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Verification of Wind Parks and their Integration into Small-Interconnected Power System

J. Kilter, M. Landsberg, I. Palu and O. Tšernobrovkin

Abstract--**Continuously increasing percentage of wind power that is integrated into power system is causing additional challenges to system operators, especially in the case of small-interconnected power system. Estonian power system is an excellent example of that situation due to its configuration and load characteristics. Therefore, adequate requirement for connection of wind parks are needed. In this paper, the present situation of wind power development in Estonia and probable future scenarios and their influence to power system operation and development are discussed and analyzed. Moreover, comprehensive clarification of requirements (e.g. *P, Q* and *V* regulation, fault-ride-through and power quality criterions etc.) and legislation for connection of wind parks, considering system security and operational aspects, are discussed and compared with different requirements specified by other system operators. An example of integration of wind park into Estonian power system is presented. Adequate requirements will assure permissible operation of the Estonian power system in steady-state and in different contingencies.**

Index Terms--**Fault-ride-through (FRT), grid code, power system control, power system monitoring, power system protection, security of supply, power system stability, testing, wind energy, wind power generation.**

I. Introduction

INCREASE of the share of renewable energy in the electricity production is an important issue everywhere in the world. The use of wind energy is one of the most attractive options, especially in the countries with long coastline and islands, e.g. Estonia. Considering the location and environmental conditions the wind potential in Estonia is remarkable. However, today there is only 65 MW of wind capacity installed in Estonia. One of the main means for Estonia to achieve environmental targets, set by EU, is to install large amount of wind generators into the network. Nevertheless, one must consider that even a small quantity of wind power installed into Estonian power system may cause various problems if the requirements considering network security are not fulfilled by the wind parks [1].

Estonian power system is operating in parallel with power system of IPS/UPS of Russia. As most of wind production is connected to western European countries, belonging to UCTE and NORDEL synchronous areas, the wind turbine installations are developed according to operating standards and grid codes imposed in those synchronous areas. The main requirements for wind parks connected to Germany or Danish transmission network are presented in local Grid Codes [2]-[4]. Good surveys of local standards and technical requirements in different countries are presented in [5]-[8]. Operating practices and technical rules for power plants connected to the system differ significantly in IPS/UPS area, thus compliance with those rules is critical when maintaining operational reliability and security of supply when connecting large amount of wind power into Estonian power system [9], [10]. One of the means to achieve this target is comprehensive verification of compliance, starting from analysis of connection application by means of simulations with wind turbine model until final acceptance tests after connecting to the grid and latter monitoring of compliance during its lifetime.

Wind power integration and its influence to the network operation is a complex problem. A lot of research has been conducted to understand wind park operation and its behavior in different contingencies [11]-[14]. Besides the direct connection of wind parks to the network and related problems also different reserves and their requirements in case of wind power must be considered [15]. Good example of wind power influence to the grid operation is the event that occurred November 2006, which almost caused the blackout of UCTE network [16].

II. Estonian power system – a part of IPS/UPS of Russia

Estonian power system is operating in parallel with power system of IPS/UPS of Russia. Estonia, together with other Baltic power systems, Latvia and Lithuania, are only EU countries that belong to synchronous zone of IPS/UPS of Russia.

Baltic interconnected power system is located at a crossroad between three large synchronous networks - UCTE, Nordel and IPS/UPS. It has strong connections to IPS/UPS power system forming the so-called loop (Fig. 1). Therefore, Baltic power system operation is strongly influenced by the IPS/UPS system and in normal conditions cannot be observed and analyzed separately. For example, when something happens in some part of the system e.g. power plant or some line trip etc., all loop members and their system operation is influenced. Hence, common rules between concerned parties must be fulfilled and close cooperation must exist. Furthermore, to main-

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tain operational reliability in the loop, wide use of system protection automation exists.

A. Basic data of Estonian Power System

The transmission grid within Estonia comprises 1300 km of 220-330 kV lines and 3500 km of 110 kV lines. Estonia is interconnected with Russia and Latvia via five 330 kV AC links and a DC link to Finland (Fig. 1). Interconnections to the neighboring areas have a net transfer capacity of 200-1100 MW, depending on real-time operation of power system [17]. Transit flows through Estonia are typically ±200 MW.

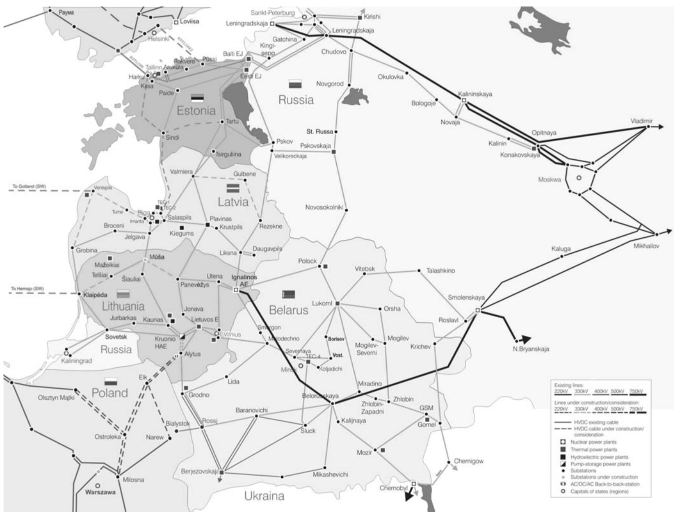

Fig. 1. Power loop of IPS/UPS of Russia

In 2007, around 90% of domestic electricity consumption, 7,2 TWh, in Estonia was covered by conventional thermal power plants burning local oil-shale [18]. At the moment installed net production capacity in the Estonian power system is 2322,6 MW. In September 2008, the installed net capacity of condensing, oil-shale fired power plants was 2000 MW, installed net capacity of CHP-s is ca 200 MW, wind parks 65 MW and all other power plants (hydro included) – 40 MW. The peak load during wintertime is about 1600 MW.

B. Wind power developments

During negotiations with the EU, Estonia set an indicative target for production of electricity from renewable energy sources (RES). The electricity produced from RES must cover at least 5.1% (ca 400 GW/h) of the gross inland electricity consumption by 2010. This is a heavy task as the share was 1,7% in 2007. The wind energy projects were infeasible during a long period due to low electricity price and Estonia's very limited subsidies for wind-generated electricity. Nowadays, the purchasing obligation and feed-in tariffs for electricity from RES have been written into legislation and construction of wind generators have improved substantially [19], [20]. This has recently caused a peak of interest in wind energy investments. The overall amount of wind power capacity that is applied for connection is around 5000 MW. It is a huge number compared to overall consumption. Winter peak load in 2007 reached up to 1525 MW and summer minimum was around 450 MW [18]. Consumption forecast, made by Estonian TSO, is foreseeing winter peak load for year 2010 according to most probable base scenario 1665 MW and for year 2020 it will be 2016 MW. So it is clearly seen that the capacity of planned wind farms is decidedly exceeding the foreseen peak demand until year 2020 [21].

Based on the amount of connection applications and considering the characteristics of Estonian transmission network it can be clearly seen that integration of wind parks into system is challenging. The influence to short and long-term development, operational planning and system control and also for power market operation is remarkable (Fig. 2). The situation at Fig. 2 presents the situation in 2020 and afterwards.

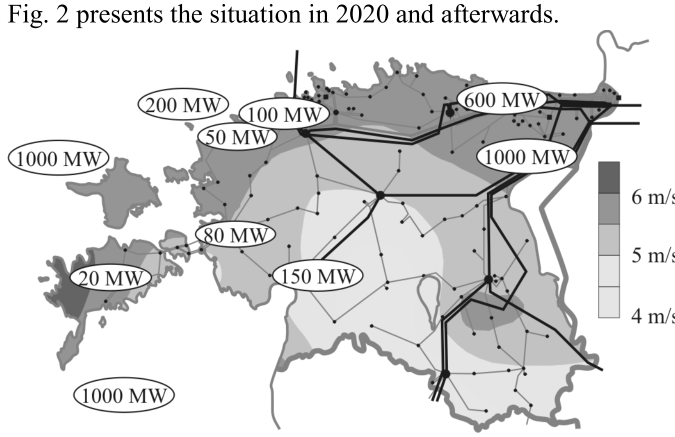

Fig. 2. Estonian wind resources, transmission network (110…330 kV) and possible locations of the wind parks and their output (MW) according to connection applications

C. Balancing and reserves

Nature of production availability in Estonia, e.g. slowly regulating thermal units (startup up to 14 hours), constitutes requirements for balancing and reserves for wind parks. Currently there are no fast regulating units available and therefore balancing power should be imported. Unfortunately two large limitations exist. For regulating purposes, it is only possible to buy energy from systems synchronously connected to Estonian power system. Scandinavian regulated market is only useable for Scandinavian TSO-s and power form spot-market can be bought two hours in advance. In addition, limitations due to transfer limits arise and may therefore not be useable for export/import additional power. Usually one should consider that Estonian export/import possibilities are 650 MW.

Therefore, Estonian TSO requires installation of fast-start generating units to be installed together with new connections of wind power - all new wind parks, which are planned to connect to grid, after 1st of July 2007, are obligated to have fast regulating power plant in Estonian territory.

III. Requirements to Generating Units Connected to Transmission Grid

Most important requirements for the connection of Wind Parks into Estonian power system are described in Estonian National Grid Code (in force since 1st of July 2003) [22]. Additional requirements affecting the wind parks are described in Estonian Electricity Market Act [19]. Estonian Grid Code covers specifications concerning supply security and technical requirements for electrical installation due to security of supply. The issues concerning the connection of power plants is covered in Gird Code chapter three - "Technical requirements for production units" (incl. special requirements for WTG-s). The technical conditions for connection of wind farms to the grid are elaborated by the transmission system operator OÜ Põhivõrk. According to the Grid Code, a wind farm with installed capacity over 200 kW must be able to participate in the control tasks on an equal level with the conventional power plants, constrained only by the limitations imposed at any time by the existing wind conditions. All wind parks over 10 MW must only be connected to transmission network. The most important requirements are described as following.

A. Frequency and voltage variation in the transmission grid

Most of the wind farms are connected to 110 kV grid. During normal operation voltage varies between 115…123 kV and in exceptional and post-disturbance operation in a range 97…123 kV. Frequency in normal operation is in a range 49,8…50,2 Hz. In exceptional operation, the generator may have to operate with the grid in a range of frequency 47,0…53,0 Hz.

B. Active power regulation

Wind farms must participate also in control tasks of active power regulation, equally to conventional units. Capabilities can be constrained only by wind conditions. The active power regulation includes primary (frequency dependent) control, secondary control and curtailments of its production. For system protection reasons, the wind park must be able, if necessary, to curtail its active power on the network operator's order through the *SCADA* system (secondary control) or from external signal (frequency, system protection, etc.). Under normal power system condition, ramping speed must be at least 8% per minut and in both directions adjustable within given band of 0-8%. When using active power reduction for system protection, the maximum power down-ramping speed should correspond to a reduction in production from 100% of rated power to below 20% in 2 seconds. That is also allowed to be done by switching off single wind turbines or a part of wind park with circuit breakers.

C. Fault ride through capability.

All generating units must withstand without switching off from the network (Fig. 3) sudden drop of the voltage to 0% of the rated voltage of network during 0,37 seconds and following linear increase of the voltage up to 90% of rated voltage during 0,5 second, without substantial loss of active power after clearing the fault in case if the connection point (CP) is at grid voltage level (HV side of coupling transformer).

The requirements for the wind park to successfully survive the sudden voltage drop occurring in the network are somewhat different in different countries (Fig. 3) depending on their system characteristics, configuration, control and system automation principles etc. [23], [24].

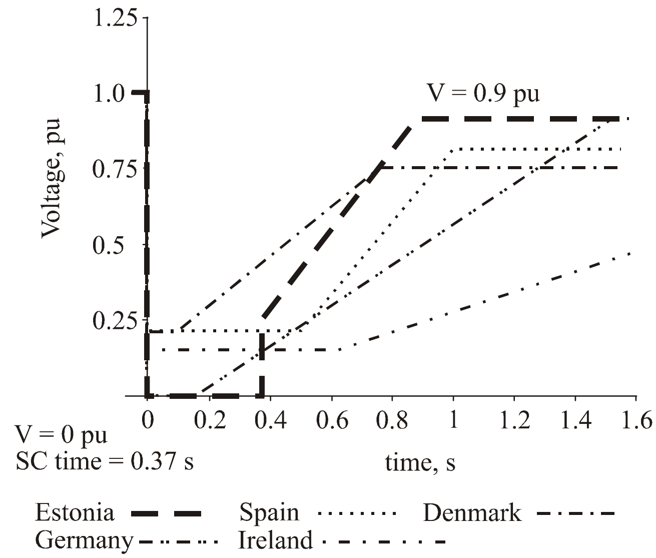

Fig. 3. Requirements for fault ride through capability (at transmission network) compared with requirements by other countries

D. Other requirements

Other requirements include requirements for voltage quality, testing of wind power units and specific instructions for control and automation of wind park. Power Quality issues are covered in company standard [25], it proceeds standard IEC 61400-21 [26], EN 50160 [27] and corresponding IEC [28], [29], CIGRE [30] technical reports and Russian power quality regulations [31]. The wind park must fulfill all power quality requirements before it is allowed to work in cooperation with the power system without any additional constraints.

For pre-connection network calculations, all generators are required to present report of network simulations with generator's electrical model where the compliance with requirements is shown. After that the presentation of electrical models to System Operator is required.

E. Consequences of incompatibility

The main concerns in Estonian case are FRT capability and stable operation during large frequency and voltage deviations. Moreover, active participation in frequency and voltage control tasks is essential. The most critical in Estonian case is the FRT capability of wind parks, because Estonian power grid is in its nature has radial configuration, generation at one end and consumption at another end. Therefore, short-circuit in EHV network will cause large voltage dip all over the power grid. In worst case single disturbance can cause voltage dip followed by disconnection of all wind turbines if fault with duration 0,37 seconds is not withstanded by staying connected by wind turbines. This can cause large inflow from other synchronous systems, exceeding import capability of transmission system and jeopardize security of the system.

Another concern is islanding of Estonian power system during large frequency deviation. If primary reserve is not sufficient at each moment, the islanding is followed by blackout of the whole system. For that reason guaranteed operation of all power plants, incl. wind turbines, during temporary low and high voltages is mandatory. If wind power forms large part of generation, the active participation in frequency control is essential to restore normal operation.

IV. Wind Park Study

Adequate understanding of future behavior of wind parks is essential and the best possibility to obtain that information is through the modelling of wind park and network operation [32]. Stochastic nature of wind should be adequately considered. The main reason for comprehensive analysis is the requirement to the TSO to assure system stability and security.

During the system analysis the system is modeled and different operational scenarios are observed. The compliance of the wind park and also the modeled results to the real conditions are afterward verified through real test conducted in the network.

A. *Wind park models*

It is required by the Estonian Transmission System Operator that the wind park developer must present the adequate models 90 days before the testing and acceptance of the wind park connected to the grid. Modelling of the power system operation (system steady-state and dynamic stability studies) in Estonian TSO is performed using PSS/E [33]. Therefore presented models must be compatible to PSS/E and their explanation with correct parameters and schematics must be included. Also all information about wind park electrical connections and control system, with appropriate relay and automation settings is to be presented.

B. *Wind park testing*

In addition to factory testing and wind tests by accredited laboratories, comprehensive verification and acceptance tests on site, after connection to the grid, are performed. The tests and measurements in the wind farm are carried out in order to test the conformity of electric installation being incorporated into the transmission grid and to test the transmission of real-time information and verify that the park is in correspondence with the Grid Code [22]. The profoundness of the test is induced by the characteristics of Estonian power system, its connection to IPS/UPS system and special regulations for upholding the frequency and voltage.

The purpose of the tests are to identify the depth of voltage dip caused by short-circuit, determine the circumstances of transition to the auxiliary power generation, to identify the power curve on *PQ*-diagram, to control the irregular change of generator's voltage, to determine the circumstances of overload characteristics, power quality parameters, etc. The testing comprises fast reduction and up-regulation of active power (for example, it is required that active power must be reduced from 80% to 20% in 2 seconds), the regulation of voltage/reactive power (V = const, Q = const at different active power values etc.), a short-term disconnection (10 seconds) and reconnection of the connection between the wind farm and the power grid, wind farm in operation with and with out central control system and etc. Additionally, real short circuit is induced in the network to test wind turbines fault-ride-through ability. Intervals of all measurements, measurement configuration and testing and measurement techniques should correspond to IEC standard 61400-21 [26] and IEC Technical Report 61000-4-30 [34].

It is essential that all requirements should be fulfilled before connecting the wind park into Estonian power system without any restrictions. Furthermore, the information received from the testing is used additionally for wind park model verification.

C. *On-site testing of wind parks*

In October 2008, Estonian TSO performed acceptance test for one of the wind park connected to 110 kV transmission network. The purpose was to verify wind park fault ride through (FRT) function. The wind park consisted three fully decoupled (AC-DC-AC) synchronous wind generators with total installed capacity of 6,9 MW. To maintain the security of supply for other customers in area, the wind park was connected to the system through radial scheme (Fig. 4). Wind park is located at substation E, three phase short-circuit was performed in the line departing from substation A. The park was connected to the main grid through 110 kV and 35 kV overhead lines and cables, respectively, and through six transformers. To perform the test relay and other automation functions were disabled/adjusted. Through calculation it was determined that as a result of this scheme the voltage in the region was satisfactory and during short-circuit the voltage at substation E will be as required by the Grid Code.

The measurements were performed using a special power quality analyzer. The equipment enables to record voltages, currents, active, reactive and apparent power, short and long time flicker and voltage and current harmonics up to 50th order. The short-circuit transient was recorded with sampling rate of 9600 Hz.

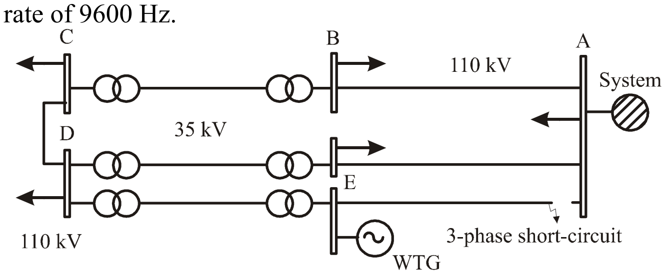

Fig. 4. Principal diagram of the network during the testing of the wind park

The duration of the short-circuit at substation A was 0,56 seconds and remaining voltage at substation E was 3,3 kV (voltage dip 95,4%). Results of the FRT test (active, reactive and apparent power and voltage values) are shown in Fig. 5. In addition, changes of wind park current and voltage instantaneous values of each of the three phases before, during and after the performed short-circuit are shown in Fig. 6 and in Fig 7, respectively. Before the fault, the wind park power output was near maximum of its nominal (6,73 MW). Power generation continued 1,4 seconds after the fault, while generation was 6,26 MW (difference 0,47 MW). The remaining value was above the required 10% limit. Moreover, measurements proved that during normal operation the reactive power was kept constant, i.e. $Q = 0$ MVAr. During the fault wind park consumed 3 MVAr of reactive power and afterwards reactive power support to the grid was given. These reactive power changes during and after the fault are acceptable. Therefore, no limitations concerning active and reactive power or voltage were noticed. Furthermore, wind park harmonics were analysed. The results showed that during normal operation the total harmonic distortion of voltage and current were both in the limits set by the standards, e.g. 2,3% and 1,5%, respectively [25].

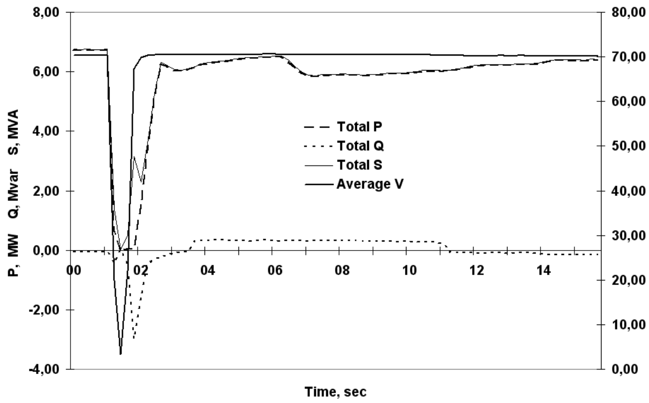

Fig. 5. *P*, *Q*, *S* and *V* RMS 0,2 second values during FRT-test

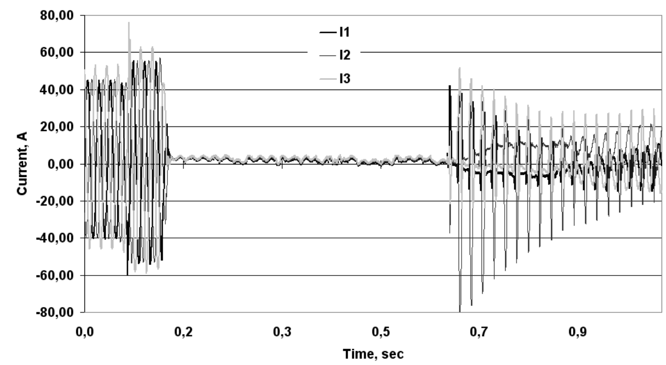

Fig. 6. Current instantaneous values during FRT-test

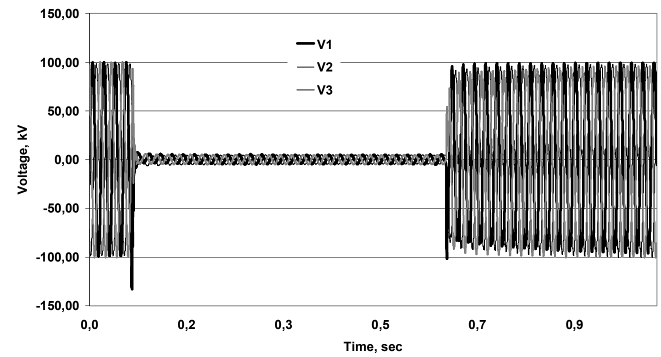

Fig. 7. Voltage instantaneous values during FRT-test

The performed test was also simulated using the wind park models presented to the TSO by wind park developer. The results of modelling of voltage, active and reactive power are presented in Fig. 8. As it can be notice the modelled and actual measured results from the test correspond quite satisfactory, but some differences are noticeable, especially in case of reactive power. Nevertheless, one should consider that tuning and validating the presented models is in vital importance and sufficient knowledge and understanding of network operation is required to adequately simulate wind park operation in different contingencies and study scenarios.

The results here are only the first step to obtain adequate wind park models corresponding to real operation. The validation of wind park models and studies will be continued in the near future because similar types of wind turbines are to be connected to Estonian transmission network.

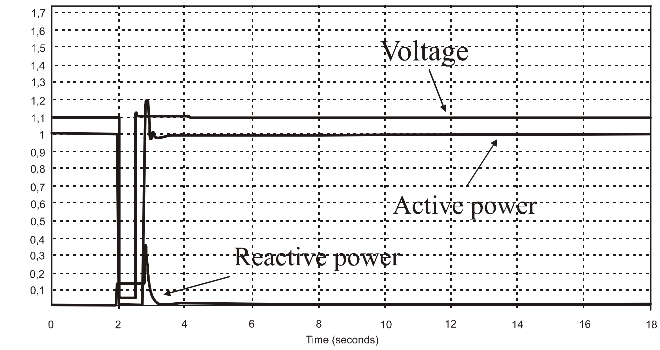

Fig. 8. Modelled values of voltage, active and reactive power during 0,5 second three phase short-circuit in the network

As a result of performed tests, it is possible to determine that the FRT and other requirements set by the TSO were fulfilled in the observed case. Therefore, the wind park operation does not jeopardize the security of the system and it is allowed to be connected into Estonian power system.

V. Conclusions

Due to the independent development of Russian power system (incl. Estonian power system) in the past major differences in system structure and certain operation philosophy variations exist between western European power systems and power systems of IPS/UPS. While both systems follow the n-1 criteria, in IPS/UPS a wider range of means are used to overcome the consequences of disturbances (i.e. power imbalances, grid elements tripping or overloads, violations of voltage limits, etc.): protection, re-dispatching and automation actions comprising load and generation shedding. The system operation is also affected by the relay protection principles (relatively long short-circuits are allowed) and equipment used (for example, short-circuiter and interrupter[1]). Therefore, the generators connected to the Estonian power system must be able to sustain larger frequency and voltage intervals and also participate in the system control process. Consequently the testing of wind parks is essential.

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Ivo Palu was born in Rakvere, Estonia, on July 26, 1979. He graduated from the Tallinn University of Technology (TUT) and received M.Sc degree in electrical power engineering in 2005. He is continuing his Ph.D at TUT, where his topic of research is ”Emissions Reduction of Thermal Power Plants using Wind Turbines”. Currently he is teaching assistant at the department of electrical power engineering at TUT. He is a member of Estonian Society for Electrical Power Engineering.

Oleg Tšernobrovkin was born in Kuressaare, Estonia. He graduated from the Tallinn University of Technology in 2008. Currently he is a PhD student and is working at the Estonian TSO-s Planning Division as a Power System Analyst. His main fields of expertise are transmission grid long term planning, steady state and dynamic calculations, network modelling and wind park connections.