Prospective Options for the Republic of Moldova Power System Transport Network Development in Conditions of Parallel Operation with ENTSO - E

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Abstract. The work objective is to determine the optimal topology and strategic development directions for interstate and power system transport networks capable of ensuring electricity supply diversification, increasing the country's energy security, and successfully integrating it into the European electricity market. This goal is achieved through the following tasks: developing promising scenarios and creating corresponding computational models, using these models to calculate normal and enhanced modes, and analyzing operational parameters to assess the technical efficiency of the proposed options. A comparative analysis was carried out by modeling several alternative development scenarios, including the modernization of existing ones, as well as the construction of new 330 and 400 kV transmission lines, followed by an assessment of the technical efficiency of the proposed solutions. The most important result is the identification of promising scenarios for the Moldova energy system development, which, under current conditions, can ensure not only the fulfillment of ENTSO - E (European Network of Transmission System Operators for Electricity), but also minimize electricity losses and increase the safety factors for static stability. The options considered can lead to a reduced probability of system failures, greater flexibility in changing the power balance, and, consequently, increased reliability of energy supply. The significance of the obtained results lies in their potential to provide a basis for optimizing decision-making regarding the long-term development of Moldova's energy sector. The study's findings can also be used for capital investment planning and the development of long-term development programs in the energy sector, enabling the national energy system to function effectively within the European energy interconnection, promoting sustainable development and increasing energy independence.

Keywords**:** power transmission line, intersystem connections, energy exchange, normal mode, static stability, power losses.

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Opțiuni avantajoase de dezvoltare a rețelelor de sistem ale sistemului electroenergetic al Republicii Moldova în contextul funcționării paralele cu ENTSO-E

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***Rezumat*.** Obiectivul studiului este de a determina topologia optimă și direcțiile strategice de dezvoltare pentru rețelele interstatale și celor de sistem capabile să asigure diversificarea aprovizionării cu energie electrică, creșterea securității energetice a țării și integrarea cu succes pe piața europeană de energie electrică. Acest obiectiv este atins prin rezolvarea următoarelor probleme: dezvoltarea de scenarii promițătoare și crearea de modele computaționale corespunzătoare, efectuarea de calcule pentru regimurile normale și severe pe baza acestor modele și analiza parametrilor de performanță pentru a evalua eficiența tehnică a opțiunilor propuse. Studiul a inclus un program de experimente computaționale, determinarea caracteristicilor de performanță ale opțiunilor de dezvoltare a rețelei și evaluarea rezervelor de stabilitate statică. O analiză comparativă a fost efectuată prin modelarea mai multor scenarii alternative de dezvoltare, inclusiv modernizarea liniilor electrice existente și construirea unora noi cu tensiuni de 330 și 400 kV, urmată de o evaluare a eficacității tehnice a soluțiilor propuse. Cel mai important rezultat este identificarea unor scenarii promițătoare de dezvoltare pentru Sistemul Energetic Republican care, în condițiile actuale, pot nu numai să asigure respectarea cerințelor tehnice ENTSO-E (Rețeaua Europeană a Operatorilor de

Sistem de Transport pentru Energie Electrică), dar şi să minimizeze pierderile de energie şi să crească factorii de siguranţă la stabilitate statică. Opțiunile luate în considerare pot duce la o probabilitate redusă de defecțiuni ale sistemului, la o flexibilitate mai mare în modificarea bilanțului energetic și, în consecință, la o fiabilitate sporită a alimentării cu energie. Semnificația rezultatelor obținute constă în potențialul lor de a oferi o bază pentru optimizarea luării deciziilor privind dezvoltarea pe termen lung a sectorului energetic al Republicii Moldova. Rezultatele studiului pot fi utilizate și pentru planificarea investițiilor de capital și dezvoltarea de programe de dezvoltare pe termen lung în sectorul energetic, permițând astfel Sistemului Energetic Republican să funcționeze eficient în cadrul sistemului energetic european, promovând dezvoltarea durabilă și crescând independența energetică.
Cuvinte-cheie**:** linie de transport a energiei electrice, conexiuni intersistemice, schimb de energie, mod normal, stabilitate statică, pierderi de putere.

Перспективные варианты развития системообразующих сетей энергосистемы Республики Молдова при параллельной работе с ENTSO-E

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Аннотация. Цель работы заключается в определении оптимальной топологии и стратегических направлений развития межгосударственных и системообразующих сетей, способных обеспечить диверсификацию электроснабжения, повышение энергетической безопасности страны и успешную интеграцию в европейский рынок электроэнергии. Поставленная цель достигается посредством решения следующих задач: формированием перспективных сценариев и созданием соответствующих расчетных моделей, проведением на их основе расчетов нормальных и утяжеленных режимов, а также анализом режимных параметров позволяющих оценить техническую эффективность предлагаемых вариантов.
В ходе исследования была выполнена программа расчетных экспериментов и определены режимные характеристики вариантов развития сетей, а также оценены запасы статической устойчивости. Сравнительный анализ осуществлялся путем моделирования нескольких альтернативных сценариев развития, включающих модернизацию существующих, а также строительство новых линий электропередачи на напряжение 330 и 400кВ, с последующей оценкой технической эффективности предлагаемых решений. Наиболее важным результатом является определение перспективных сценариев развития Республиканской энергосистемы, которые в современных условиях могут обеспечить не только выполнение технических требований ENTSO-E (European Network of Transmission System Operators For Electricity), но и минимизацию потерь электроэнергии, а также позволят увеличить значения коэффициентов запаса по статической устойчивости. Рассмотренные варианты могут привести к снижению вероятности системных аварий, большей гибкости при изменении баланса мощности и, следовательно, повышению надежности энергоснабжения. Значимость полученных результатов состоит в том, что они могут представлять основу для оптимизации принятия решений в области перспективного развития энергетического сектора Молдовы. Результаты исследования также могут быть использованы для планирования капиталовложений, разработки долгосрочных программ развития в энергетической сфере, что позволит республиканской энергосистеме эффективно функционировать в составе европейского энергообъединения, способствуя устойчивому развитию и повышению энергетической независимости.
Ключевые слова**:** линия электропередачи, межсистемная связь, энергообмен, нормальный режим, статическая устойчивость, потери мощности.

INTRODUCTION

The general desire to interconnect power systems stems from the significant advantages of large systems over energy pools consisting of individual power plants and consumers connected to them. Power systems located in different economic regions within the ENTSO-E are linked by high-voltage intersystem transmission lines [1–4]. Interconnecting power systems enables the exchange of power and offers the following advantages:

- reduce the total installed capacity of power plants due to longitudinal and latitudinal effects;
- more fully utilize energy resources through optimal coverage of the load schedule;
- increase the efficiency of electricity generation;
- increase the unit capacity of units with better technical and economic indicators.
- increase the reliability of power supply to consumers through redundancy;

- increase maneuverability in energy systems and provide mutual assistance in case of accidents and scheduled repairs;
- relieve the load on main power transmission lines and reduce electricity losses during transmission;
- optimize the number of repair personnel.

The disadvantages of integrated systems include more complex relay protection, automation, and mode control.

The development of cross-border relations is given great attention in the energy programs of both Moldova and its immediate neighbors – Romania and Ukraine [5–7].

Currently, much attention is being paid to issues related to cross-border electricity trade and increasing the reliability of integrated energy systems [8-13]. The consolidation of energy systems allows for the joint use of large volumes of electricity produced from renewable sources, i.e., it can reduce the impact of instability in renewable energy sources through the import and export of electricity between neighboring regions [14-15].

ENTSO - E interconnections operate under rules that help regulate operators and determine how electricity is provided to consumers across the EU. As electricity supplies across the EU become increasingly interconnected, pan-European rules enable efficient management of electricity flows. These rules, known as network codes or guidelines, are legally binding implementing regulations of the European Commission. They govern all cross-border transactions in the electricity market and the operation of systems, along with the Regulation on Network Access Conditions for Cross-Border Electricity Exchanges [16–18]. Since the Republican Power System is connected to ENTSO - E, future developments of cross-border networks must take into account the current regulations.

Energy security in the Republic of Moldova has been one of the most pressing issues facing the country for decades. The electricity supply system has historically been highly dependent on a limited number of external sources, leading to structural problems in terms of reliability and diversification of supplies. In recent years, this challenge has become critical due to the deteriorating geopolitical situation, necessitating the immediate development and implementation of promising scenarios for the development of high-voltage interconnections.

Currently, the state of the Moldova energy system can be characterized as follows:

- Generating sources: the possible abandonment of in-house generating sources will lead to a significant reduction in the reliability of electricity supply to consumers, a sharp increase in active power losses in the networks, and the need to resolve issues with the voltage regime.
- Network infrastructure: for successful integration into ENTSO-E and to meet internal needs, it is necessary to determine the optimal topology and strategic directions for the development of interstate and system-forming networks [19].

The military conflict in Ukraine has sharply exacerbated all the challenges facing the republic's energy system, transforming them from strategic to operational:

- Threat to transit and supplies: Ongoing attacks on Ukraine's energy infrastructure are destroying a significant portion of its generating capacity, impacting regional energy exchanges, and jeopardizing the security of supply, including to Moldova.
- Regional Synchronization: The crisis and military action have made synchronization with ENTSO-E an urgent necessity. Energy cooperation is an important factor in strengthening the energy security of Ukraine and Moldova within the pan-European energy space.
- Investment climate: Proximity to a conflict-affected area negatively impacts investment in the energy sector, making it difficult to implement long-term modernization and construction projects.

In the development of cross-border connections, considerable attention is paid to issues of stability analysis [20–24], as well as the reduction of power losses [25–35].

Thus, the task of determining the optimal topology and strategic directions for the development of interstate and system-forming networks capable of ensuring the diversification of electricity supply, increasing the country's energy security, and successful integration into the European electricity market is significant and relevant.

CHARACTERISTICS OF THE CURRENT STATE OF THE MOLDOVA ENERGY SYSTEM

Currently, the state of Moldova's transport networks is characterized by the following features:

- The low reliability of single-circuit transit between the Straseni 330 kV substation and the Balti 330 kV substation, as well as the N.Dnestrovskaya 330 kV substation in the northern part of the republic, significantly complicates the execution of various switching operations during repairs, etc.;

- not entirely satisfactory reliability of the Vulcanesti 400 kV junction in the southern part of the country;
- impossibility of guaranteed flow exchange between the Ukrainian and Moldovan power systems in the sections of the Podolskaya 330 kV substation – the Rybnitsa 330 kV substation;
- The existing topology of the system network does not allow for full access to the European electricity market.

The geographical position of the republic, with the increasing transit importance of its transport networks, suggests the implementation of various scenarios and solutions to the issues that arise in this regard.

The main characteristics of the baseline mode are given in Table 1.

Table 1

Main characteristics of the baseline mode.

	Moldova	Romania	Ukraine	Another network
P_{gen}, MW	112 7	1026 7	3241 8	78 183
Q_{gen}, Mvar	5 20	230 5	12459	30476
P_{load}, MW	1151	941 6	30502	7776 9
Q_{load}, Mvar	434	3449	10046	32591
ΔP, MW	44.31	2 98	91 1	19 02
ΔQ, Mvar	- 70	-868	4126	-3949
P_{ext}, MW	- 69	5 52	1004	-14 88
Q_{ext}, Mvar	155	-276	-1713	1834

When modeling promising cross-border grid development options, a database derived from an analysis of forecasts for 2015–2025 was used as a basis. The database contains information on the power systems of Romania, Moldova, Ukraine, and the Black Sea basin countries. All simulation experiments were conducted using the maximum winter conditions, which were adopted as the baseline and used to construct experimental simulation models.

The components of active power losses in the baseline mode for Moldova as a whole, as well as by voltage classes, are given in Table 2.

Table 2

Components active losses power

U n	$\Delta P_{load} = \Delta P$, MW	ΔP_{ol}, MW	ΔP_{tr}, MW	ΔP_{id}, MW
Moldova	40.87	37.26	3.61	3.44
400kV	3.92	3.75	0.18	0.75
330kV	12.5	11.59	0.91	2.27
110kV	21.97	21.93	0.04	0.42

PROMISING OPTIONS FOR DEVELOPING CROSS-BORDER CONNECTIONS WITH ENTSO - E

For comparative analysis, 7 scenarios for the development of intersystem and system-forming connections of the Moldovan energy system were proposed:

1. Construction and commissioning of 400 kV lines from Vulcanesti 400 kV substation to Chisinau 330 kV substation and Balti 330 kV substation to Suceava 400 kV substation.
2. Construction and commissioning of the 400 kV lines Vulcanesti 400 kV – Chisinau 330 kV and Balti 330 kV – Suceava and the second circuit of the 300 kV line Chisinau 330 kV – Straseni 330 kV – Balti 330 kV – N.Dnestrovskaya 330 kV.
3. Construction and commissioning of 400 kV lines Vulcanesti substation - Chisinau substation 330 kV and Balti substation 330 kV - Suceava 400 kV, Straseni substation 330 kV - Gutinash.
4. Construction and commissioning of 400 kV lines Vulcanesti substation - Chisinau substation 330 kV and Balti substation 330 kV - Suceava 400 kV. Disconnection of 330 kV lines Rybnitsa substation 330 kV - Podolskaya substation 330 kV.
5. Construction and commissioning of 400 kV lines from Vulcanesti 400 kV to Chisinau 330 kV and Balti 330 kV to Suceava 400 kV, Straseni 330 kV to Gutinas 400 kV. Disconnection of 330 kV lines from Rybnitsa 330 kV to Podolskaya 330 kV.
6. Construction and commissioning of 400 kV lines Vulcanesti 400 kV – Chisinau 330 kV line and Balti 330 kV line – Suceava 400 kV line. The second circuit of the 300 kV line Chisinau 330 kV – Straseni 330 kV line – Balti 330 kV line – N.Dnestrovska 330 kV line. Two parallel 330 kV lines Balti 330 kV – Rybnitsa 330 kV line.

6* Implementation of option #6 with the shutdown of two 330 kV lines: Rybnitsa 330 kV substation – Podolskaya 330 kV substation.

7. Construction and commissioning of 400 kV lines Vulcanesti 400 kV substation – Chisinau 330 kV substation, Balti 330 kV substation – Suceava substation, Straseni 330 kV substation – Gutinash 400 kV substation. The second circuit of

the 300 kV line Chisinau 330 kV substation - Straseni 330 kV substation – Balti 330 kV – N.Dnestrovskaya 330 kV substation. Two parallel 330 kV lines Balti 330 kV substation – Rybnitsa 330 kV substation.

7 * Implementation of option No. 7 with the disconnection of two circuits of the 330 kV lines Rybnitsa substation 330 kV – Podolskaya substation 330 kV, and the line Beltsy substation 330 kV – N. Dnestrovskaya substation 330 kV.

The power transmission lines included in the above scenarios are shown as dotted lines in the diagram Fig. 1.

Fig. 1. Scheme of development of cross-border connection with ENTSO - E.

The static stability of the power system was assessed by analyzing the values of the safety factors for active power and voltage in the modes under consideration and compared with the minimum permissible standard indicators $K_{P\min}$ and $K_{U\min}$ (see Table 3).

Table 3

Standard safety factors for static stability

Regime	$K_{P\min}$	$K_{U\min}$
Normal	≥0.2	≥0.15
Hard	≥0.08	≥0.10

The safety factor for static stability by voltage K_U was determined for the node with the lowest voltage in normal mode using the formula:

$$K_U = \frac{U - U_{kr}}{U_{kr}}, \text{ where}$$

U – node voltage in the analyzed mode;

U_{kr} – the critical voltage at the same node.

The critical voltage at a load node corresponds to the static stability limit of the electric motor load and is usually determined based on actual data on its permissible operating conditions. In the absence of this information, the value U_{kr} at the load nodes was assumed to be the greater of two values: $U_{kr} = 0,7 \cdot U_{nom}$, or $U_{kr} = 0,75 \cdot U_{norm}$, where

U_{nom} – nominal voltage of the electrical network;

U_{norm} – voltage at the considered load node in normal mode.

To control compliance with the standard static stability reserves for voltage, their permissible values in the controlled nodes were established by calculations of the power system modes.

The safety factor for static (aperiodic) stability for active power in the cross-section K_P was calculated according to the expression:

$$K_P = \frac{P_{extr} - \left(P + \Delta P_{if}\right)}{P_{extr}}, \text{ where}$$

P_{extr} – the maximum static aperiodic stability flow of active power in the controlled section, MW;

P – active power flow in the controlled section in the considered mode, MW;

ΔP_{if} – amplitude of irregular oscillations of active power in the controlled section, MW.

The amplitude magnitude of the active power irregular oscillations in a controlled section, including a set of elements of one or more electrical connections, the simultaneous disconnection of which leads to the power system separation into two isolated operating parts, was calculated using the formula:

$$\Delta P_{if} = K\sqrt{\frac{P_{L1} \cdot P_{L2}}{P_{L1} + P_{L2}}}, \text{ where}$$

P_{L1}, P_{L2} – total load power from each side of the section under consideration, MW;

K – a coefficient characterizing the method of regulating the active power flow in the controlled section $\left(\sqrt{MW}\right)$.

The value of the coefficient K was taken to be equal to: 1.5 - for operational regulation of the active power flow in the controlled section; 0.75 - for automatic regulation or limitation of the active power flow in the controlled section.

To determine the static stability safety factors for the Moldova power system, a cross-section was selected, i.e., a set of cross-border connections whose disconnection would lead to complete separation of the power system from adjacent ones (see Fig. 2). The safety factors were determined for limiting modes obtained by weighting the initial normal ones using a stepwise increase in load at network nodes by 100+ j 20 MVA.

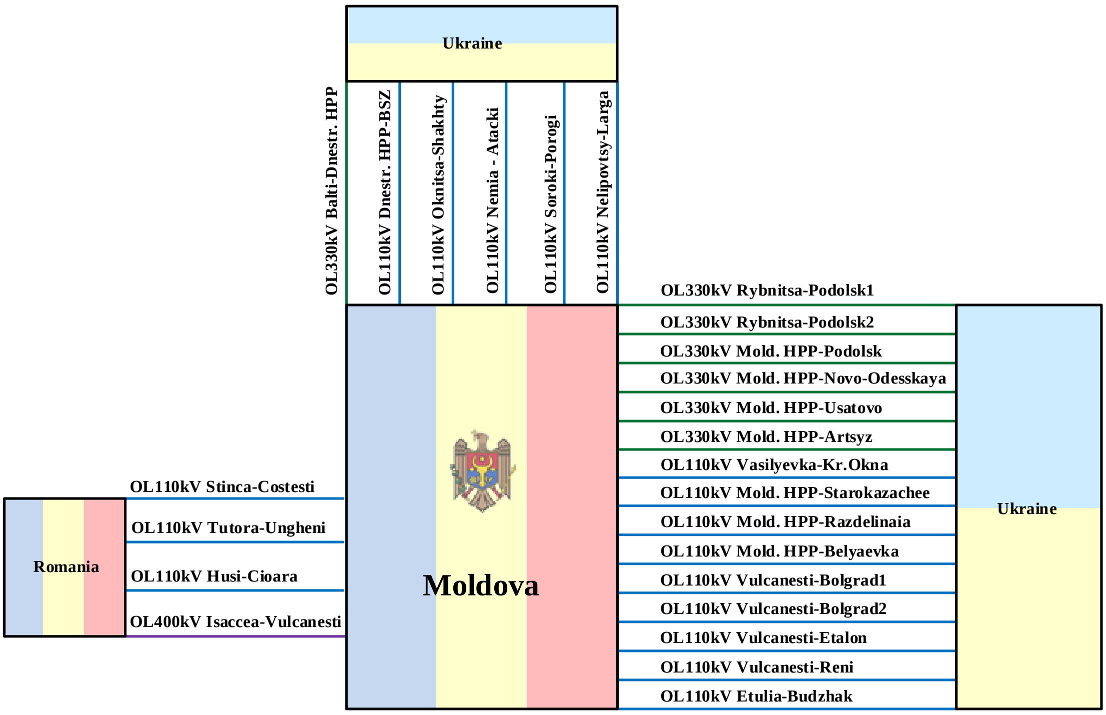

Fig. 2. List of cross-border relations of the Republic of Moldova.

COMPARATIVE ANALYSIS OF THE OBTAINED RESULTS

The modeling results were analyzed using a specific set of parameters: the level of active power losses in the Moldova power system both overall and by voltage level, the level of active power imports in extreme conditions, and the static stability factors for active power and voltage. Comparisons were made both relative to the baseline and between the proposed development scenarios.

For clarity, the analyzed parameters are presented in histograms. Thus, the active power loss levels in the Moldova power system under normal and extreme conditions are shown in Fig. 3.

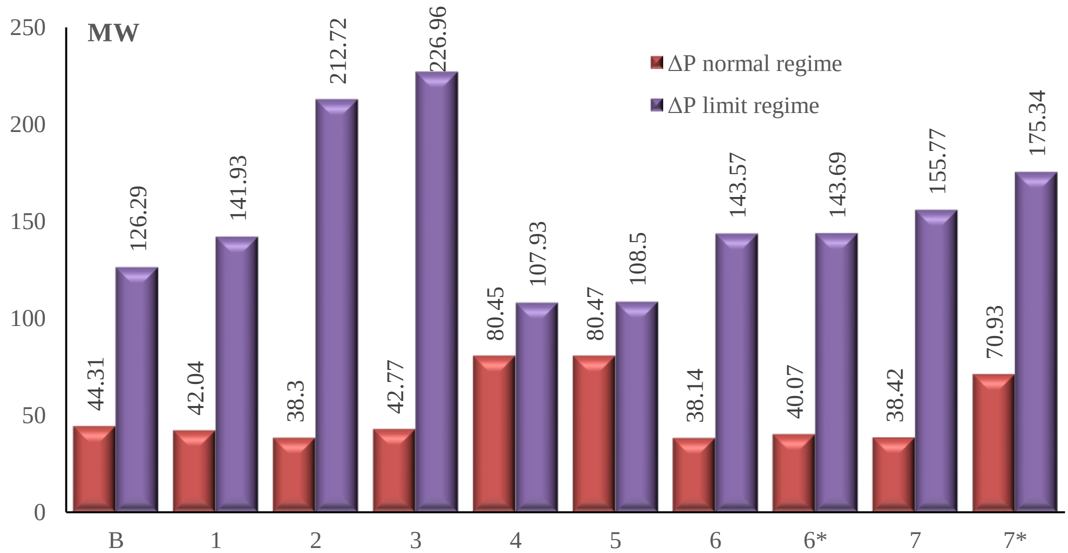

Fig.3 . Active power losses in the power system.

Analyzing the information presented in Fig. 3, it is evident that all options 1, 2, 3, 6, 6*, 7 provide a reduction in normal mode in the range of 1.54 ÷ 6.17 MW or 3.5 ÷ 13.9% relative to the baseline, respectively. It should be noted that in options 4, 5, 7*, losses in normal mode are higher than in the baseline and vary in the range of 26.6 ÷ 36.16 MW. In percentage terms, the increase in active power losses will be in the range of 60.1 ÷ 80% of the baseline.

When comparing losses in limiting modes, an opposite trend is observed, due to the higher throughput capacity of the calculated sections (Fig. 4) and the increase in the number of introduced cross-border connections.

The nature of the distribution of active power losses in networks of different voltage classes in normal modes is shown in Fig. 5.

Fig. 5 shows that all the considered options provide a reduction in active power losses in 400 kV networks. Losses in 330 kV networks are reduced for options 2, 6, 7, and 7* by a percentage in the range of 10–32%, while for options 1, 3, 4, 5, and 6*, losses increase in the range of 1.2–34%. The highest active power losses are localized in the 110 kV network. This is especially noticeable in scenarios 4, 5, and 7, with the loss of 330 kV cross-border connections.

As the results of calculation experiments have shown, the degree of 110 kV network losses is quite significant.

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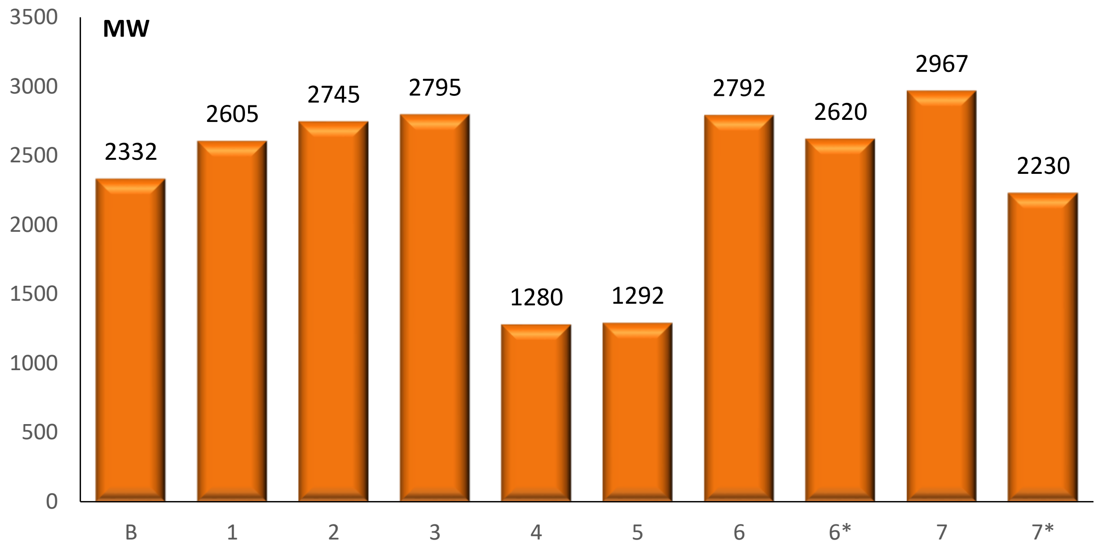

Fig.4. Capacity of cross-border lines.

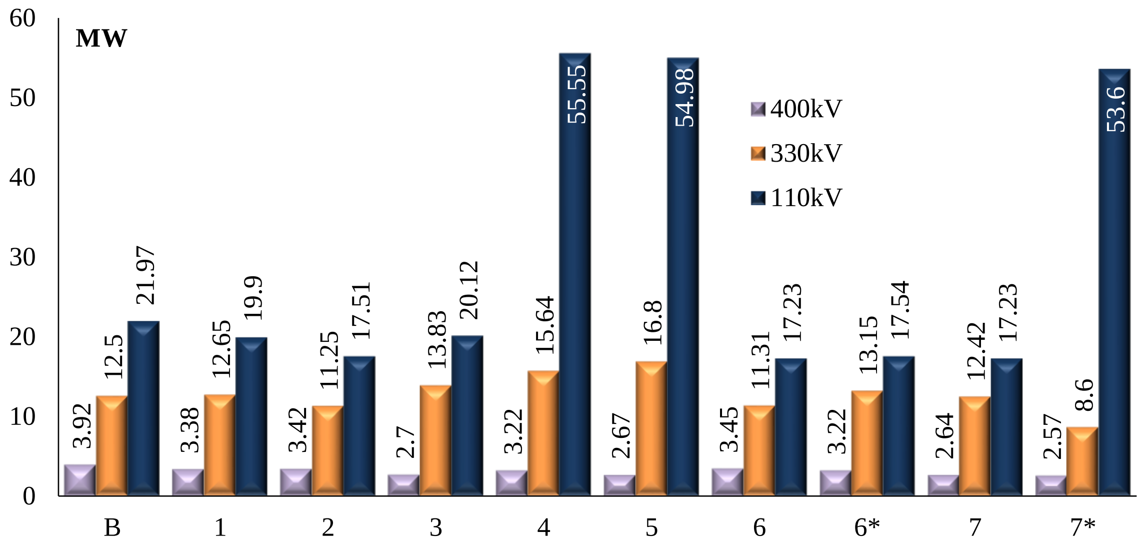

Fig.5. Losses in the power system in normal regime.

Histograms of the distribution of active power losses in networks of different voltage classes in the limiting static stability modes are shown in Fig. 6. It is evident that, compared to normal modes, active power losses in all voltage classes increase significantly due to the increase in the throughput of the equivalent cross-section.

The maximum level of active power losses, as in normal modes, is concentrated in the 110 kV network.

Fig. 7 shows information on the static stability safety factors for active power and voltage for various cross-border grid development scenarios, as well as information on the standard values (shown as straight lines). The top line indicates the standard value of the active power safety factor, and the bottom line indicates the standard value of the voltage safety factor.

Analyzing the diagram Fig. 7, the following conclusions can be drawn:

- The static stability reserve factor for active power for all considered options is higher than the standard indicators;
- factor for static stability in voltage for the options under consideration is around 25% with a standard of 15% in all cases under consideration, except for options 4.5.

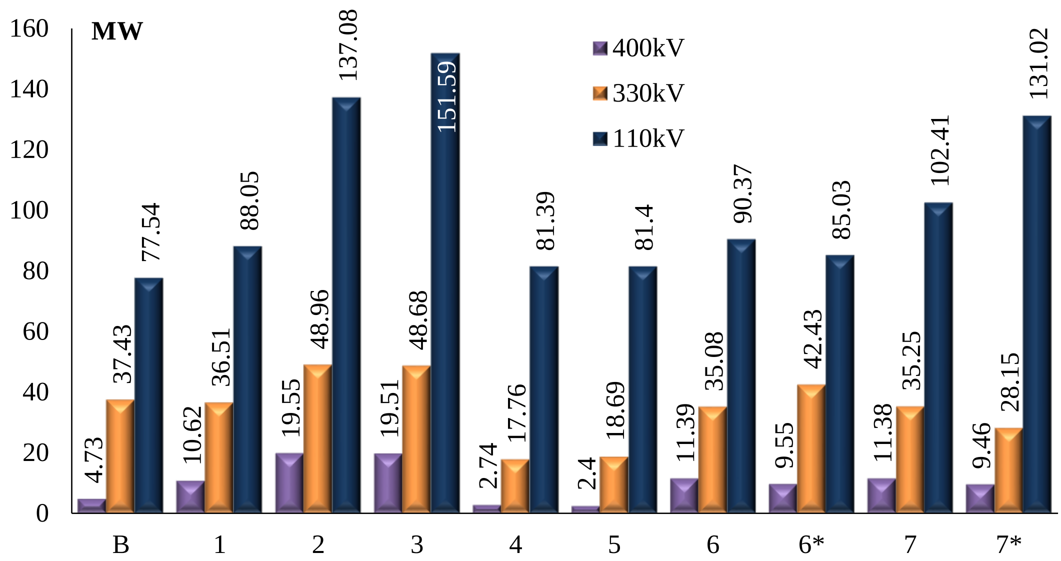

Fig.6 . Losses in the power system in limit regime.

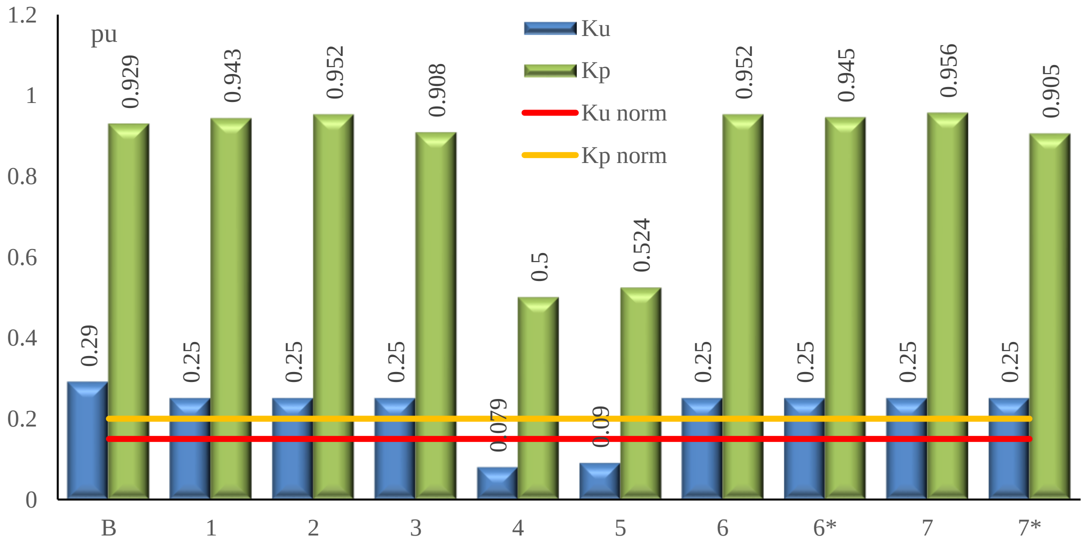

Fig.7 . Static stability safety factors .

Summarizing the obtained data, the following provisions can be formulated:

- For the first stage of the energy system modernization, it is advisable to consider scenario 1. It is the least capital- and resource-intensive and allows for the unification of energy systems and entry into a new market;
- Scenario 6 is recommended to be considered as the main vector for the development of the energy system. It covers all areas of development, including both integration with ENTSO - E and strengthening of the energy system.
- Scenarios 4 and 5 lack sufficient reliability, as disconnecting the Rybnitsa-Podolsk lines results in a sharp reduction in the capacity of the external cross-section and, consequently, in the safety factors. Any emergency on these lines causes an imbalance in the entire system.
- Options 6 and 7 make it possible to fully compensate for possible outages of intersystem high-voltage connections with Ukraine in the northern part of the republic;
- In Scenario 3, the transmission capacity, net of losses, increased by only 20 MW. In Scenario 7,

it increased by 150 MW due to the increased 330 kV transit through the Republic of Moldova.

- From a technical point of view, the capacity of cross-border connections of the Republic of Moldova can be increased by ±400 MW.

CONCLUSIONS

As a result of this work, a comparative analysis of the technical effectiveness of the proposed options for developing cross-border connections in the Moldova energy system was conducted. Based on these results, conclusions were drawn regarding the acceptability of using certain options in the long-term development planning of the republic's backbone electrical connections.

The completed research can be used to formulate the key principles for the strategic development of Moldova's high-voltage transmission grids. A comparative analysis of alternative development scenarios (including the modernization of existing and the construction of new 330 and 400 kV transmission lines) will identify those that minimize losses, increase static stability reserves, and, consequently, maximize power supply reliability in the new regional reality. The results obtained can serve as a basis for optimizing decision-making in the strategic development of Moldova's energy sector.

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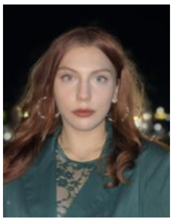

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