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PHYSICAL AND TECHNICAL ENERGY PROBLEMS

INFRASTRUCTURE OF BALTIC REGION TRANSMISSION SYSTEM: ANALYSIS OF TECHNICAL AND ECONOMIC FACTORS OF ITS DEVELOPMENT

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The operational conditions of new networks dictate new requirements for the transmission planning, which would include the electricity market figures and a sizable involvement of renewable generation. This paper focuses on the transmission expansion planning techniques based on the calculations of optimal power flows and on the concept of development planning and sustainability. A description is given for the mathematical model of calculations and analysis of transmission system. The results have shown that the Baltic transmission system infrastructure can successfully be analyzed based on the proposed methodology and developed mathematical model.

Keywords: *electricity market, optimal power flow, power system (PS), PS development.*

1. INTRODUCTION

Power systems (PSs) of the Baltic States (Latvia, Lithuania and Estonia) are closely related historically, and their operation is impossible without mutual cooperation in the development and operational modes. Implementation of economic relations in the energy sector has accelerated the development of the energy market. Nowadays, the energy policy of these states is an integral part of the EU's energy strategy, identifying three main objectives: competitiveness of the energy sector, its sustainable development, and security of supply. In all the three Baltic PSs a considerable volume of work has been carried out on the modernization of equipment and harmonization of standards in compliance with the EU requirements as well as on the introduction of market relations and new technologies that are meant to ensure the energy security and availability of electricity to consumers.

Nevertheless, taking into account the rapidly changing external conditions, especially geopolitical factors, the energy policy of Lithuania, Latvia and Estonia is to be revised in order to determine the influence of these factors on the sustainable development of the energy system as a whole. This means that a new international energy strategy is needed for strengthening the sustainable development of effective economic and social bases of the national economies.

The aim of this work was to analyze the infrastructure of the Baltic transmission systems based on the developed mathematical model, taking into account the interests of each of the Baltic countries in the field of energy policy.

2. BACKGROUND FOR THE MODEL OF BALTIC STATES' POWER SYSTEM

Based on the new energy policy and the policy for environment conservation the European Union developed a political and economic programme whose main goals are: sustainable development, competitiveness, and security of supply. To realize these goals, the EU has committed to the "20-20-20" initiative: reducing greenhouse gas emissions, increasing the share of renewables (RES) and improving the energy efficiency by 20%. With adoption of the 20-20-20 package, the EU poised to take the key next steps towards a more sustainable, more secure, more technology-based energy policy for creation of wealth and jobs [1].

A distinctive feature of electrical networks is their continuous development associated with increasing load, implementation of measures for improving the reliability of electricity supply and the formation of Unified Energy System. The problem of PS development is multi-objective. Each criterion involved – even if not of economic nature – should be estimated from the viewpoint of the investments and expressed in terms of money or in the form of restrictions. This often implies serious problems and requires special methods and mathematical models that would take into account the reliability and security of supply in liberalized energy systems and the comparative features of different development alternatives.

3. DEVELOPMENT TRENDS OF TRANSMISSION SYSTEM'S GRIDS AND ELECTRICITY MARKETS IN BALTIC

The Baltic energy market interconnection plan (BEMIP, confirmed by the European Commission) provides implementation of several vital energy projects in the Baltic States with a view to avert their energy isolation. Several of the proposed BEMIP infrastructure projects are an integral part of the European Economic Recovery Programme (EERP) [2].

According to this plan, the projects carried out and planned in the Baltic are as follows.

Estonian power system:

- strengthening the internal transmission networks (Tartu-Viljandi-Sindi, Harku-Lihula-Sindi);
- construction of an emergency reserve 250 MW power plant (Kiisa);
- creation of an Estonia-Latvia interconnection (Sindi-Riga);
- creation of a 2nd Estonia-Finland interconnection (Estlink 2).

Latvian power system:

- strengthening the western electrical networks (Kurzeme ring);
- laying a 330 kV cable to connect the Riga CHP-1 and the Imanta substation.

Lithuanian power system:

- strengthening the internal transmission networks (Klaipėda-Telšiai, Kruonis HPSP-Alytus, Kretinga-Benaičiai, Klaipėda-Marios 3, and Pagėgiai-Bitėnai);
- creation of an interconnection transmission line: DC link LitPol Elk (PL)-Alytus (LT);
- laying an HVDC submarine cable NordBalt for Sweden-Lithuania interconnection.

The main activities that laid the groundwork for achieving the Baltic States' integration into the EU electricity market were as follows.

- April 1, 2010: via Estlink I interconnection Estonia joined the Nord Pool Spot (NPS).
- June 18, 2012: Lithuania became a separate NPS price area.
- June 3, 2013: opening the Latvian price area successfully started, which was of utmost importance for integration of the Baltic energy market into European PSs and creation of a common electricity market based on the Scandinavian model.
- February 4, 2014: the price coupling of Northwest Europe regions was performed under common computational model EUPHEMIA [3].
- May 13, 2014: South-Western Europe joined the common computation model (Fig. 1).

The price coupling of regions (PCR) as the initiative of seven European Power Exchanges (APX, Belpex, EPEX SPOT, GME, NPS, OMIE and OTE) was implemented for harmonization of the European electricity markets by developing a single-price coupling algorithm for calculation of the electricity prices across Europe.

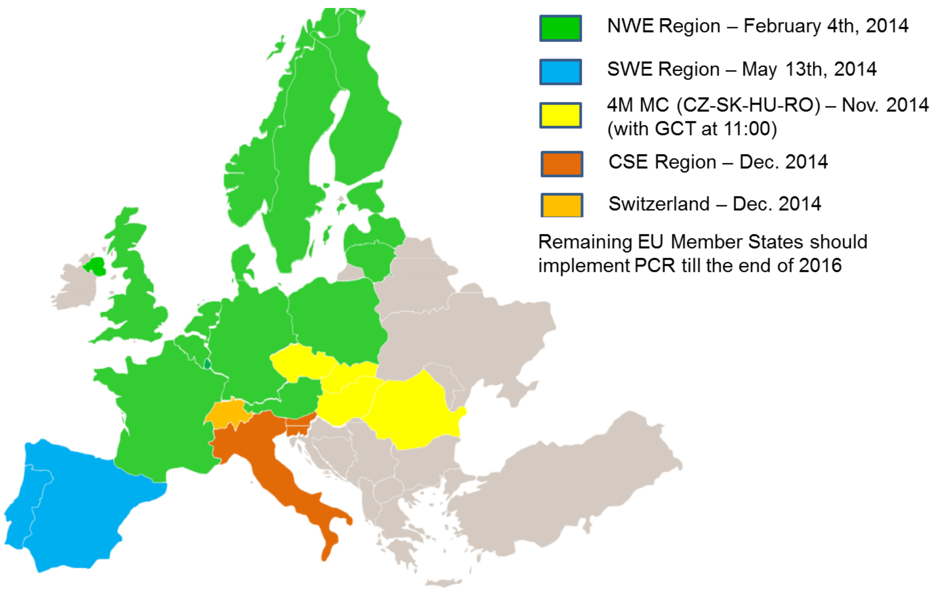

Fig. 1. Implementation of Price Coupling of Regions in Europe [4].

The PCR benefits are as follows.

- Increased liquidity, efficiency and social welfare.
- Guarantees for the overall welfare and optimal use of interconnection capacities.
- Removing the unnecessary risks of trading separately the short-term transmission capacities and energy.
- Possibility of using the cross-border capacities by all market participants.
- Promotion of liquidity, transparency and efficiency on the power markets across Europe [5].

4. MATHEMATICAL MODEL FOR CALCULATION AND ANALYSIS OF TRANSMISSION SYSTEM INFRASTRUCTURE

The influence of liberalized electricity market on the PS development is explained by the fact that the electricity generators are independent of transmission and distribution operators, so their interests differ. As a result, high uncertainty exists for the perspective forecasts, which means that the PS development planning and optimization are hampered. Therefore, in the development tasks it is necessary to consider the pricing mechanisms in more detail in order to better define the benefits and costs with the introduction of new or liquidation of old PS elements. To achieve these targets, the sustainable development planning concept based on the optimal power flow (OPF) techniques was proposed and AC/DC OPF algorithms with planning approach was created; also, the optimal expansion planning/strategy was determined, which will ensure the adequacy of a grid as well as of generation and demand in the future.

The development planning is a process intended to determine an optimal strategy for expansion of the existing PS transmission network in order to meet the demand for possible load growth and generation mix, while maintaining the reliability and security of the PS. Generally, the planning task of PS transmission network development is to determine *where*, *how many*, and *when* new elements/devices must be added to a network in order to make its operation viable for a pre-defined horizon of development planning, with cost minimization and social welfare maximization thus allowing the optimal expansion/development plan to be worked out.

In real tasks, the number of comparable development plans attains an astronomic level; therefore, it is required to apply specialized dynamic optimization methods (see, e.g. [6]). The objective function for the network development plan displays and integrates the technical and economic parameters as well as the power supply reliability, ecological, etc. parameters. The formula below represents the social welfare expressed as the aggregated demand utility bid function minus the generator offer function and minus the cost of investment in new lines. Therefore, this objective function is a network development plan g quality criterion, denoted as $F(T,g)$ and expressed as

$$\max F(T,g) = \max_{g\in\{G\}} \sum_{t=1}^{T} (SW(t,e(t),g) - IC(t,e(t),g) \qquad (1)$$

where t is the development step's serial number;

T is the number of development steps in the estimation period;

g is the development process;

$\{G\}$ is the set of all possible development plans;

$SW(t,e(t),g)$ is the social welfare criterion in development step *t*, development state $e(t)$ and development process g;

$IC(t,e(t),g)$ are the investment costs in development step *t*, development state $e(t)$, and development process g.

To consider the impact of liberalized electricity market on the technical and economic criteria, each development state is to be observed on the hourly basis. Application of OPF-based hourly calculation allows taking into account the major trends of production and consumption during a day, the consumption time shifting at considering multiple time zones, the demand response, the distributed generation, etc.

Development modelling should include a network's dynamic behaviours and reflect the real processes going there as much as possible. Figure 2 shows the created development model which relies upon the main functioning factors proposed above.

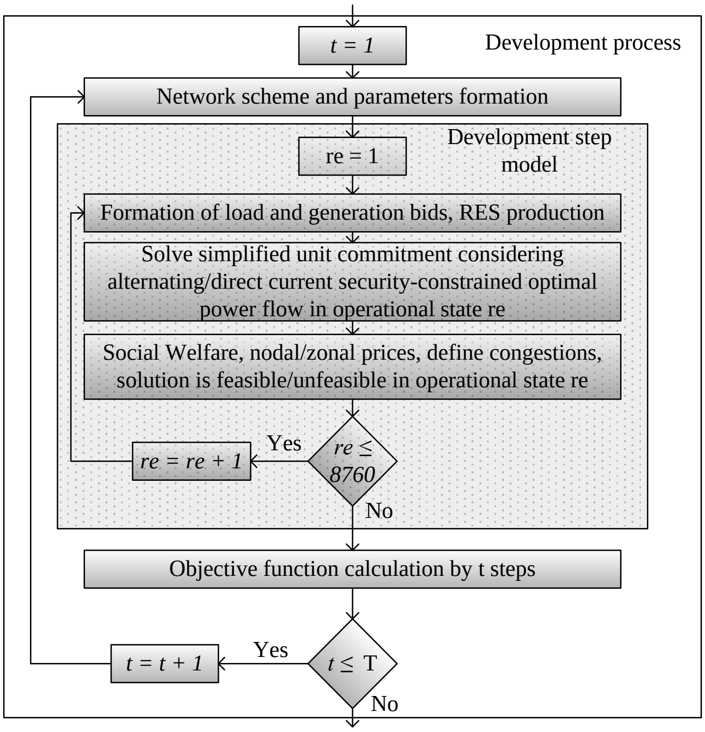

Fig.2. A mathematical model of the network development process on hourly basis.

This process allows the hourly consideration of RES impacts on the power system and market formation. In [7], the methodology and algorithms are proposed for evaluation of the RES integration effect on the price formation and the level of system penetration.

The OPF development is closely following the progress in numerical optimization techniques and computer technology, for which many approaches have been proposed. The optimization techniques include nonlinear programming, quadratic programming, linear programming, mixed programming, interior point and artificial intelligence algorithms, etc. [8-10]. The most successful interior point methods are based on using a primal-dual formulation and applying Newton's method to the set of equations arising from the *barrier* method – see, e.g. Fiacco and McCormick's barrier method for optimization with inequality constraints [11]. Two other achievements upon which the theory of nonlinear primal-dual interior point methods (PDIPM) relies are Lagrange's method for optimization with equality constraints, and Newton's method for solving nonlinear equations. This method is widely employed in PS optimization problems because of its favourable convergence, robustness, and insensitivity to infeasible starting points. The primal-dual interior point method presents the algorithm of choice for OPF-based hourly calculation in long-term development planning strategies

The SCOPF problem [9] is an extension of the OPF problem, adding some important features of reliability to the optimization model. It guarantees stable work of the whole PS, without changing the active power generation at occurrence of some predetermined contingencies (e.g. outages of transmission line). Figure 3 provides a flowchart of iterative SCOPF algorithm which starts by solving an OPF problem with (N-0) constraints.

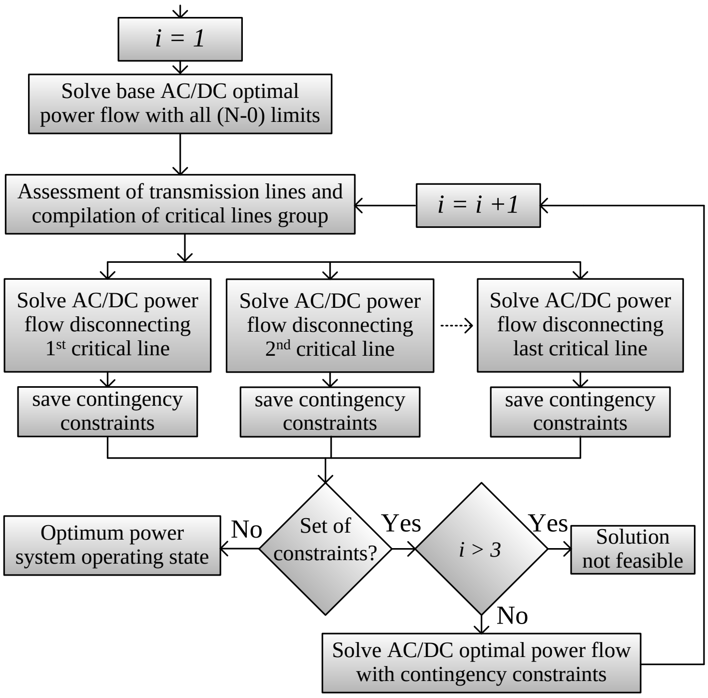

Fig. 3. Mathematical model of security-constrained OPF algorithm.

After solving this problem, the contingency analysis starts with the aim to identify the critical group of lines selected according to the criterion:

$$K^{*}_{L,re} = \chi_L \cdot Ps_{L,re}, \tag{2}$$

where L is the transmission line's ordinal number;

$Ps_{L,re}$ is the transmission line L flow in operational state re;

χ_L is the interruption probability for transmission line L.

In the development planning tasks for optimal steady-state operation determination only 10% of electric transmission lines (TLs) should be taken into consideration in which flow, interruption probability, and, therefore, criterion K* are of the highest values. Criteria of the type are necessary for selection of the critical group of lines, which would allow reducing the volume of optimization problem and the calculation time.

5. THE BALTIC REGION MODEL FOR ANALYSIS OF TRANSMISSION SYSTEM INFRASTRUCTURE

The extensive Baltic power simulation model developed by the *JRC IET ESU* in cooperation with the Latvian Institute of Physical Energetics (*IPE*) was initially based on the BRELL (Belarus, Russia, Estonia, Latvia, Lithuania) power systems' parallel operation. The developed model presented in Fig. 4 features a full geo-referencing of the buses and TLs, the Finland Estlink 1&2 interconnections, with updating the information on recently commissioned/decommissioned wind farms and power plants.

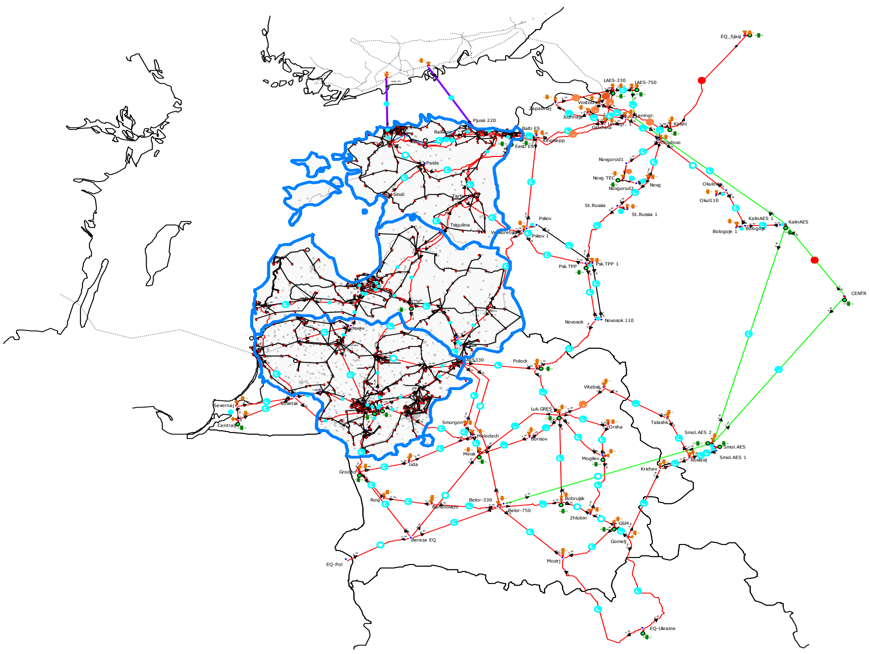

Fig. 4. The developed model of BRELL transmission system.

Table 1 presents the components of the extended BRELL model's nodal representation for 110-750 kV transmission lines.

Table 1

Components of the extended BRELL model

	EE	LV	LT	RU	BL	$FI_{eq.}$	$PL_{eq.}$	$UK_{eq.}$	All states
Buses	182	238	479	40	22	2	1	1	955
Gen	16	14	12	11	8	0	0	1	62
Loads	141	148	291	23	20	2	0	0	625
Lines	247	323	646	56	30	2	1	2	1307
Voltage [kV]	110/220/ 330	110/ 330	110/ 330	110/330/ 550/750	330	330	330	330	110/220/330/ 550/750

The baseline load demand data for the model include the peak and off-peak load profiles registered in 2012. To ensure a continuous assessment of the model, the actual real-time data retrieved from the Nord Pool Spot are scaled up using the initial 2012 load distribution, assuming an average power factor and similar load distribution within the existing BRELL nodes.

Table 2 illustrates the power generation mix within the Baltic States where thermal generation shares are 60% from the overall generation. It is worth mentioning that Lithuania – once relying mainly on nuclear power generation (70%) – has decommissioned its last nuclear power plant (NPP) Ignalina in 2010 due to EU strong concerns over the RMBK type. This resulted in power flow changes, and Lithuania (once a net exporter) is now becoming a net importer.

Table 2

Generation capacity mix in the Baltic States

Generation capacity per type [MW]	Estonia	Latvia	Lithuania	All Baltic
Thermal	2373	930	2610	5913
Hydro PP and Kruonis HPSP	7	1580	1030	2617
Nuclear	-	-	-	-
Wind and Biomass	359	150	410	919
Total	2739	2660	4050	9449

Although the three Baltic States seem to be capable, in absolute terms, of balancing their energy supply and demand during typical winter peak loads (Table 3) only Estonia prevails as a net exporter.

Table 3

Energy supply and demand in Baltic States in a typical winter (2013/2014).

	Estonia	Latvia	Lithuania	Total
Total net capacity [MW]	2739	2660	4050	9449
Typical peak load [MW]	1440	1280	1740	4460
Available capacity [MW]	2070	1320	2400	5790
Export capability [MW]	630	40	660	1330

The developed model is aimed to simulate the projected transfer allocations and to assess their impact for normal and contingency operations. Figure 5 illustrates a simulation snapshot of the cross-border power flow exchange featuring the imports of Lithuania from Belarus and Latvia, while Estonia acts in absolute terms as an exporter mainly to Latvia.

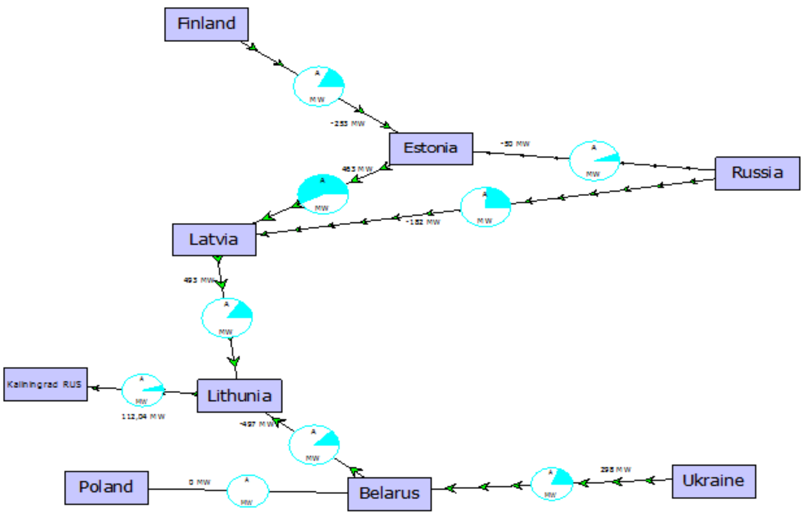

Fig. 5. Simulation snapshot of cross-border power flow exchanges

6. ANALYSIS OF TRANSMISSION SYSTEM INFRASTRUCTURE IN THE BALTIC REGION

Figure 6 illustrates the actual Baltic network characterized by dependence on the imports, primary control and frequency control from Russian TSO, with significant threat resulting from the bottleneck between Russia and Belarus. The extra loading of this sensitive section is a direct result of decommissioning the Lithuanian Ignalina NPP. Failure at the aforementioned section is reported to result in negative consequences, including equipment failure, non-served load and frequency/voltage drops.

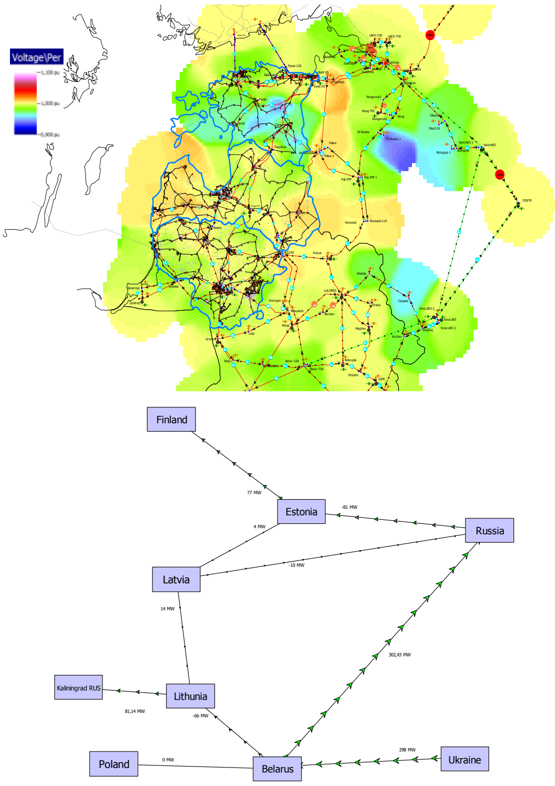

Fig. 6. Baseline scenario: per unit voltage contour and cross-border power flows.

The structure of Baltic TL network has significant drawbacks that reduce the reliability of power supply to certain regions and hamper further development. The existing 110 kV network does not provide a sufficient reliability of power supply in these regions. The main cause of tripping the power lines is wind loads (III and IV the wind zone). Therefore, we could expect a possible repeat of the complete energy supply cessation like that occurred in 2005. With implementation of priority projects in the Baltic region, the existing 330 kV network will be strengthened, the reliability of power supply for consumers will increase – in particular owing to widespread use of wind power and increasing transit flows between the Nordic countries and Central Europe. New transmission lines are expected to meet the existing and future electricity demand for regional development (e.g. in the cases of repairs).

7. CONCLUSIONS

Analysis performed for the infrastructure of Baltic region transmission system resting on the baseline scenario and the developed mathematical model, taking into account the interests of each country in the field of energy policy, has shown the following. Current trends, in terms of reliability, are highly important, and now the integration of the Baltic market into the EU market could be observed. As expected, shortly impressive power exchange will take place between the Nordic countries and the Central Europe owing to the introduction of LitPol and NordBalt interconnections.

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BALTIJAS REĢIONA PĀRVADES TĪKLU INFRASTRUKTŪRAS ANALĪZE IEVĒROJOT ATTĪSTĪBAS TEHNISKI-EKONOMISKOS FAKTORUS

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K o p s a v i l k u m s

Baltijas valstu (Latvijas, Lietuvas un Igaunijas) energosistēmas ir cieši saistītas vēsturiski, un to darbība nav iespējama bez savstarpējas sadarbības attīstības un darba režīmu jautājumos. Ekonomisko attiecību īstenošanu enerģētikas sektorā paātrināja elektroenerģijas tirgus attīstība. Baltijas valstu enerģētikas politika ir integrēta ES enerģētikas stratēģijas sastāvdaļa, nosakot trīs galvenos mērķus: enerģētikas nozares konkurētspēja, ilgtspējīga attīstība un drošība. Visas trīs Baltijas energosistēmas veica lielu darba apjomu iekārtu modernizācijā un standartu saskaņošanā, kuras ir saskaņā ar Eiropas Savienības prasībām, kā arī par tirgus attiecību un tehnoloģiju standartu ieviešanu, lai nodrošinātu energoapgādes drošību un elektroenerģijas pieejamību patērētājiem.

Tomēr, ņemot vērā strauji mainīgos ārējos apstākļus, it īpaši ģeopolitiskos faktorus, Baltijas valstu enerģētikas politika būtu jāizskata ar mērķi novērtēt, kā šie faktori ietekmē energosistēmas ilgtspējīgu attīstību kopumā. No iepriekš minētā izriet, ka nepieciešama jauna nacionāla enerģētikas stratēģija, kura stiprinātu efektīvu ekonomisko un sociālo pamatu ilgtspējīgu attīstību Baltijas valstu nacionālā ekonomikā.

Šī darba mērķis ir Baltijas valstu pārvades sistēmas infrastruktūras analīze, pamatojoties uz izstrādāto matemātisko modeli, ņemot vērā katras valsts intereses enerģētikas politikas jomā.

21.07.2014.