortunately, existing legislation still does not cover all the aspects of the implementation of RES. This situation is determined by lack of standardization related to RES to a certain degree. However, the new set of National State Standards P 56124.x-2014, that was mentioned earlier, will improve the situation with respect to implementation of small-scale renewable energy sources in remote rural areas.

Although there are some problems with legislation and standardization, there are no serious obstacles for the implementation of RES in energy production. Power generation facility with installed capacity up to 25 MW (incl. RES-based generation facilities) are selling electrical energy on the retail market (Government decree № 442, 4 May 2012.) However, in order to be able to sell electricity on the retail market, renewable energy based generation facility should go through the qualification process. Furthermore, one of the criterions of qualification requires generation facility to be included in power industry prospective development program of the region, where it is located. (Government decree № 426, 3 June 2008)

The research results show that currently there are no direct standards or regulation on the use of energy storage systems in distribution utility in Russia. However, the new set of

National State Standards P 56124.x-2014 can be considered as a guideline for electrification of remote rural areas using LVDC microgrid concept. The set of standards includes parts related to use of energy storage systems and power converters in remote rural areas. Unfortunately, at the time of writing, these parts of the set are not available. National State Standard № 30331.1-2013 “Low-voltage electrical installations” (based on IEC 60364-1:2005) defines general characteristics of LVDC distribution networks, such as grounding arrangements and protection.

From the perspective of regional or territorial distribution company, an implementation of energy storage system may be prohibited due to combination of competitive (electricity generation/sales) and non-competitive (electricity distribution) businesses (Federal Act N36 2003, R.E. №10, 29.12.2014), if a storage system is somehow considered by legislation as a power generating unit. Analysis of regulatory framework shows that law is silent on this issue. Energy storage systems are not directly considered as a power generation units in legislation, thus for a distribution company it can be possible to utilize them in a distribution grid.

4.3. Challenges and opportunities for the implementation of LVDC microgrids

According to the results of regulatory framework analysis, Russian electric power industry experiences a lack of standardization related to the use of RES and Microgrid systems. Although there will be the new set of standards P 56124.x-2014 related to the use of microgrid systems, it will be applicable only for remote rural areas without centralized electricity distribution. Hence, an implementation of an LVDC microgrid concept can be problematic in city areas from the regulatory point of view.

Although there are challenges for the implementation of an LVDC microgrid concept in terms of centralized electricity distribution in Russia, it can be possible with further development of electricity market and legislation related to use of renewable energy sources. According to the Electrical Installations Code, there must be a backup power supply source for consumers of the first category. In this regard, power supply of a settlement should be provided by means of two independent power lines, in case if there are consumers of the first category. In grid-connected mode, an LVDC microgrid can be considered as a backup supply source, thus eliminating the need for a backup power line. Furthermore, local generation along with energy storage systems can be utilized for reduction of power consumption peaks, thus reducing load in the main network and increasing transmission capacity without changing the cross-section of conductors. Consequently, renovation of the existing power transmission lines can be postponed.

In case of an LVDC microgrid system, that is giving electricity generated from RES-based units back to the main grid, a qualification process should be gone through for each generation unit to be allowed to sell the electricity on the retail market. In addition, generation facilities should be included in the prospective development program of the region, where a Microgrid system will be located. (Government decree № 426, 3 June 2008)

An LVDC microgrid system is relatively expensive to be built by a group of customers themselves. However, it can be inexpensive compared to the conventional power supply system, and thus, it can be an interesting solution for a regional electricity distribution company. Therefore, challenges for the implementation of an LVDC microgrid should be observed from the perspective of an electricity distribution company. It can be concluded from the analysis of regulatory framework and electricity distribution business in Russia that an implementation of an LVDC microgrid can be challenging. It is unclear whether a microgrid will be considered as an electric power generation facility or not. However, in an isolated energy system of East (Eastern UES), a combination of monopoly and competitive electricity businesses by an electricity distribution company is possible. Furthermore, in case of an autonomous electricity distribution system, which is not connected to the Unified ES of Russia, a distribution company is allowed to sell electricity. (Federal Act N36 2003, R.E. №10, 29.12.2014)

The government determines electricity prices for public customers in territories, which are technically isolated or not interconnected with Unified ES of Russia (Government decree № 442, 4 May 2012). Therefore, a distribution company may experience difficulties with implementation of an LVDC microgrid system, based on RES, since in general, a price for electricity generated by RES is higher when compared to conventional power sources.

Since Russia is a big country with a variety of different climate zones, it is difficult to develop a unified model of an LVDC Microgrid system applicable everywhere. Therefore, each case should be considered individually. However, it is possible to distinguish a group of consumers with similar conditions, which can utilize unified LVDC microgrid solution based on the generation units chosen in accordance with available energy sources.

From the technical applicability point of view, there are no serious constraints for the implementation of LVDC microgrids in Russian distribution networks. The analysis of the market revealed that there is a company, which provide solutions for power augmentation based on LVDC microgrid technology. “PLUSPOWER” from Moscow offers LVDC microgrid solutions for administrative buildings, residential houses, industry and network companies to develop their grids. In addition, the company is developing and manufacturing power electronics and control systems. The example of the LVDC microgrid solution provided by PLUSPOWER is presented in Figure 22.

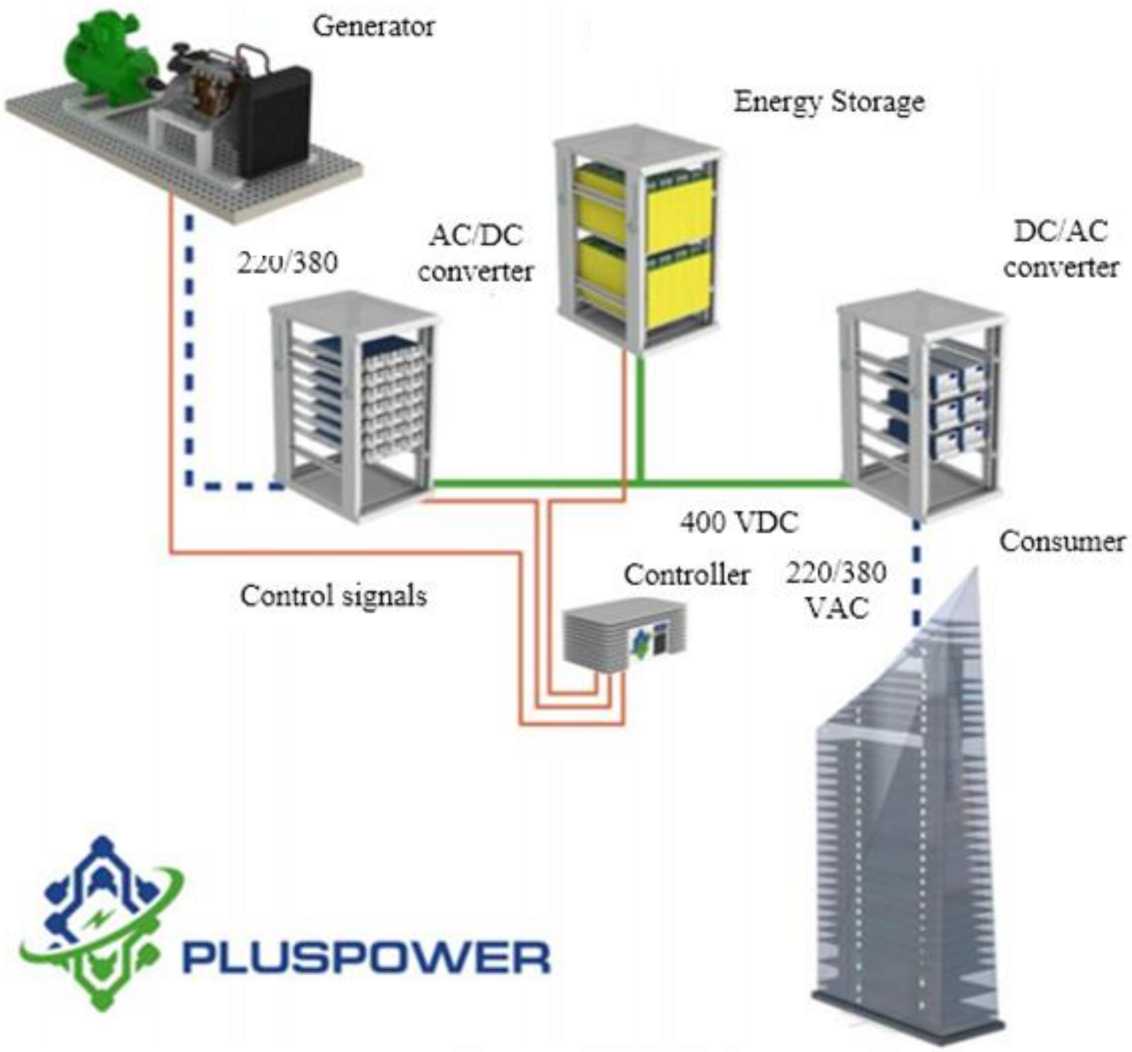

Figure 22. Autonomous energy system solution by “PLUSPOWER” company (LLC “PLUSPOWER”, 2016)

Subsequently, the implementation of LVDC microgrid distribution solutions in Russia can be considered possible.

5. POTENTIAL APPLICATIONS AND ECONOMIC FEASIBILITY

In order to define the potential of LVDC microgrids in Russian distribution networks, the analysis of possible drivers for its implementation needs to be carried out along with the determination of its suitable properties based on the performed research. To estimate the economic feasibility, the economic potential analysis should be performed. A theoretical case was selected for the analysis as not all the necessary information of a real case was available at the moment of the research work. In this chapter, the results of the analysis of above-mentioned issues are presented along with the estimated economic benefits.

5.1. Possible drivers for adopting LVDC microgrids

The main driver for the distribution system development in Russia is a growing electricity consumption mainly represented by increasing domestic loads. Along with a lack of available capacity and congestion problems, it leads to a deficit of electricity and increase of grid losses. Residential energy consumption growth affects mainly low- and medium-voltage distribution networks. Therefore, their development is of high priority.

As it was defined in Chapter 3.3, power losses in distribution networks up to 11.4 % are another main driver for the development. About 60% of total power losses in Russian power industry accrue from medium- and low-voltage distribution networks (Vorotnitsky et al., 2005). Partially, the problem is determined by relatively long transmission distances. It can be unfeasible to use bigger cross-sections or higher voltage level due to the high cost. Therefore, existing network topologies and approach to allocation of power generation should be revised. Furthermore, the problem can be considered as a driver for the development of distributed generation, which is a characteristic feature of LVDC microgrid.

A significant share of overaged network equipment (incl. cables, overhead lines, transformers) stipulates a strong necessity for a renovation of existing electricity distribution systems. The overaged condition of distribution networks leads to an increasing number of outages and supply quality decrease, which affects both distribution companies and consumers. According to the strategy for the development of Russian power grid, by the year 2017 distribution companies’ responsibility for the reliability and quality of power supply will be increased (Government decree “on approval of the Strategy for Development of the Russian power grid”, 3 April 2013). Implementation of such reliability indices as CAIDI and SAIFI will have an impact on revenue of distribution network companies and will be a driver for renovation and development.

Nearly 60% of Russian territory is not connected to the Unified ES due to remote location. The number of autonomous energy sources in local energy systems of remote areas exceeds 5000 units. Local generation is mainly comprised of diesel power plants and gas turbines. (Suslov, 2012) In case of an isolated energy system, problems with availability, stability and reliability of power supply can be considered as possible drivers for the implementation of LVDC microgrids. Utilization of renewable energy sources available in the region under consideration can help to reduce the problem with fuel supply. Analysis of regulatory framework shows that the Government is planning to develop the unified energy systems of East and Siberia in conjunction with a forthcoming development of industry and growth of minerals’ extraction. Furthermore, the potential of renewable energy sources in Eastern regions of Russia is significantly high. As an example, on Sakhalin Island there is a large number of geothermal sources, which can be and already are utilized for heat and power production (Ivanova et al., 2010).

A possible driver for implementation of an LVDC microgrid in non-isolated UES is a necessity of transmission capacity increase in distribution networks. There are transmission congestion problems in a number of regional distribution networks. Existing network is not capable to handle the growing power consumption since the majority of the distribution networks exceeded their maximum operational lifetime. (Government decree “on approval of the Strategy for Development of the Russian power grid”, 3 April 2013.) Furthermore, a necessity in new large-scale power plants will be eliminated by utilization of local small-scale power and heat generation.

5.2. Suitable properties for an LVDC microgrid

Summarizing the properties of an LVDC microgrid, considered in the chapter 2.5, and the results of the regulatory framework analysis as well as the analysis of the grid development needs, suitable technical properties of an LVDC microgrid system in Russia can be concluded.

As the possible use case at the moment is the isolated settlements in the eastern part of Russia, an LVDC microgrid should be operating in the islanded mode. The system can utilize local generation units, based on either existing conventional or new renewable energy sources. Selection of generation units, based on RES, depends on a specific case.

Based on the analysis of the LVDC microgrid concept and Russian standardization, related to the use of LVDC in distribution networks, possible voltage levels for a microgrid system are in the range: 120 - 1500 VDC. However, the choice will be determined by operational conditions and size of the system. Furthermore, it should be noted, that requirements of a new set of National State Standards P 56124.x-2014 are applicable only for the systems with voltage level up to 750 VDC and nominal power up to 100 kVA.

The techno-economic limit for the power that can be transmitted by means of LVDC technology is 500 kW on the distance up to 10 km (Partanen and Kaipia, 2014). Although, only small settlements with the population about 500 people or less are suitable for an LVDC distribution, interconnection of these settlements or districts of bigger settlements can be feasible. As it was stated in Chapter 2.2, implementation of an energy system, based on interconnected microgrids will increase its overall reliability. Furthermore, considering the long-term orientation of Russian electric power industry on the centralized power supply, utilization of local generation can reduce transmitted power and enable smaller cross-sections with the same capacity of the connection to the Unified Energy System.

5.3. Potential use cases for LVDC microgrids

Small isolated settlements in the eastern regions of Russia can be considered as suitable use cases for LVDC distribution at the moment. The amount of settlements in Russia, which are operating autonomously (without centralized energy supply) with respect to the population is presented in Table 3.

Table 3. Number of settlements without centralized power supply in Russia. (Surzhikova, 2012)

The number of residents in a settlement, persons.	The number of settlements
Under 50	13500
51-500	11100

As an example, there are 21 settlements with the total number of residents around 33700, isolated from centralized electricity distribution in Tomsk region of Siberia. (Surzhikova, 2012). In practice, 75% of territories in Siberian and Eastern united energy systems are utilizing local decentralized energy systems (Government decree №480, revised 26 November 2015). For settlements with the number of residents under 200 minimum required generation capacity is under 30 kW and the bigger settlements (< 500 residents) required capacity is under 200 kW (Konovalova, 2007).

In isolated UES of East and local isolated networks of small settlements in Siberian UES, an LVDC microgrid can be used in the islanded mode. Due to long transmission distances along with low power consumption, it is not economically feasible to connect isolated settlements to the centralized electricity distribution. According to (Surzhikova, 2012) the maximum length of 10 kV power transmission line for required power of 250 kW is 10 km when considering the voltage drop limit (5%). It is not economically feasible to build power transmission lines with higher voltage level (35 kV as an example), as they will be operating nearly unloaded (Surzhikova, 2012). Existing isolated energy systems of small settlements with local power generation are already forming islanded microgrids. Considering this and the possibility of utilization of existing AC power lines for the LVDC distribution, an LVDC microgrid in the islanded mode is a suitable solution for the case. According to the review of LVDC distribution technology, the problem with synchronization of local generation units is eliminated in LVDC distribution networks. New renewable energy sources can be easily integrated in an LVDC microgrid in addition to existing power generating units.

It is feasible to interconnect neighboring independent LVDC microgrids that are close enough with each other. This improves the efficiency in exploitation of the regional energy sources and at the same time brings redundancy, thus increasing the reliability of electric supply. A surplus of generated power from one microgrid can be used to cover electricity deficit in the neighboring LVDC microgrid (Konar and Ghosh, 2015).

5.3.1. Use case example

The Batakan settlement in the East of Russia can be considered as a possible case for the implementation of the LVDC microgrid. It is located in Trans-Baikal region, which is a part of Siberian UES. The view of the Batakan settlement is presented in Figure 23.

Figure 23. The Batakan settlement (Case from qualification phase in power engineering of International championship “Case-in”, 2016)

The UES of Siberia is operating synchronously with the Unified ES of Russia. The electricity network of Batakan settlement is owned by the regional distribution grid company “Chitaenergo”, which is a branch of JSC “Interregional Distribution Grid Company of Siberia” (Interregional Distribution Grid Company of Siberia, 2016). Electric power supply of the settlement is autonomous and is provided by the 2x300 kW diesel power plant. According to the initial power supply plan dated by the year 1985, there are 17 - 10/0.4 kV single-transformer substations with total installed capacity over 3000 kVA, which are connected to the power plant by means of 10 kV network. Electric supply of end-consumers such as residential houses is executed via 0.4 kV grid. The electric power transmission is provided by means of bare steel-reinforced aluminum overhead lines, which were a typical solution in the 1980s in USSR.

According to the resolution of the settlement council №26 from 30.12.2015, the number of households in the Batakan settlement is 264, which means that there are 264 residential customers. Other loads are: one school, one kindergarten, one hospital, three shops, one administrative building, three community centers, a library and three sawmills. The annual peak load profile is presented in Figure 24.

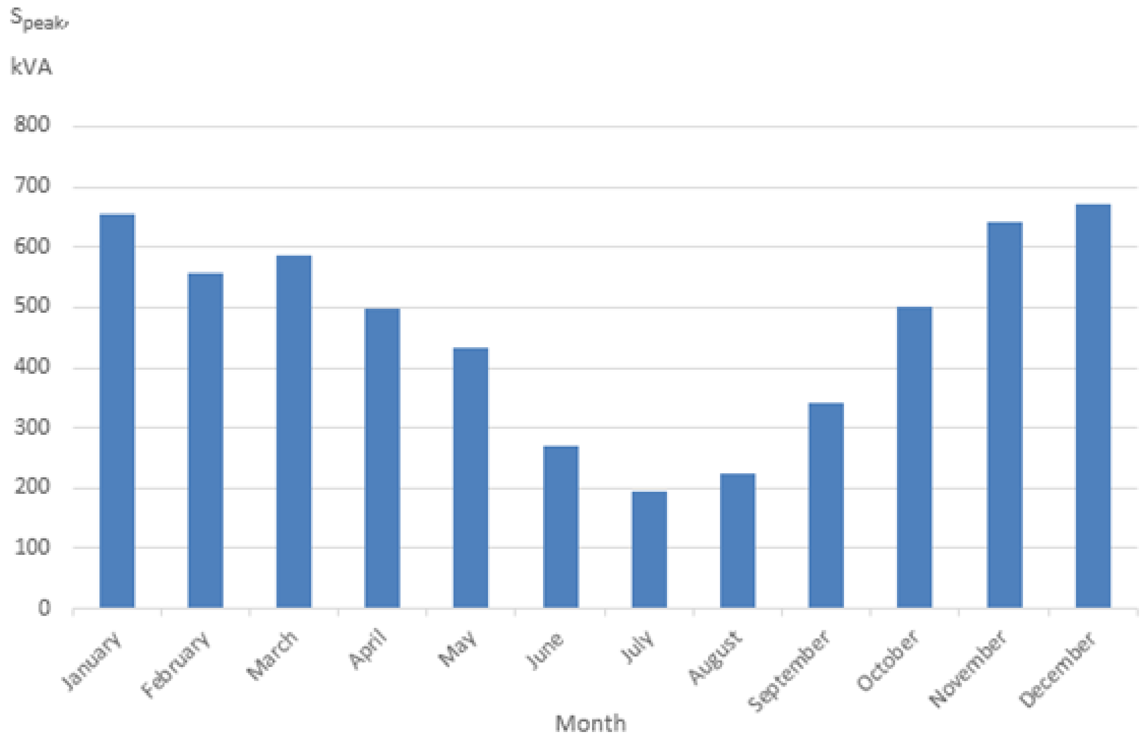

Figure 24. The annual peak load profile of the Batakan settlement based on the measurements from the main substation. (Case from qualification phase in power engineering of International championship “Case-in”, 2016)

5.4. Economic potential analysis

In order to find out if there are any possible economic benefits of the LVDC microgrid’s implementation in Russia, the economic analysis of the theoretical case based on the Batakan data and the official document “Procedural Guidelines for Calculation of Electrical Loads in Agricultural 0.38-110 kV Networks” is performed. For the purposes of the economic estimation, the comparative calculation model is made using the PTC Mathcad 14.0 software.

The Batakan itself is relatively big for the LVDC microgrid to be applied at once. Therefore, for the purposes of the analysis, a theoretical case is made from the Batakan data. As it can be seen from the description of the Batakan settlement, the main customer type is a residential house. Thus, a small district, which consists of residential houses, can be used as a representative model. The objective is to compare 10/0.4 kV AC network with ± 750 V

LVDC network. The voltage level ± 750 V was used since it enables the use of cheaper power converters with rated voltage 750 V, when the connections schemes 1 and 2, which were defined in the Chapter 2.1, are used. Furthermore, the bipolar solution enables the operation of a half of the network, when there is a fault in the other. Thus, the reliability of power supply increases. (Partanen et al., 2010) The representative case is depicted in Figure 25.

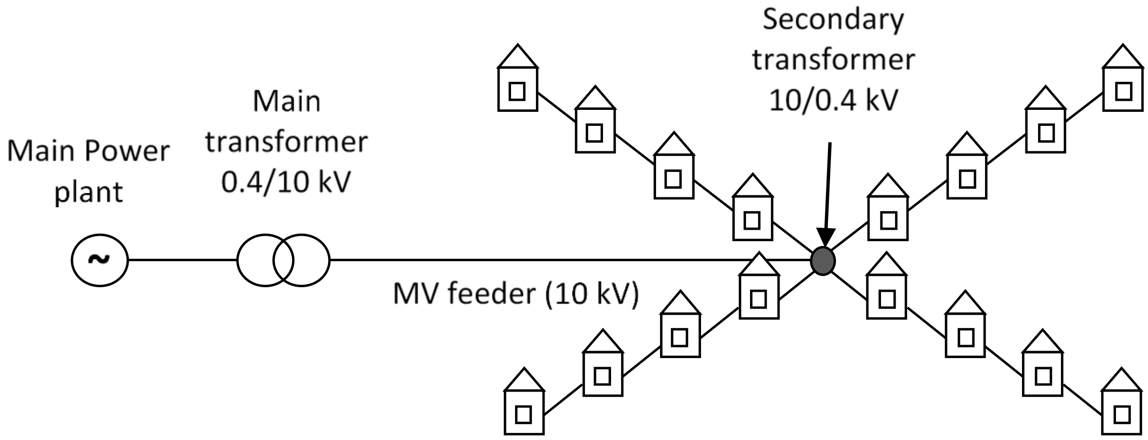

Figure 25. Representative AC network

As it can be seen from Figure 25, the theoretical AC network is radial and consists of 16 residential houses in total. Each of four branches feeds four customers. In order to determine the maximum size of a settlement, in which the LVDC solution can be considered feasible, the analysis of the case with 2-3 similar interconnected neighborhoods is carried out in addition.

According to the RD № 34.20.178 “Procedural Guidelines for Calculation of Electrical Loads in Agricultural 0.38-110 kV Networks”, the annual peak power of residential houses without an electric stove is 4 kW. The average distance between the residential houses in small isolated settlements in Russia is around 0.1 km, therefore the length of the lines between customers is assumed to be similar. (RD № 34.20.178, 1982) For the purpose of the analysis, the length of the feeder in both AC and DC cases is considered as a variable, which depicts the distance from the centralized network or from another microgrid. The total load of the secondary transformer is determined using the coincidence factor for 16 customers CF = 0.37 and the power factor for residential hoses without an electric stove PF = 0.93 according to Table 4 obtained from (RD № 34.20.178, 1982).

Table 4. Coincidence factors for low-voltage distribution networks in rural areas (RD № 34.20.178, 1982)

Type of consumer	Number of consumers										
	2	3	5	7	10	15	20	50	100	200	500 and more
Residential house with load more than 2 kW	0,75	0,64	0,53	0,47	0,42	0,37	0,34	0,27	0,24	0,20	0,18

Power supply of the district is provided by the main power plant similar to the Batakan case. The connection between district and power plant is made by 10 kV feeder overhead line, and power supply of the customers is provided by 0.4 kV overhead lines. Aerial bundled cables “СИП-2” and “СИП-3” are used for 0.4 and 10 kV lines correspondingly. The characteristics of these cables are defined by TS 16-705.500-2006. The main and the secondary substations are considered as unitized transformer substations of terminal type with “ТМГ” oil-filled waterproofed transformers, which are typical for rural areas in Russia. The load of the transformers is obtained from the sum of the annual peak powers of a residential house (4 kW), multiplied by coincidence factor (CF = 0.37) and divided by power factor (PF = 0.93). Calculated load of the transformer equals 25.46 kVA. Since there are no standard “ТМГ” transformers with nominal power between 25 and 40 kVA, the latter was chosen. Loads of the secondary and the main transformer are equal, thus their nominal power is identical.

The theoretical DC solution is made as a bipolar network, since the cost of inverters for a bipolar system is lower, when compared to the unipolar system (Partanen, 2015). The connection of the customers of each branch to the network is made between positive pole and middle conductor, and between negative pole and middle conductor, to maintain the load symmetry. The LVAC lines and the MVAC feeder are replaced by ± 750 VDC lines. The main transformer is replaced by two rectifiers and the secondary transformer is removed. Each customer has its own inverter, which provides AC power supply. In the LVDC distribution same conductor types are assumed to be applied, thus the suitable conductor for ± 750 VDC is “СИП-2”.

The average cost of energy losses for the East of Russia is obtained from the information on the official web pages of the Far-Eastern Distribution Company and the Interregional Distribution Grid Company of Siberia, and is C_{EL} = 2.147 rub/kWh (Far-Eastern Distribution Company, 2016; Interregional Distribution Grid Company of Siberia, 2016). The cost of power losses is obtained from the energy losses and equals C_{PL} = 1288 rub/kW. The current interest rate p for electricity distribution companies is 13 %. The load growth rate r is considered to be equal 0 %/a.

Table 5. General initial parameters

Parameter	Value
Cost of energy losses	2.147 rub/kWh
Cost of power losses	1288 rub/kW
Interest rate	13 %
Load growth rate	0 %
Study period	20 a
Lifetime of converters	15 a
Price of converters	7400 - 22200 rub/kVA
Max voltage drop DC	25 %
Max voltage drop AC	5 %

5.4.1. Calculation methodology

The economic analysis comprises of calculation of the total costs of the DC and AC distribution lines, calculation of the total costs of the power converters for DC and calculation of the total costs of the transformers for AC. The total costs of the LVDC and typical AC solutions are than compared and the economic benefit is estimated.

The total costs of the network components over the planning horizon T comprise of the investment costs, loss costs, maintenance costs, outage costs and can be calculated using the following equation (Lakervi and Holmes, 1998):

$$C_{tot} = \int_0^T C_{inv} + C_{loss} + C_{out} + C_{main} dt \tag{1}$$

However, maintenance and outage costs are neglected in this research, since there are no available values of maintenance costs for Russia and the outage costs are not implemented yet. For the representative AC network, the total costs of the single main transformer, single secondary transformer, LV distribution lines and the MV feeder are considered. For the DC solution, the total costs of LVDC distribution lines, two rectifiers and 16 customer inverters are calculated. In addition, for both AC and DC solutions, cases with 2-3 theoretical neighborhoods are calculated in order to estimate possible economic benefits of the implementation of LVDC microgrids in bigger settlements. Calculation of the total costs is described further for each network component.

Investments are one-off costs, thus the lifetime of the component is not usually considered. However, as it can be seen from Table 5, lifetime of the power converters is less than considered study period. Therefore, the investment costs are doubled. As opposite to the investment costs, loss costs are referred to the whole operating time of the network component, therefore the sum of these costs will not provide the correct result. In order to define the present value of the loss costs and evaluate correct total cost the present value ψ and capitalization coefficient κ should be defined at first. The following equations can be used for that (Lakervi and Partanen, 2015):

$$\Psi_V = \frac{\left(1+\frac{r}{100}\right)^2}{1+\frac{p}{100}} \tag{2}$$

$$\kappa = \Psi \cdot \frac{\Psi^t - 1}{\Psi - 1} \tag{3}$$

where r – interest rate
p – load growth rate
t – operating time

However, equation (2) describes only variable recurrent costs such as cost of the transformer or power converter load losses. For the constant recurrent costs (no-load losses) the following equation should be used (Lakervi and Holmes, 1998):

$$\Psi_c = \frac{\left(1+\frac{p}{100}\right)^t - 1}{\frac{p}{100} \cdot \left(1+\frac{p}{100}\right)^t} \tag{4}$$

Overhead power transmission lines

Calculation of the investment costs of the network equipment is similar for AC and DC case and comprises of the component’s price and the construction or installation costs, as follows:

$$C_{inv} = C_{price} + C_{cons} \tag{5}$$

where C_{price} is the component price and C_{cons} the construction costs. Construction costs of the overhead lines made with aerial bundled cables are obtained from (Construction Price Norms 81-02-12-2014, 2014). The costs are converted in the prices of the year 2016 and are applicable for the eastern regions of Russia. The prices on the overhead lines are presented in the Appendix A.

The cross-section of the conductors depends on the maximum load current and the voltage drop. The voltage drop for DC and AC networks is calculated differently. In the LVAC and MVAC systems, the asymmetry of the load is rarely considered, whereas in the LVDC system it is always taken into an account (Kaipia et al., 2008). Additionally, the inductance of the line is neglected in the LVDC network. The AC load flow can be calculated as follows (Lakervi and Holmes, 1998):

$$\Delta V_{AC} = V_i - V_{i+1} = \frac{P_{i+1} \cdot R_i + Q_{i+1} \cdot X_i}{V_{i+1}} \tag{6}$$

$$\Delta V_{AC}\% = \frac{\Delta V_{AC} \cdot 100}{V_i} \tag{7}$$

where V_i - voltage in the node i of the line

V_{i+1} – voltage in the node i+1 of the line

P_{i+1} – total active power transmitted through the line

Q_{i+1} – total reactive power transmitted through the line

R_i – resistance of the line

X_i – inductance of the line

Equations (6) and (7) determine the voltage drop in volts and in percentage of the voltage at the beginning of the AC line correspondingly (Kaipia et al., 2008). The following equations can be used for the voltage drop calculations in the DC network (Kaipia et al., 2008):

$$\Delta V_{DC+} = V_{1,i} - V_{1,i+1} = \frac{P_{1,i+1}(t) \cdot (R_{1,i} + R_{N,i})}{V_{1,i+1}} - \frac{P_{2,i+1} \cdot R_{N,i}}{V_{2,i+1}} \tag{8}$$

$$\Delta V_{DC+}\% = \frac{\Delta V_{DC+} \cdot 100}{V_{1,i}} \tag{9}$$

$$\Delta V_{DC-} = V_{2,i} - V_{2,i+1} = \frac{P_{2,i+1}(t) \cdot (R_{1,i} + R_{N,i})}{V_{2,i+1}} - \frac{P_{1,i+1} \cdot R_{N,i}}{V_{1,i+1}} \tag{10}$$

$$\Delta V_{DC-}\% = \frac{\Delta V_{DC-} \cdot 100}{V_{2,i}} \tag{11}$$

where $P_{1,i+1}(t)$ – total active power fed through the node *i+1* of the positive pole at the time *t*
$P_{2,i+1}(t)$ – total active power fed through the node *i+1* of the negative pole at the time *t*
$R_{i,1}$ – resistance of the positive pole of the line *i*
$R_{i,2}$ – resistance of the negative pole of the line *i*
$R_{N,i}$ – resistance of the middle pole of the line *i*

Equations (8), (9) determine the voltage drop in the positive pole of the bipolar DC network in volts and in percentage of the voltage at the beginning of the DC line correspondingly. Equations (10), (11) are used for calculation of the voltage drop in the negative pole of the bipolar DC network in volts and in percentage of the voltage at the beginning of the DC line correspondingly. (Kaipia et al., 2008)

Loss costs are also depend on the type of the system. For the AC network the following equation can be used for the calculation of the costs (Lakervi, Holmes, 1998):

$$C_{loss} = \kappa \cdot \left(\left(\frac{P_m}{V_i}\right)^2 \cdot l_m \cdot\right) \cdot (C_{PL} + t_{PL} \cdot C_{EL}) \tag{12}$$

where C_{PL} – cost of power losses
C_{EL} – cost of energy losses
t_{PL} – peak operating time of losses
V_i – voltage in the beginning of the line
κ – capitalization coefficient, obtained from equations (2) and (3)

The peak operating time of losses is estimated from the peak operating time of load as follows (Partanen, 2015):

$$t_{PL} = 0.17 \cdot t_P + \left(0.83 \cdot \frac{{t_P}^2}{8760}\right) \tag{13}$$

where t_P – peak operating time of load, obtained and scaled from the Batakan case.

This formula is based on empirical research and it is made for peak operating time of losses in 3-phase system decades ago for a certain type of customers, thus it is not applicable for precise calculations. However, it can be used for the purposes of these kinds of feasibility studies, as no better understanding is available.

Equation (14) is derived based on equations (8), (9) and can be used for the cost of losses in bipolar DC network.

$$C_{loss} = \kappa \cdot \begin{bmatrix} \Big[\Big(\Big(\Big(\frac{P_{m+}}{V_i}\Big)^2 \cdot l_m \cdot R_{i,1}\Big) \cdot (C_{PL} + t_{PL} \cdot C_{EL})\Big] + \\ \Big[\Big(\Big(\Big(\frac{P_{m-}}{V_i}\Big)^2 \cdot l_m \cdot R_{i,2}\Big) \cdot (C_{PL} + t_{PL} \cdot C_{EL})\Big] + \\ \Big[\Big(\Big(\Big(\frac{P_{m+} - P_{m-}}{\cdot V_i}\Big)^2 \cdot l_m \cdot R_{i,m}\Big) \cdot (C_{PL} + t_{PL} \cdot C_{EL})\Big] \end{bmatrix} \tag{14}$$

where P_{m+} – total active power transmitted through the positive pole
P_{m-} – total active power transmitted through the negative pole
$R_{i,1}$ – resistance of the positive pole of the line *i*
$R_{i,2}$ – resistance of the negative pole of the line *i*
$R_{i,m}$ – resistance of the middle conductor of the line *i*

Transformers

As it was stated earlier, both main and secondary transformer were chosen as a 40 kVA oil-filled waterproofed transformers “ТМГ”, since the total load of the district S_d = 27,83 kVA. Characteristics and prices of “ТМГ” transformers are presented in Appendix B and Appendix C correspondingly. Installation cost is obtained from Regional Unit Prices RUPm-08-2001 and converted in the prices for the eastern regions of Russia in the year 2016.

Cost of the transformer losses comprises of load and no-load losses. Load losses and cost of load losses are calculated in the following manner (Lakervi and Holmes, 1998):

$$P_{LoadT} = P_{lnom} \cdot \left(\frac{S_d}{S_{nom}}\right)^2 \tag{15}$$

$$C_{LoadT} = P_{LoadT} \cdot C_{PL} + P_{LoadT} \cdot t_{PL} \cdot C_{EL} \tag{16}$$

where P_{lnom} – nominal value of the transformer load losses
S_d – apparent power of the district
S_{nom} – nominal power of the transformer
t_{PL} – peak operating time of losses

The present value of the load loss cost is calculated as follows (Lakervi and Partanen, 2015):

$$C_{PLoadT} = \kappa \cdot C_{LoadT} \tag{17}$$

where κ – capitalization coefficient, obtained from equations (2) and (3).

Cost of no-load losses is calculated using the following equation (Lakervi and Holmes, 1998):

$$C_{NoLoadT} = P_{NoLoadNom} \cdot C_{PL} + P_{NoLoadNom} \cdot t_{aT} \cdot C_{EL} \tag{18}$$

where $P_{NoLoadNom}$ – nominal value of the transformer no-load losses
t_{aT} – annual operating time of the transformer

The present value of the load loss cost is calculated as follows (Lakervi and Partanen, 2015):

$$C_{PLoadT} = \kappa \cdot C_{NoLoadT} \tag{19}$$

where κ – capitalization coefficient, obtained from equations (3) and (4).

Power converters

Unfortunately, prices of power electronic converters in Russia are not in the open access. Thus, the average European prices of the converters from 100 to 300 €/kVA (7400 – 22200 rub/kVA, according to the average exchange rate in May) were used. Installation costs of the power converters are included in the price.

Similar to the transformer, costs of both rectifier and inverter losses comprise of load and no-load losses. The following equations are used for calculation of the load loss costs (Kaipia et al., 2008):

$$P_{Load} = S_{nom} \cdot \left(\frac{S}{S_{nom}}\right)^2 \cdot \left(\frac{1}{\eta} - 1\right) \cdot 0.96 \tag{20}$$

$$C_{Load} = P_{Load} \cdot C_{PL} + P_{Load} \cdot t_{PL} \cdot C_{EL} \tag{21}$$

where S_{nom} – nominal power of the rectifier/inverter
S – apparent power of a district/residential house
η – efficiency of rectifier/inverter
t_{PL} – peak operating time of losses

The present value of the load loss cost is calculated as follows:

$$C_{PLoad} = \kappa \cdot C_{Load} \tag{22}$$

where κ – capitalization coefficient, obtained from equations (2) and (3).

Cost of no-load losses is calculated using the following equations (Kaipia et al., 2008):

$$P_{NoLoad} = S_{nom} \cdot \left(\frac{1}{\eta} - 1\right) \cdot 0.04 \tag{23}$$

$$C_{NoLoad} = P_{NoLoad} \cdot C_{PL} + P_{NoLoad} \cdot t_{PL} \cdot C_{EL} \tag{24}$$

where t_a – annual operating time of rectifier/converter.

The present value of the load loss cost is calculated as follows:

$$C_{PLoad} = \kappa \cdot C_{NoLoad} \tag{25}$$

where κ – capitalization coefficient, obtained from equations (3) and (4).

5.4.2. Benefits

The results of the economic feasibility calculations revealed that the implementation of the proposed LVDC microgrid solution in case of the network that supplies 1-3 neighborhoods can be considered beneficial, when compared to the conventional AC system. The calculation results for a single neighborhood case are presented in Figure 26.

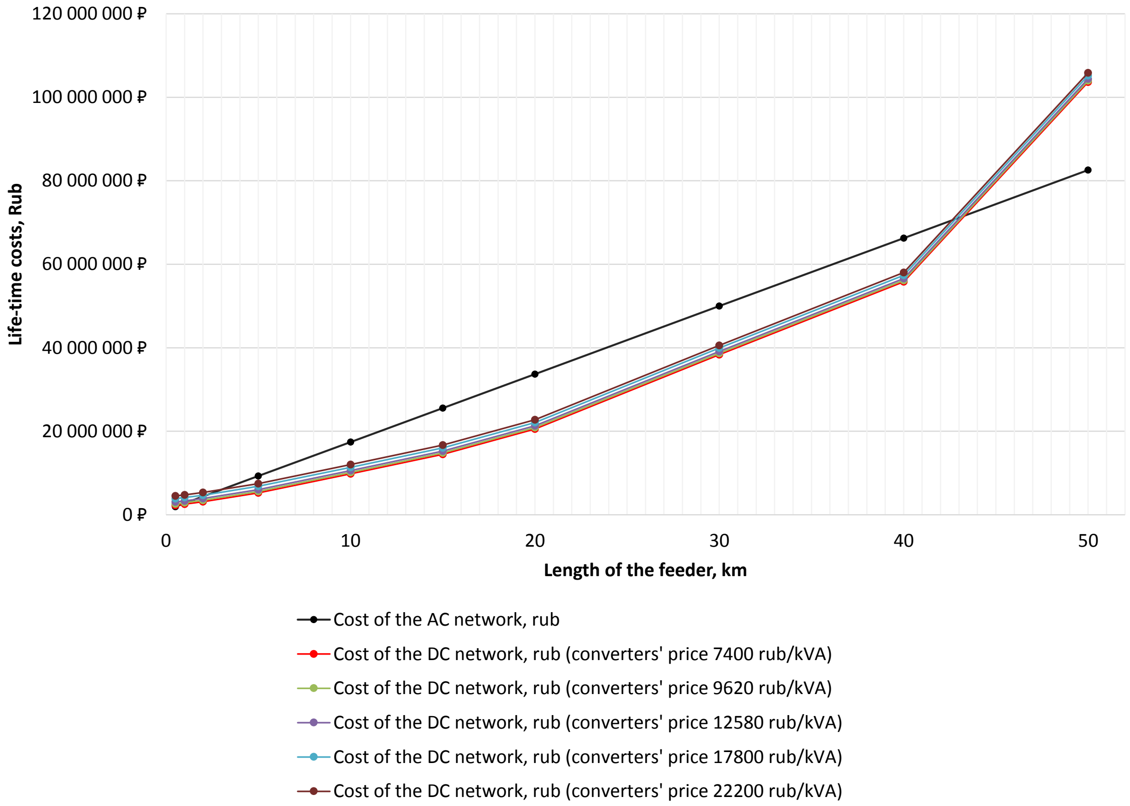

Figure 26. Comparison of the AC and DC solution’s costs over the study period 20a for a single neighborhood with respect to the length of the main feeder and converters’ prices

As it can be seen from Figure 26, the LVDC solution becomes economically feasible on the main feeder lengths’ range from 1 km to about 44 km. The minimum techno-economic length of the main feeder is 1 km with converters’ price 7400 rub/kVA (100 €/kVA) and 3 km with 22200 rub/kVA (300 €/kVA). The maximum techno-economic length of the main feeder is about 44 km with converters’ price 7400 rub/kVA (100 €/kVA) and 43 km with 22200 rub/kVA (300 €/kVA). The maximum economic feasibility of LVDC solution in this case is observed around 15 km.

It has to be noted, that the ability to feed short circuit currents over this extensive length and thus the functionality of any protection system were not examined. Taking this kind of boundary in account would probably limit the line length. However, the LVDC would still remain economical compared to the alternative AC solution.

The next two cases are considering the small settlements of 2-3 similar interconnected neighborhoods. The results of the economic comparison are presented in Figure 27 and Figure 28.

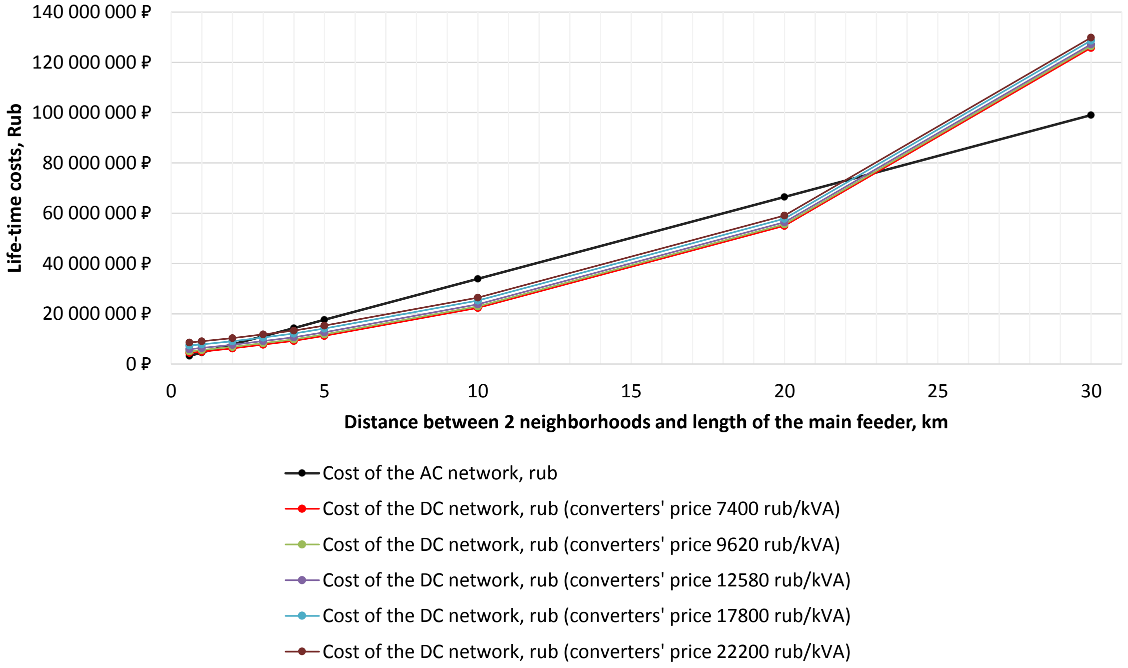

Figure 27. Comparison of the AC and DC solution’s costs for 2 interconnected neighborhoods over the study period - 20a plotted against the distances between them and the main feeder length with respect to the converters’ prices

In the case of two interconnected neighborhoods with the main feeder (Figure 27), the minimum techno-economic length of the lines between neighborhoods and length of the main feeder is about 1.5 km with converters’ price 7400 rub/kVA (100 €/kVA) and 3.5 km with 22200 rub/kVA (300 €/kVA). The maximum techno-economic distance between neighborhoods and length of the main feeder is 23 km with converters’ price 7400 rub/kVA (100 €/kVA) and 22 km with 22200 rub/kVA (300 €/kVA). The maximum economic feasibility of LVDC solution in this case is observed around 10 km.

The benefit of the LVDC solution in this case is still observed. Although, the difference of the DC solution’s costs with respect to the price of converters is greater, it has the same impact on the maximum and minimum techno-economic distances as in the network with a single neighborhood. In the case of three interconnected neighborhoods with the main feeder, as depicted in Figure 28, the converters’ price has a significant impact on the feasibility of the LVDC solution.

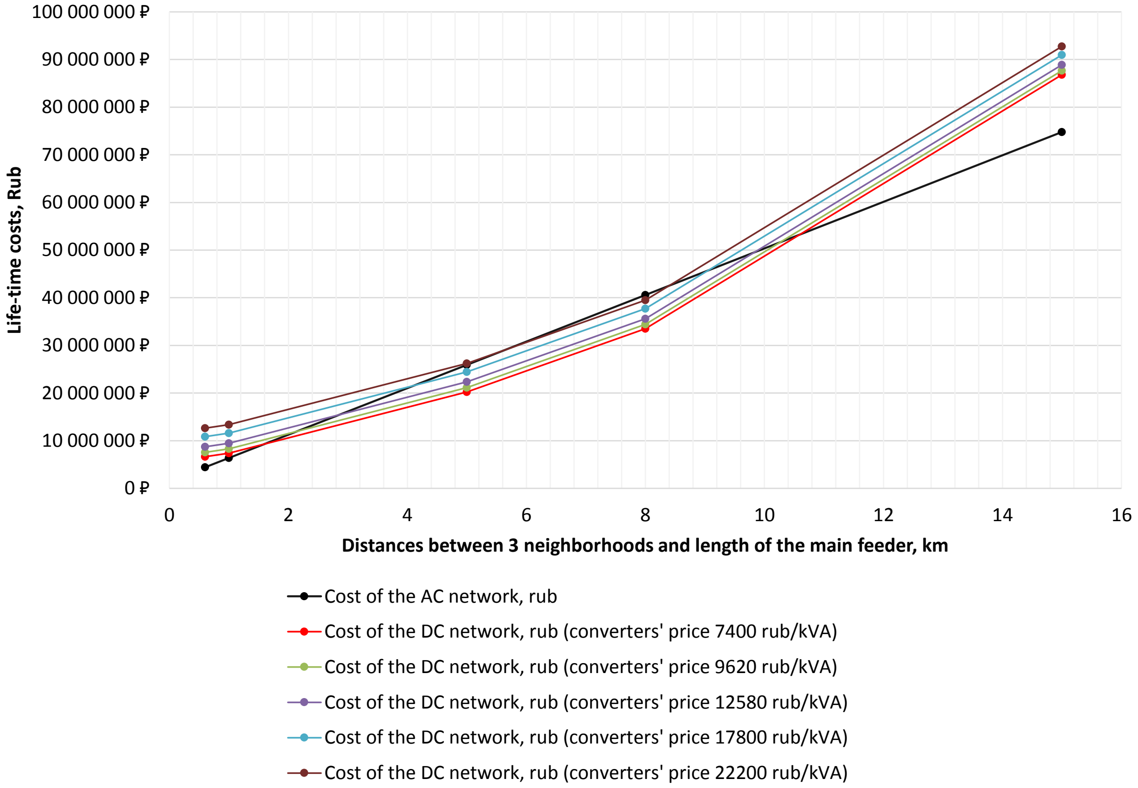

Figure 28. Comparison of the AC and DC solution's costs for 3 interconnected neighborhoods over the study period - 20a plotted against the distances between them and the main feeder length with respect to the converters' prices

With the price 7400 rub/kVA (100 €/kVA) minimum techno-economic distance is 1.6 km, whereas with the price 22200 rub/kVA (300 €/kVA) it is 5 km. The maximum techno-economic distance between neighborhoods and length of the main feeder is about 8.5 km with converters' price 7400 rub/kVA (100 €/kVA) and about 10.5 km with 22200 rub/kVA (300 €/kVA). The maximum economic feasibility of LVDC solution in this case is observed around 8 km.

From the obtained results, it is possible to conclude that the main factor affecting the total cost of the LVDC system in theoretical cases is the price of the power converters. The difference between the total costs of the LVDC solution with respect to the inverters' prices increases with the number of customers. Furthermore, in Russian case, the cost of losses has no such significant impact on the total cost of the system as the inverters' price. Thus, economic feasibility decreases with the scaling up of the settlement.

Since the cost of losses is not as significant in considered conditions, it gives a way to the voltage drop limit, which becomes a determining factor for the selection of cable cross-section. In all examined cases, the voltage drop determined the selection of cables' cross-sections.

The sensitivity analysis needs to be performed in order to analyze the impact of the interest rate. It is a volatile value, thus it is feasible to analyze what impact it has on the total cost of the AC and DC system. The length of the main feeder is fixed – 2 km. The results shows that with the lower interest rate 8% the total cost of the DC solution for the single neighborhood case increases on 6.9-9.5 %, depending on the price of converters. In the AC solution, the impact of the interest rate reduction on the total cost of the system is not as significant (about 1% increase), when compared to the interest value - 13%. The reason for the observed difference is the number of the network components, the costs of which are influenced by the interest rate value: in the LVDC system, each customer has a power inverter, whereas in the AC system only one secondary transformer per one neighborhood is required. Another reason is the time value of losses. Considering higher losses in the LVDC solution compared to AC, it should be mentioned that the total costs are influenced by this value more. The lower the interest rate, the higher is the time value of losses.

The obtained results show that the suitable case for the LVDC technology in considered conditions are small remote settlements with the number of residents under 50. From the perspective of the distribution grid company, it would be economically feasible to implement LVDC solution instead of AC system for electrification (or renovation of the existing network) of remote settlements in the Eastern part of Russia. According to the results, the LVDC distribution technology allows utilization of smaller voltage levels than AC system, providing the same transmission capacity. It is possible due to the allowed in LVDC voltage drop limit < 25%, since the voltage can be boosted by the customer inverters. The most beneficial distances between the power supply source and the last neighborhood are presented in Table 6.

Table 6. The most economically feasible distances with respect to the number of neighborhoods in the network

	Single neighborhood	Two neighborhoods	Three neighborhoods
Most feasible length of the network, km	15	10 x 2 = 20	8 x 3 = 24

It can be seen from Table 6 that the most economically feasible distance between the power supply source and the last neighborhood is increasing with the number of neighborhoods in the network. The more customers/neighborhoods are in the network, the longer the total distance needs to be. Evidently, the LVDC is an economical solution compared to AC when a certain amount of MV line is replaced.

6. SUMMARY AND CONCLUSIONS

Summarizing the performed research, it can be pointed out that the current distribution networks in Russia have strong need for renovation. Furthermore, the existing Unified Energy System of Russia is unable to provide the electric power supply to the significant territory on the East. Thus, there is a need for the efficient and reliable power supply solutions for isolated settlements of the Russian East. According to the undertaken study, the LVDC microgrid can successfully meet these requirements in conditions that were taken into a consideration.

The main objective of the work was to determine whether it is possible to implement the LVDC Microgrid concept in Russia or not. In order to answer this question, the following researches have been carried out:

- Analysis of the Russian electric power industry’s current situation
- Analysis of the Russian electricity market
- Analysis of the Russian electricity distribution business
- Study of the regulatory framework and standardization related to the use of LVDC distribution and microgrids

For the purpose of the economic estimation of the LVDC Microgrid solution in Russian utility distribution, the representative theoretical case was made on the basis of the Batakan settlement and RD № 34.20.178 “Procedural Guidelines for Calculation of Electrical Loads in Agricultural 0.38-110 kV Networks”.

6.1. Key results and main conclusions

According to the performed research and analysis, the implementation of the LVDC microgrids in Russian distribution networks can be considered possible. There are no serious obstacles for the use of the energy storage systems, distributed generation based on RES and LVDC distribution. However, the lack of regulation and standardization related to these technologies is observed.

The isolated settlements in Siberia and the East of Russia are considered as the most suitable use cases at the moment. The maximum techno-economic distance for LVDC distribution from the power source (length of the main feeder) with the load 4 kW per customer and the number of customers 16 was determined as 44 km with converters’ price 7400 rub/kVA (100 €/kVA) and 43 km with 22200 rub/kVA (300 €/kVA). These results can be applied for both the case with local small-scale power plant and the case with connection to the main grid.

From the perspective of an electricity distribution company, it is feasible to implement such technology as the LVDC Microgrid, especially considering the fact, that the System Average Interruption Frequency Index (SAIFI) and Customer Average Interruption Duration Index (CAIDI) will be used for assessment of reliability of the network in foreseeable future. Hence, the outage costs will appear in the total cost of the network.

Another possible driver for the distribution company is that the LVDC microgrid is a cheaper solution for the isolated settlements than the AC network. Considering the fact, that there are 13500 settlements with the number of residents under 50, which is the most suitable use case, it can be concluded that there is a huge potential for the LVDC microgrids on the East of Russia.

6.2. Suggestions for further work

Unfortunately, the time limits of the work made the economic estimation of the LVDC microgrid with the energy storage systems and distributed generators impossible. Thus, further detailed research, which considers distributed energy resources should be carried out. Furthermore, the actual data for a specific case should be considered and more detailed calculations should be made to obtain accurate results.

Since the lack of regulation and standardization is observed, the improvement of current regulatory framework should be done with respect to the implementation of LVDC distribution and microgrids. Although, there is the set of standards, related to the use of RES and LVDC microgrids in rural distribution networks, there are still some unclear moments, such as utilization of energy storage systems in utility distribution.

Another topic for further research is the LVDC microgrid as the electricity market party. Possibility of the sales of electricity, generated by means of distributed generation within the microgrid, on the retail market should be analyzed in more depth, in order to investigate the applicability of the LVDC microgrid solution within the energy systems with centralized electricity distribution.

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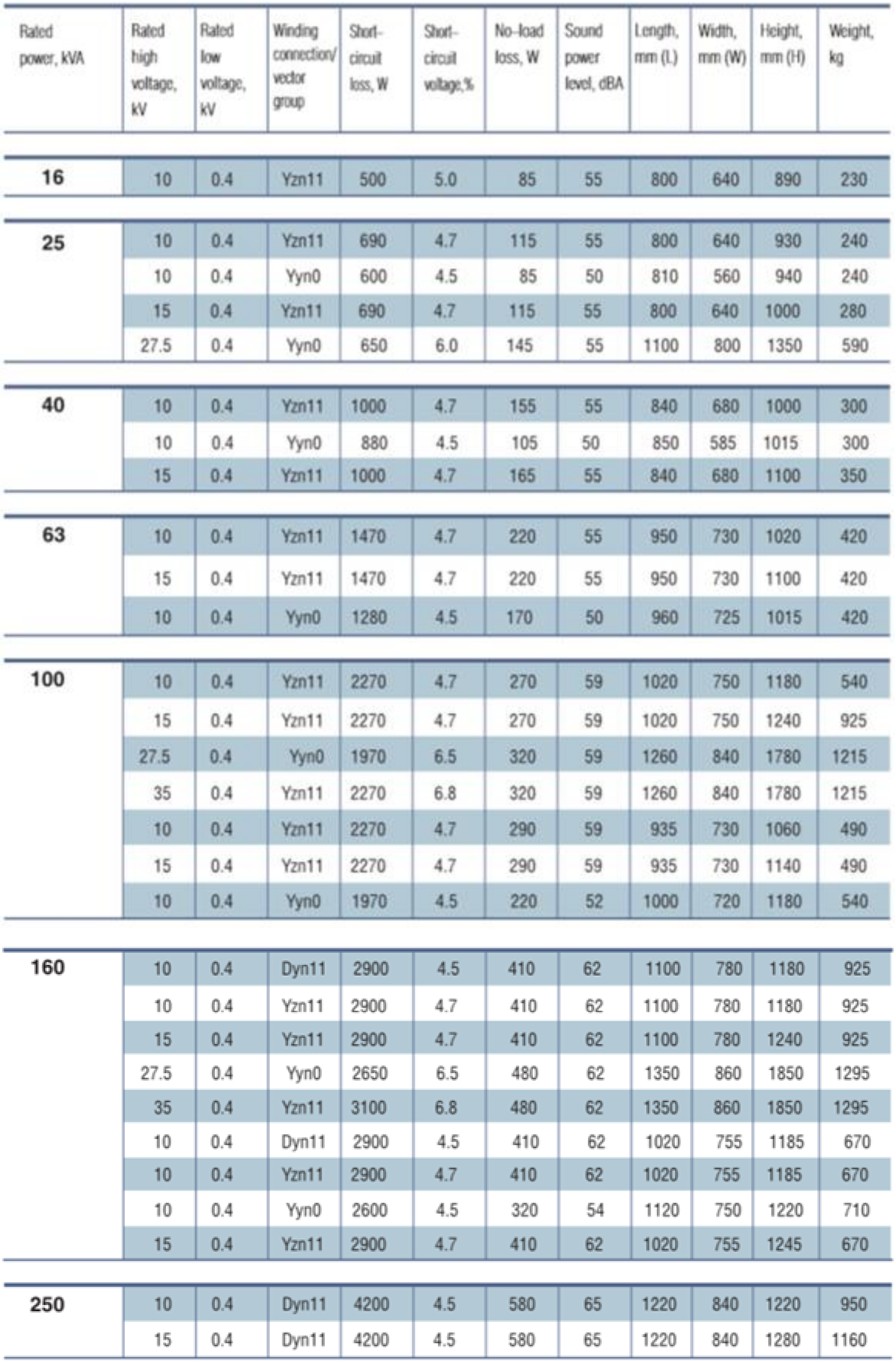
APPENDICES

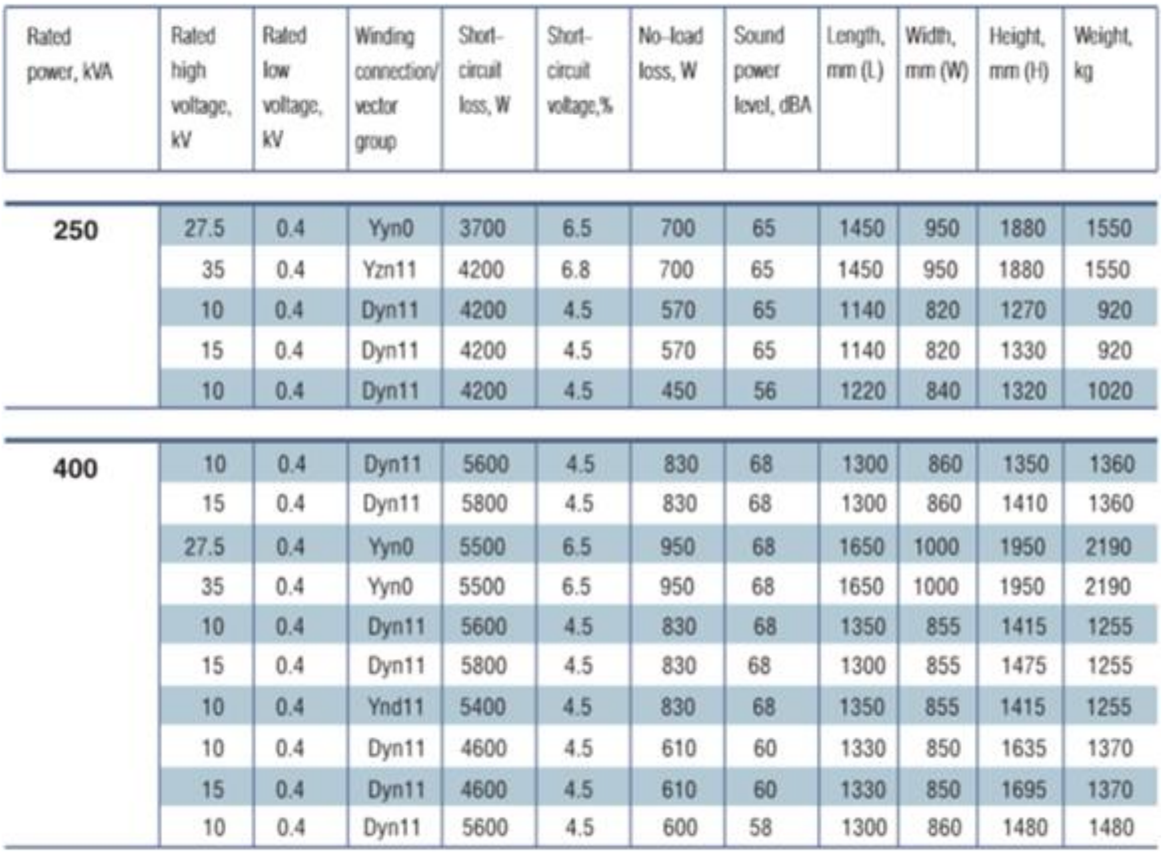
Appendix A (Source: kolchkck.ru)

Overhead line cross-section	Price, rub/km
СИП-2	
3x16+1x25- 0.6/1	46 152
3x16+1x54.6- 0.6/1	64 413
3x25+1x35- 0.6/1	63 119
3x25+1x54.6- 0.6/1	75 859
3x35+1x50- 0.6/1	83 076
3x35+1x54.6- 0.6/1	87 709
3x50+1x70- 0.6/1	114 006
3x50+1x50- 0.6/1	101 128
3x50+1x54.6- 0.6/1	105 819
3x70+1x95- 0.6/1	159 462
3x70+1x70- 0.6/1	142 217
3x70+1x54.6- 0.6/1	134 016
3x95+1x95- 0.6/1	192 512
3x95+1x70- 0.6/1	176 189
3x120+1x95- 0.6/1	222 810
3x150+1x95- 0.6/1	259 935
3x185+1x95- 0.6/1	306 609
3x240+1x95- 0.6/1	376 886
СИП-3	
1x35 -20	27 583
1x50 -20	35 270
1x70 -20	47 373
1x95 -20	64 167
1x120 -20	77 028
1x150 -20	94 117
1x185 -20	112 614
1x240 -20	161 682

Appendix B (Source: eng.metz.by)



Rated power, kVA	Rated high voltage, kV	Rated low voltage, kV	Winding connection/ vector group	Short-circuit loss, W	Short-circuit voltage,%	No-load loss, W	Sound power level, dBA	Length, mm (L)	Width, mm (W)	Height, mm (H)	Weight, kg
16	10	0.4	Yzn11	500	5.0	85	55	800	640	890	230
25	10	0.4	Yzn11	690	4.7	115	55	800	640	930	240
	10	0.4	Yyn0	600	4.5	85	50	810	560	940	240
	15	0.4	Yzn11	690	4.7	115	55	800	640	1000	280
	27.5	0.4	Yyn0	650	6.0	145	55	1100	800	1350	590
40	10	0.4	Yzn11	1000	4.7	155	55	840	680	1000	300
	10	0.4	Yyn0	880	4.5	105	50	850	585	1015	300
	15	0.4	Yzn11	1000	4.7	165	55	840	680	1100	350
63	10	0.4	Yzn11	1470	4.7	220	55	950	730	1020	420
	15	0.4	Yzn11	1470	4.7	220	55	950	730	1100	420
	10	0.4	Yyn0	1280	4.5	170	50	960	725	1015	420
100	10	0.4	Yzn11	2270	4.7	270	59	1020	750	1180	540
	15	0.4	Yzn11	2270	4.7	270	59	1020	750	1240	925
	27.5	0.4	Yyn0	1970	6.5	320	59	1260	840	1780	1215
	35	0.4	Yzn11	2270	6.8	320	59	1260	840	1780	1215
	10	0.4	Yzn11	2270	4.7	290	59	935	730	1060	490
	15	0.4	Yzn11	2270	4.7	290	59	935	730	1140	490
	10	0.4	Yyn0	1970	4.5	220	52	1000	720	1180	540
160	10	0.4	Dyn11	2900	4.5	410	62	1100	780	1180	925
	10	0.4	Yzn11	2900	4.7	410	62	1100	780	1180	925
	15	0.4	Yzn11	2900	4.7	410	62	1100	780	1240	925
	27.5	0.4	Yyn0	2650	6.5	480	62	1350	860	1850	1295
	35	0.4	Yzn11	3100	6.8	480	62	1350	860	1850	1295
	10	0.4	Dyn11	2900	4.5	410	62	1020	755	1185	670
	10	0.4	Yzn11	2900	4.7	410	62	1020	755	1185	670
	10	0.4	Yyn0	2600	4.5	320	54	1120	750	1220	710
	15	0.4	Yzn11	2900	4.7	410	62	1020	755	1245	670
250	10	0.4	Dyn11	4200	4.5	580	65	1220	840	1220	950
	15	0.4	Dyn11	4200	4.5	580	65	1220	840	1280	1160



Rated power, kVA	Rated high voltage, kV	Rated low voltage, kV	Winding connection/ vector group	Short-circuit loss, W	Short-circuit voltage,%	No-load loss, W	Sound power level, dBA	Length, mm (L)	Width, mm (W)	Height, mm (H)	Weight, kg
250	27.5	0.4	Yyn0	3700	6.5	700	65	1450	950	1880	1550
	35	0.4	Yzn11	4200	6.8	700	65	1450	950	1880	1550
	10	0.4	Dyn11	4200	4.5	570	65	1140	820	1270	920
	15	0.4	Dyn11	4200	4.5	570	65	1140	820	1330	920
	10	0.4	Dyn11	4200	4.5	450	56	1220	840	1320	1020
400	10	0.4	Dyn11	5600	4.5	830	68	1300	860	1350	1360
	15	0.4	Dyn11	5800	4.5	830	68	1300	860	1410	1360
	27.5	0.4	Yyn0	5500	6.5	950	68	1650	1000	1950	2190
	35	0.4	Yyn0	5500	6.5	950	68	1650	1000	1950	2190
	10	0.4	Dyn11	5600	4.5	830	68	1350	855	1415	1255
	15	0.4	Dyn11	5800	4.5	830	68	1300	855	1475	1255
	10	0.4	Ynd11	5400	4.5	830	68	1350	855	1415	1255
	10	0.4	Dyn11	4600	4.5	610	60	1330	850	1635	1370
	15	0.4	Dyn11	4600	4.5	610	60	1330	850	1695	1370
	10	0.4	Dyn11	5600	4.5	600	58	1300	860	1480	1480

Appendix C (Source: enetra.ru)

Type and rated power of the transformer	Price, rub
ТМГ-16/10	61 050
ТМГ-25/10	67 950
ТМГ-40/10	76 950
ТМГ-63/10	90 550
ТМГ11-100/10	109 700
ТМГ11-160/10	134 400
ТМГ11-250/10	180 750
ТМГ11-400/10	228 850