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Assessment of the impact of small scale HPP generator connection to the existing distribution network under operation optimization

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The paper presents the main goals and achievements of the SmartGrids ERA-NET project named "Efficient Identification of Opportunities for Distributed Generation Based on the Smart Grid Technology (SmartGen)" during two years of project realization in Latvia.

In the paper we proposed the basic principles of optimization of hydro power plant (HPP) working conditions under forecasted electricity prices and probabilistic water inflow values, as well as assessment of the impact of asynchronous generator connection to the existing network taking into account technical limitations.

The developed model considers the most important technical parameters of HPP and the network, allowing to make HPP generation forecasts and its impact on the network using time-varying and constant input parameters. The mathematical model of a small scale HPP was developed for simulation of HPP electricity production and transient processes.

The paper also includes the description and results of a case study performed to test the proposed mathematical model. The case study was carried out using the real distribution network part with the connected HPP. Different generation and load scenarios have been modelled. Load-generating interaction scenario modelling was implemented in the Matlab environment.

The elaborated model can be used for representing a wide range of HPPs in electrical market and assessment analysis of the distribution network, as well as adapted for modelling of other types of power plants that use asynchronous generators.

Key words: distributed power generation, dynamic programming, hydroelectric power generation, mathematical model, optimization, power distribution, smart grids

INTRODUCTION

It is expected that the production of electrical energy from renewable energy sources and liberalized market further development can cause changes in the distribution network operating modes, as with time more small scale power plants will operate in liberalized market rather than ones with subsidies. Such situation can cause more frequent starts and stops of power plants comparing to the current situation. You can also expect larger roll-out of other distributed energy sources like photovoltaics and small scale wind power plants as well as new electrical energy consumers – electric vehicles and heat pumps.

Challenges related to grid connection and grid capacity are frequently the main barrier to the development of distributed generation (DG) and load management (LM) projects. Appropriate, intelligent use of the Smart Grid Technology (SGT) can mitigate these barriers and postpone the reinforcement of the grid, but neither efficient methods nor a legal framework for applying these measures exist today.

Detailed models for the basic SGT are missing and as a result, decision makers and stakeholders rely on traditional grid models. SGT-models are necessary to investigate grid capacity and grid connection opportunities for next generation DG and LM projects.

Finding the optimal connection point for renewable DG projects can be complex. There are often a number of DG opportunities in the same region, both in size and location, which influence the solution for grid connection for a specific project. The current identification process is time consuming for project developers, system operators, regulators and other actors involved in the process from the project idea to the licence for construction.

Identifying grid capacity and grid connection points for DG or LM projects is currently done separately by project developers and system operators. This work can be done more efficiently by introducing a planning tool which describes the socioeconomic value for all parties involved.

To study the problems, the SmartGrids ERA-NET project named "Efficient Identification of Opportunities for Distributed Generation Based on Smart Grid Technology (SmartGen)" was launched at the end of 2010, involving participants from 4 European countries – the Institute of Physical Energetics (IPE) (Latvia), Balslev Consulting Engineers (Denmark), Bacher Energy Ltd (Switzerland) (together with 3 other Swiss partners) and Sweco Norge (Norway).

The overall main objective of the SmartGen Project is to facilitate the complex technical, societal, environmental and financial processes of real-world DG and LM projects by enabling a more efficient detection of possible and best connection points and identifying opportunities which minimize the extension of existing grids based on SGT. More detailed information on the project can be found in [1].

IPE concentrated on development of a small scale hydro power plant (HPP) operation model. The developed model consists of the operation (generation) optimization module and transient process simulation module. The model is capable of modelling various generation and load interaction scenarios. Further there is given a description of the developed model and results of the performed case study.

MODEL DESCRIPTION

The model developed by IPE represents a small scale HPP. As it was aforementioned, it consists of two modules. Further there is given a description of the modules.

Operation optimization module

The operation optimization module was created to bring out the optimal generation curve of small HPPs and it consists of 3 logical sections: information input section; simulation and optimization section and optimal curve output section.

The first section asks for information input about the HPP, electrical network, energy price and load curves, and also specific information needed for the optimization process of the 2nd section.

In the second section of the model an optimal generation curve is formed using dynamic programming [2–4]. Dynamic programming is used to find the optimal position of floodgate's door for each time period of a day that in its turn represents generation output of HPP in a particular time period. Restrictions defined by the allowed voltage level of the network are also checked in this section. The optimal position of floodgate's door for each time period is defined by the maximum profit of HPP's owner gained during one day.

The third section gives such generation curve of a small HPP that, on the one hand, satisfies all network and HPP exploitation restrictions, but, on the other hand, it gives the maximum profit for the HPP owner.

Changing input information about loads and water increase in the water reservoir, the model can be used to find out an optimal generation curve for different seasons of a year. Usage of dynamic programming allows finding the optimal HPP generation curve from the losses minimization point of view by changing the optimization function.

Information input section

This section comprises the following information on items needed for modelling of HPP:

- Maximal and minimal water level in the water reservoir of HPP [m];
- Difference of water levels at the power plant [m];
- Area of the water reservoir [m^2];
- Maximal power of the generator [kW];
- Efficiency of HPP [%];
- Regulation step (in percent) of the water gate state [%];
- Water inflow to the water reservoir [m^3/s];
- Level of water in the water reservoir at the beginning hour of simulation [m];
- Price of electrical energy (curve with 24 price values for 24 hour period) [EUR/MWh].

The developed model takes into account changes in generated power depending on difference in water levels, that is important because there can be such working states when HPP generates energy with a fully opened water gate for more than one hour. In this case at each next hour there will be produced less energy using the same amount of water.

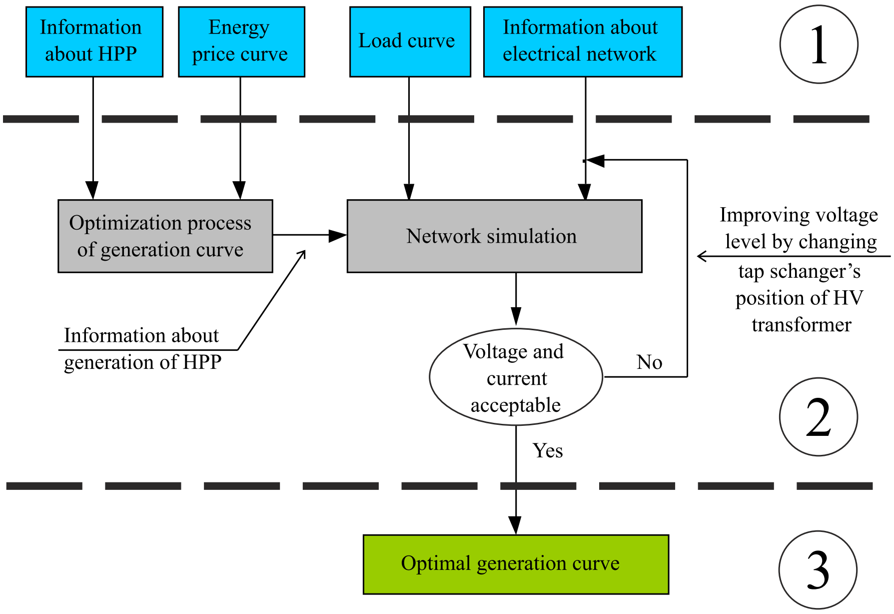

Fig. 1. Structure diagram of the operation optimization module

Simulation and optimization section

The simulation section performs network simulation and uses data about the network from the information input section. For simulation the Newton-Raphson method is used. In the simulation section admittance matrixes for branches (lines and transformers) and information about voltages in nodes are created. This is followed by the iteration process till allowable voltage unbalance reaches the pre-defined value. When the iteration process ends, we get information about voltages in nodes, current in lines, power flows and power losses. Figure 2 illustrates the simulation section.

The optimization module finds the optimal position of HPP floodgate's door for each working period. These optimal positions (from possible positions of the door) ensure the maximum profit for the HPP owner while operating in liberalized market conditions – in situation when prices of electrical energy for the next day are determined by the stock exchange price. To get the maximum profit (income) the following efficiency function is used:

$$F(H_1,\dots,H_{h+1}) = \sum_{i=1}^{h} C_i(Q_i, H_i, H_{i+1}, c_i) \rightarrow \max\ [€], \qquad (1)$$

where h is 24 hours;

C_i is income in hour i [€];

Q_i is an amount of water that goes through the turbine in hour i [m^3];

H_i, H_{i+1} are difference between water levels at the power plant in hour i and $i + 1$ [m];

c_i is the price of electrical energy in hour i [€/MWh].

Optimization is performed taking into account the following constraints:

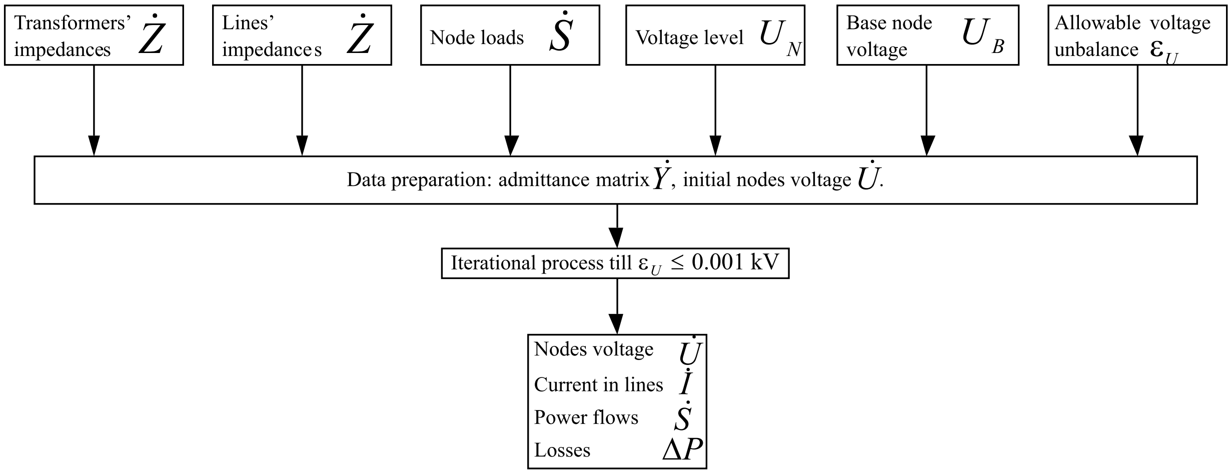

Fig. 2. Illustration to the simulation section description

$$H_{\min} \le H_i \le H_{\max}, \; i = \overline{1, h+1}, \tag{2}$$

where $H_{\min}$ is the minimal allowed water level [m]; $H_{\max}$ is the maximal allowed water level [m].

Optimization also takes into account voltage levels in the nodes. In case if after HPP start voltage in nodes is higher than mentioned in the standard LVS EN 50160 [5], the optimization module decreases the power of HPP at the hour with high voltage.

In liberalized electricity market situations HPP should work with possibly higher water level in the reservoir that in its turn will ensure the highest efficiency of water usage. In such situation it is more economical to use Kaplan turbines in such HPPs. The Kaplan turbine has adjustable runner blades that ensure operation with constant efficiency even when water level in the reservoir is changing.

For optimization it is assumed that operation of HPP will start at time 00:00 of the next day. At the start moment of HPP the level of water in the reservoir is at some level $H_{beginning}$ and lies between minimal and maximal allowed water levels of the reservoir. Making optimization it is assumed that during one day HPP should use the amount of water that is exactly the same as flows in the water reservoir.

At the beginning of the optimization process, all possible water levels should be calculated. The process starts with the water level – $H_{beginning}$. In case if the floodgate has only 3 possible states: 1) fully opened; 2) half opened and 3) closed, water level at the next hour can have 3 values. Each of the 3 possible water level positions of the second hour will give us 3 new positions in the third hour. In an ideal case some of the positions will be the same and in such a way it is possible to have economy of computer memory. But in common, at the 3rd hour there can be up to 9 different states of water level. In such manner we should make calculations for all 24 hours of a day (Fig. 3 (a)).

After all water level positions are found, we should delete all useless water levels – such levels, that exceed minimal or maximal allowed values or, for 24th hour, do not have the same value as the beginning value of water level. This process is illustrated by Fig. 3 (b). Water level states painted in red are deleted.

The second stage of the dynamic optimization process uses the so-called "backward calculation". It starts from the 23rd hour and goes to the first hour. At every stage (hour) profit from water level changes is evaluated and the way of the maximum profit is selected. Figure 4 (a) gives an example – at the 23rd hour (corresponds to 24th water level because $H_{beginning}$ is assumed to be the 1st water level) every water level (1, 2 and 3) has the only possibility of water change because there is only one water level at the 24th hour. So, water level change from position 1, 2 or 3 of 23rd hour to position 1 of 24th hour is the optimal water level change for each of positions:

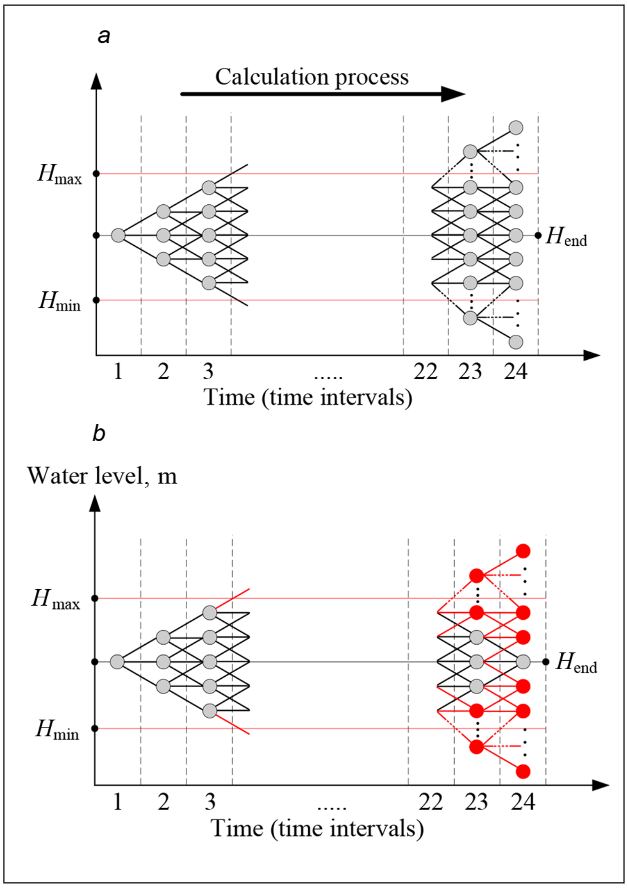

Fig. 3. *a* – illustration to the optimization module (dynamic programming); *b* – excluding useless water level

$$C_{24} = \begin{pmatrix} f(Q_{24}, H_{24.1}, H_{25}, C_{24}) \\ f(Q_{24}, H_{24.2}, H_{25}, C_{24}) \\ f(Q_{24}, H_{24.3}, H_{25}, C_{24}) \end{pmatrix}. \tag{3}$$

After getting information for 23rd hour we go to 22nd hour. At this hour water level positions 2, 3 and 4 have different possibilities for water level change because they can go to the 1st, 2nd or 3rd position of the 23rd hour. After making calculations we can compare the results for the levels of water of 22nd hour and choose the corresponding water level change for each water level with the maximum profit.

In Fig. 4 (a) the best option for the 2nd level of water of 22nd hour is to go to 1st water level of 23rd hour (green line).

In a similar way all the best ways of water level changes are calculated till we reach the first hour. When reaching the first hour program should start selection process of the best possible way of water level change (moving forward). It starts from the 1st hour and goes till the last hour. The best water level change selection is illustrated in Fig. 4 (b).

To calculate power given to the grid by HPP there can be used the following equation:

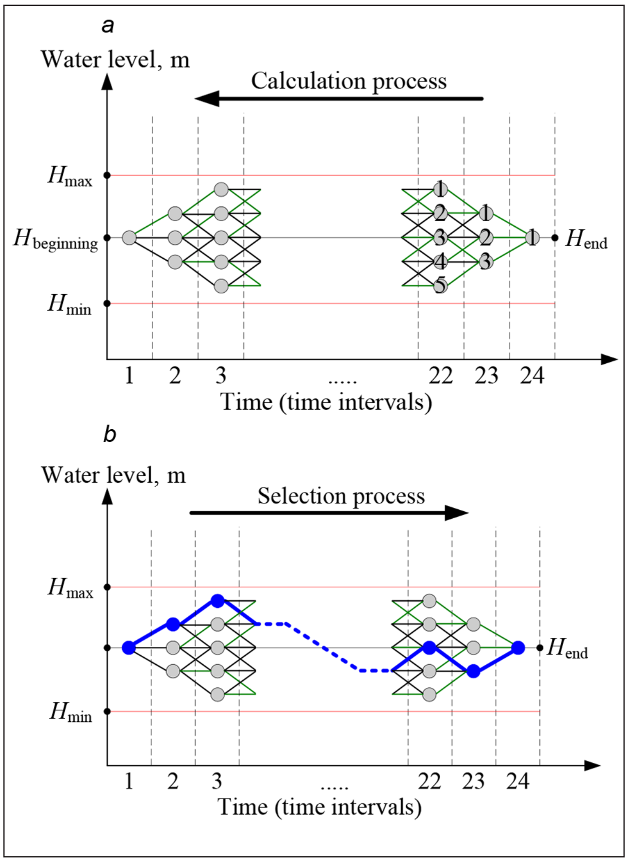

Fig. 4. *a* – backward calculation; *b* – selection process of the best water level change

$$P_i = Q_i \cdot g \cdot \eta \cdot \left(\frac{H_i + H_{i+1}}{2} \right) \text{ (kW)}, \qquad (4)$$

where g is the acceleration of free fall (constant) – 9.81 [m/s^2]; η is the efficiency of whole HPP – 0.85%.

Efficiency of HPP was assumed constant because new small HPP's use Kaplan turbines with effectively controlled blades. This allows keeping constant efficiency even with changing water level in the reservoir. Here it should be mentioned that output power of HPP still changes with changes of water level because of different pressure of water.

To calculate the maximal amount of water that can go through the HPP we used HPP's nominal data η, H and P in such a way that from the previously mentioned equation it was possible to express Q that corresponds to the maximal power of HPP.

Optimal operation schedule output section

This section gives the result – an optimal generation curve for a small hydro power plant. Taking into account that optimization uses water level changes in its optimization, the model is capable to show not only an optimal generation curve but also changes of water level in the reservoir, states of the floodgate (water gate), money earned at every hour. In addition to the aforementioned, the module allows to see technical parameters – voltages and currents of the steady state of the network – when HPP is already in operation.

Transient process simulation module

This section gives a description of the transient process simulation module developed by IPE for a small HPP impact assessment for the load-generator interaction scenario, which will then be used in the model tests (case study) on the basis of a real example. To assess the impact of a new generator connection to the existing network, taking into account technical limitations as thermal limitations (according to the maximal allowed current) of power lines and values of voltages in nodes of the network, an electric model of a small scale HPP was created (flowchart in Fig. 5), which simulates the transient process of the asynchronous machine.

Various models related to the field of transient processes appearing in an electrical machine itself have been developed with different objectives and methodologies, these are reviewed in [6, 7]. But in the model presented at this paper authors look at transient processes in the

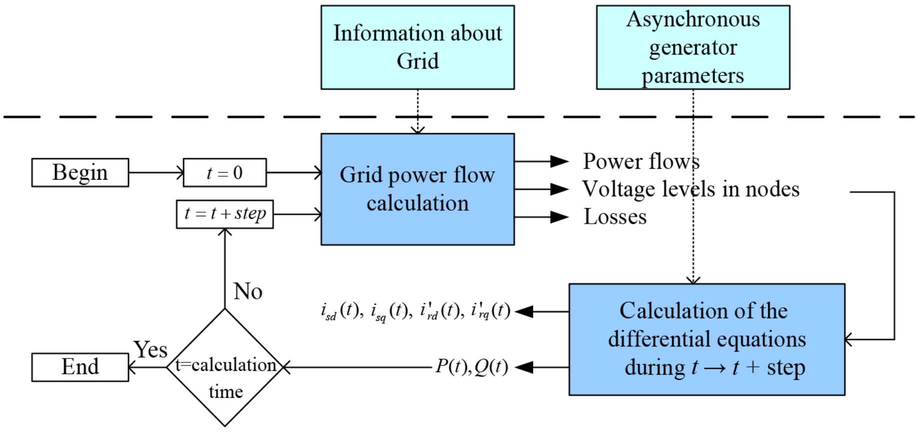

Fig. 5. Flow chart of the developed module

electrical machine (generator) together with the network. Authors of the paper do not have any evidence of models that allow studying the transient process of the generator in combination with the electrical network and due to the fact the model could be very valuable for scientists, DSOs and project developers.

The developed module for transient processes simulations consists of two parts – information input section (above dashed line) and simulation section (below dashed line). The latter is based on two mathematical submodels – the power flow model and asynchronous generation model.

Information input section

In this section, information about grid and HPP is inputted in the model.

Information about the grid consists of the following data:

- Power line and transformer impedances;
- Types of loads (load curves) and load values at load points of the grid;
- Information about grid voltage and voltage regulation possibilities;
- Base (slack) node;
- Allowable voltage unbalance (for network simulations).

Information about the HPP asynchronous machine comprises the following data:

- Maximum installed capacity of the generator;
- Nominal voltage level;
- Rated frequency;
- Stator resistance and leakage inductance;
- Rotor resistance and leakage inductance;
- Magnetizing inductance;
- Combined rotor and load inertia constant;
- Number of pole pairs;
- Shaft mechanical torque;
- Initial value of slip.

After information on the grid and generator is entered, calculation can be performed.

Simulation section

Simulations begin with the step “zero” – when HPP is not connected to the grid. When the simulation for the step “zero” has been performed, we received an initial state of the grid with known values of power flows, voltage levels in nodes as well as losses in power lines.

At the next time step “$t = t +$ step”, the generator is connected to the network. Using data of the grid from the initial state ($t = 0$), differential equations, that describe the electrical machine, should be solved. As a result, we receive the active and reactive power that is produced and consumed by the generator as well as currents of the generator. These results are then put in grid power flow calculations and the calculation process is repeated. The calculation interval “step” is chosen small enough to see dynamics of transient processes.

Calculations are being performed for such time period that is big enough for the transient process.

The electrical machine used in the transient process simulation module is assumed as an idealized electrical machine and calculations are made using the per unit system in the *dq* coordinate system. The used idealized machine, usage of the per unit system, as well as equations, that have been created and used for evaluation of transient processes, are being described further.

Idealized electrical machine

Identification of all mathematical relationships is practically impossible so the solution is in approximation of the number of factors. It means that we set aside the so-called second level factors, whose impact on the transient process is not important.

The differences between the idealized and the real machine [8–12]:

- The magnetic circuit is not saturated;
- Hysteresis phenomena and losses of the steel are not taken into account;
- Distribution of magnetization forces is assumed to be sinusoidal, higher harmonics are not taken into account;
- Leakage inductive impedance is assumed to be independent from the rotor position.

Asynchronous machine equations in relative values

In case of usage of the per unit system (p. u.), all values are expressed as a part of the base rate. The base values are different for different machines. When studying the transient process of the electrical machine, machine nominal values are being used as base values. 3-phase winding is placed in both stator and rotor. Rotor winding parameters are being reduced to the stator side. Stator and rotor windings are connected in the star connection.

Following base units are used in calculations in relative values:

$f_b = f_n$ – Base frequency [Hz];

$U_b = \sqrt{2 \cdot U_{fn}}$ – Nominal stator voltage amplitude, phase voltage value [V];

$I_b = \sqrt{2 \cdot I_{fn}}$ – Nominal current amplitude [A];

$Z_b = \frac{U_b}{I_b}$ – Base resistance [Ω];

$P_b = \frac{3}{2} \cdot U_b \cdot I_b$ – Base power [W];

$\omega_b = \omega_{\text{sinhr.}}$ – Angular base frequency [rad/s];

$L_b = \frac{Z_b}{\omega_b}$ – Base value of inductance [H];

$M_b = \frac{P_b \cdot p}{\omega_b}$ – Base value of torque [Nm];

$T_j = \frac{J \cdot \omega_b^3}{P_b \cdot p}$ – Interia constant of machine [p. u.].

Asynchronous machine equations in dq coordinate system in relative values

The induction motor unit can be operated in the generator or the motor mode. The operation mode is determined by the mechanical shaft torque:

If M_{sl} has a positive value, then machine works in the motor mode;

If M_{sl} has a negative value, then machine works in the generator mode.

The electrical part of the machine is described by a fourth-order differential equation, but the mechanical part is described by second-order differential equations. All electrical parameters are reduced to the stator side. Stator and rotor values are presented as the two-axis system – *dq* coordinate system (Fig. 6). Following subindexes are used in Fig. 6 [13]:

d – *d*-axis value;
q – *q*-axis value;
r – Value related to the rotor;
s – Value related to the stator;
l – Leakage inductance;
m – Magnetizing inductance.

For description of asynchronous machine, the system of following differential equations has been used:

$$
\begin{aligned}
&U_{sd} = R_s \cdot i_{sd} - \omega \cdot \psi_{sq} + \frac{d\psi_{sd}}{d\tau} \\
&U_{sq} = R_s \cdot i_{sd} - \omega \cdot \psi_{sq} + \frac{d\psi_{sd}}{d\tau} \\
&U'_{rd} = R'_s \cdot i'_{rd} - (\omega - \omega_r) \cdot \psi'_{rq} + \frac{d\psi'_{sd}}{d\tau} \\
&U'_{rq} = R'_r \cdot i'_{rd} + (\omega - \omega_r) \cdot \psi'_{rd} + \frac{d\psi'_{rq}}{d\tau} \\
&T_j \cdot \frac{d\omega_m}{d\tau} = M_{em} - M_{sl} \\
&\frac{d\Theta_m}{d\tau} = \omega_m
\end{aligned}
\tag{5}
$$

where:

$$
\begin{aligned}
&\Psi_{sd} = L_s \cdot i_{sd} + L_m \cdot i'_{rd} \\
&\Psi_{sq} = L_s \cdot i_{sq} + L_m \cdot i'_{rq} \\
&\Psi_{rd} = L'_r \cdot i'_{rd} + L_m \cdot i_{sd} \\
&\Psi_{rq} = L'_r \cdot i'_{rq} + L_m \cdot i_{sq} \\
&L_s = L_{ls} + L_m \\
&L'_r = L'_{ls} + L_m \\
&M_{em} = \Psi_{sd} \cdot i_{sq} - \Psi_{sq} \cdot i_{sd}
\end{aligned}
$$

where asynchronous machine parameters are defined as follows (all quantities are referred to the stator):

R_s, L_{ls} – Stator resistance and leakage inductance;
R'_r, L'_{lr} – Rotor resistance and leakage inductance;
L_m – Magnetizing inductance;
L_s, L'_r – Total stator and rotor inductances;
U_{sd}, i_{sd} – d axis stator voltage and current;
U'_{rd}, i'_{rd} – d axis rotor voltage and current;

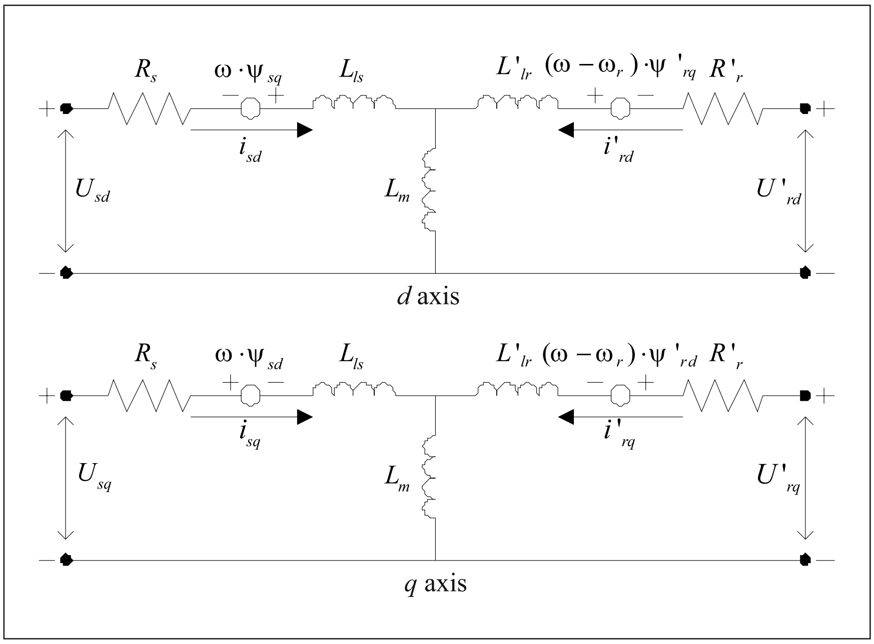

Fig. 6. Induction machine circuit schemes in *d q* coordinates

U_{sq}, i_{sq} – q axis stator voltage and current;
U'_{rq}, i'_{rq} – q axis rotor voltage and current;
Ψ_{sd}, Ψ_{sq} – Stator d and q axis fluxes;
Ψ'_{rd}, Ψ'_{rq} – Rotor d and q axis fluxes;
ω_m – Angular velocity of the rotor;
Θ_m – Rotor angular position;
p – Number of pole pairs;
ω_r – Electrical angular velocity ($\omega_r = \omega_m \cdot p$);
Θ_r – Electrical rotor angular position ($\Theta_r = \Theta_m \cdot p$);
M_{em} – Electromagnetic torque;
M_{sl} – Shaft mechanical torque;
T_j – Combined rotor and load inertia constant;
J – Combined rotor and load inertia coefficient.

The active and reactive power changes during the transient process were determined according to the following expressions:

$$\begin{aligned} P(t) &= U_{sd} \cdot i_{sd} + U_{sq} \cdot i_{sq} \\ Q(t) &= U_{sq} \cdot i_{sd} + U_{sd} \cdot i_{sq}. \\ S(t) &= P(t) + jQ(t) \end{aligned} \tag{6}$$

If a squirrel-cage rotor is used ($U'_{rd} = 0$, $U'_{rq} = 0$) and $\omega = \omega_{\mathrm{sinhr.}} = 1$ ($U_{sd} = U_{\mathrm{GRID}}$, $U_{sq} = 0$), machine's differential equations look as shown in (7) [9].

$$\begin{aligned} \frac{d\Psi_{sd}}{d\tau} &= U_{sd} - R_s \cdot i_{sd} + \omega \cdot \Psi_{sq} \\ \frac{d\Psi_{sd}}{d\tau} &= U_{sq} - R_s \cdot i_{sq} - \omega \cdot \Psi_{sd} \\ \frac{d\Psi'_{rd}}{d\tau} &= -R'_r \cdot i'_{rd} + (\omega - \omega_r) \cdot \Psi'_{rq} \\ \frac{d\Psi'_{rq}}{d\tau} &= -R'_r \cdot i'_{rd} - (\omega - \omega_r) \cdot \Psi'_{rd} \cdot \\ T_j \cdot \frac{d\omega_m}{d\tau} &= M_{em} - M_{sl} \\ \frac{d\Theta_m}{d\tau} &= \omega_m \end{aligned} \tag{7}$$

To solve equations (7), the fourth-order Runge-Kutta method was used.

CASE STUDY

A case study was performed in the Matlab environment. The case study used information about a real small scale HPP located in Latvia near Dobele city – Annenieku HPP [14]. Information about the HPP is given in Table.

Information about the distribution network around the HPP was provided by Latvian DSO – JSC "Sadales tīkls".

A more detailed information on the asynchronous generator and the network, as well as other information used in calculations, is given further.

Description of the case study

The aim of the case study was to test the model and to show its ability to perform HPP's operation optimization and give information on transient processes occurring due to start of HPP generation.

For model testing purposes, an asynchronous motor / generator with a squirrel-caged rotor has been chosen, with the parameters as follows:

$P_n = 250\,000$ W
$U_n(V_l) = 400$ V
$F_n = 50$ Hz
$R_s = 0.013$ pu
$L_{ls} = 0.09$ pu
$R'_r = 0.013$ pu
$L'_{lr} = 0.13$ pu
$L_m = 4.6$ pu
$J = 6$ kg · m^2
$p = 2$

It is known that the optimal operation of HPP and, respectively, the number of starts and stops during a day depend not only on some parameters mentioned in Table, but also on electricity price fluctuations and water inflow.

Information about daily water inflow to the HPP's water reservoir is available from data bases of the state limited liability company "Latvian Environment, Geology and Meteorology Centre" [15]. An example of daily water inflow changes for a year is given in Fig. 7. An average water inflow during a year for HPP is also available in [14].

Information about electricity price for the next day in Latvia can be found at Nord Pool Spot web page [16].

Table. **Parameters of Annenieku HPP**

Parameter	Value
Total installed capacity (kW)	300 (1 × 50 + 1 × 250)
Difference in water levels (m)	8.2
Water reservoir's area (m^2)	274 000
Maximal allowable water level (m)	8.2
Minimal allowable water level (m)	7.9
Efficiency of HPP (in percent) (assumed)	85
Regulation step (in percent) of water gate state (assumed)	1

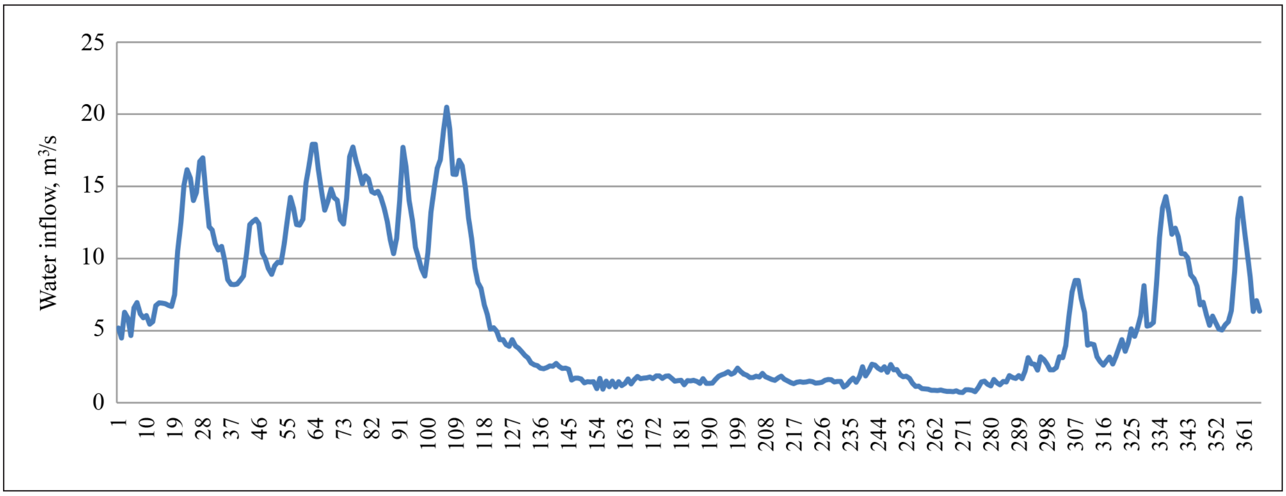

Fig. 7. Daily water inflow statistics to the Annenieku HPP's water reservoir for a year

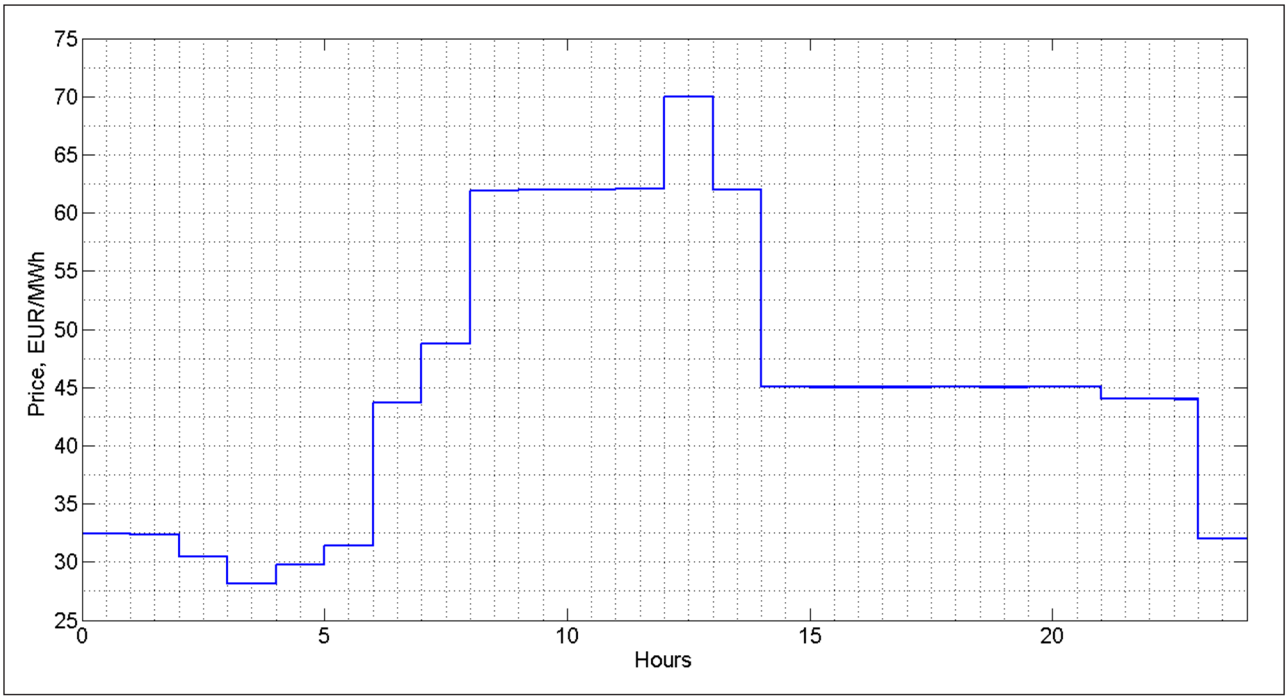

Fig. 8. Electricity price fluctuations during 24-hour period (NPS LV price zone for 1 July 2013)

Figure 8 gives illustration of electricity price changes during 24-hour period for the Latvian price zone of Nord Pool Spot that has been used for calculations.

The distribution network scheme used for calculations is given in Fig. 9. To make calculations more realistic, for each load point (L1...L66) in calculations there were used typical load diagrams of different types of customers, e. g. households, hospitals, commercial institutions, etc. White circles on the feeders represent closed disconnectors. Red circles on the feeders represent opened disconnectors. The hydro power plant is connected to the distribution point DP-2 (marked with a green square).

Making simulation we assumed that water level at the beginning of the simulation process was at 8 meter level. Calculations have been performed for HPP connection with synchronization.

Modelling of load-generation interaction has been done in the Matlab environment.

Results of the case study

Figures 10, 11 and 12 represent the results of calculations obtained in the operation optimization module.

In Fig. 10 we can see an optimal state of the floodgate (opening degree in percent) for every hour of a day (24 hours) as well as power of HPP during each hour. Here attention should be paid to the fact that in spite of constant opening percentage of the water gate the power of HPP changes (decreases). It can be explained by water level

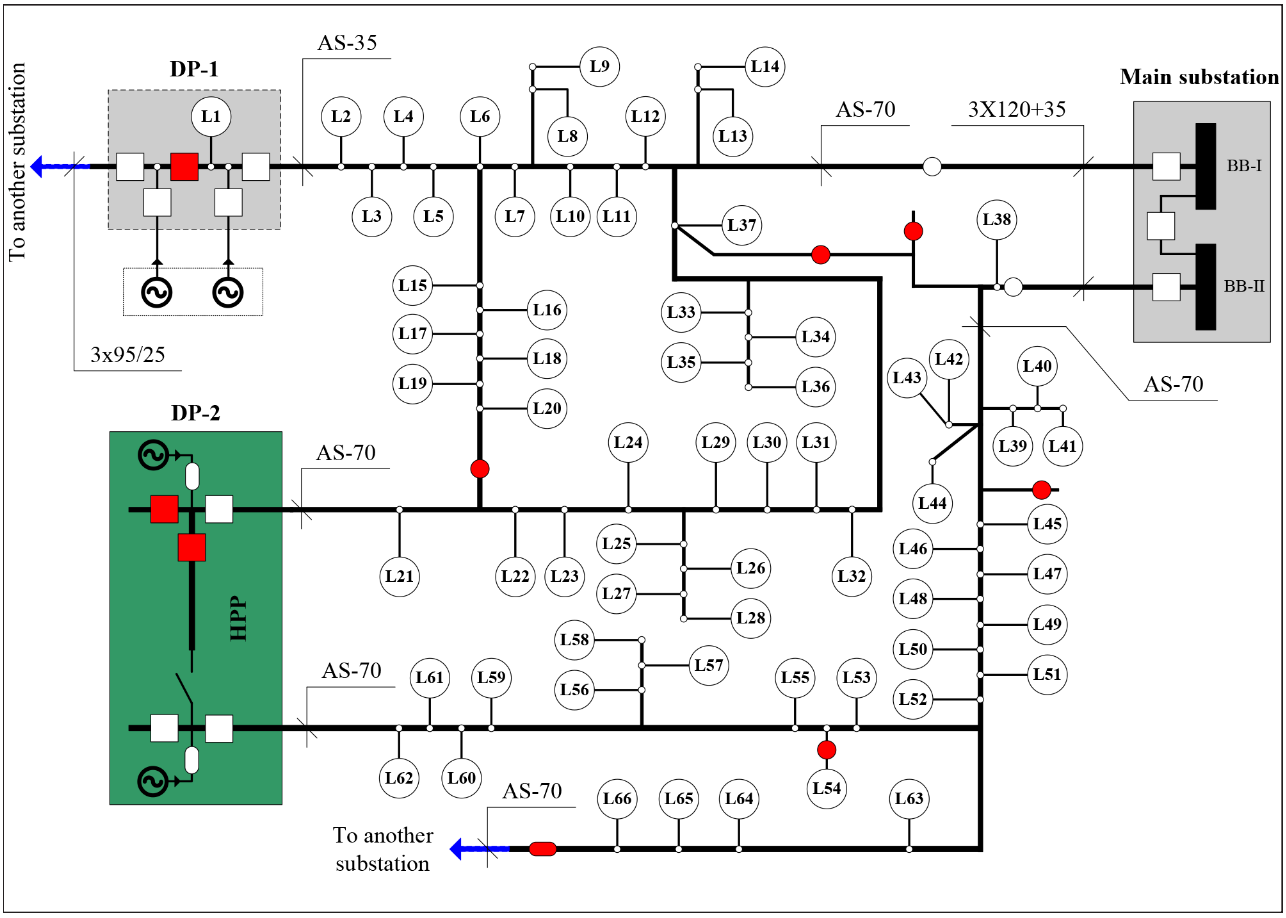

Fig. 9. Distribution network scheme with connected HPP

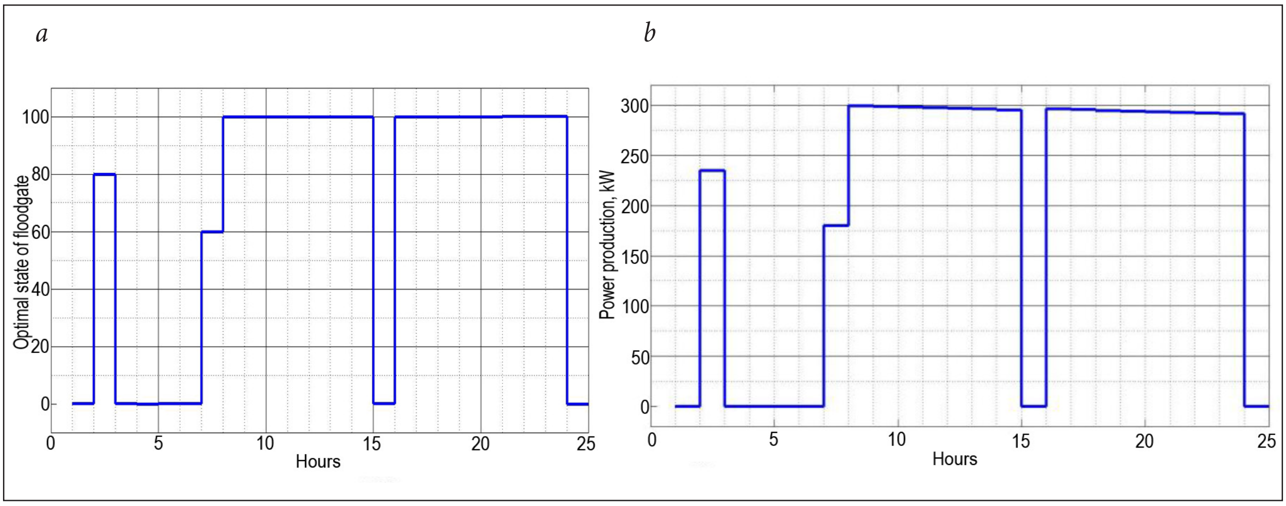

Fig. 10. *a* – optimal state of the floodgate (opening degree in percent) for every hour of a day (24 hours); *b* – power of HPP per hour

changes in the water reservoir during production and the result – lower pressure to the turbine that causes decrease of power.

Figure 5 gives a view of water level fluctuations in the water reservoir of the HPP.

As we can see from Figs. 10 and 11, HPP works at the times of the maximum electricity price, and water level does not exceed minimal and maximal water level thresholds. It means that the developed algorithm for optimization of HPP generation works well.

Calculations performed in the operation optimization module allow evaluating voltage changes in nodes in the stable operation mode after the generator has been connected to the network. Figure 12 illustrates changes of

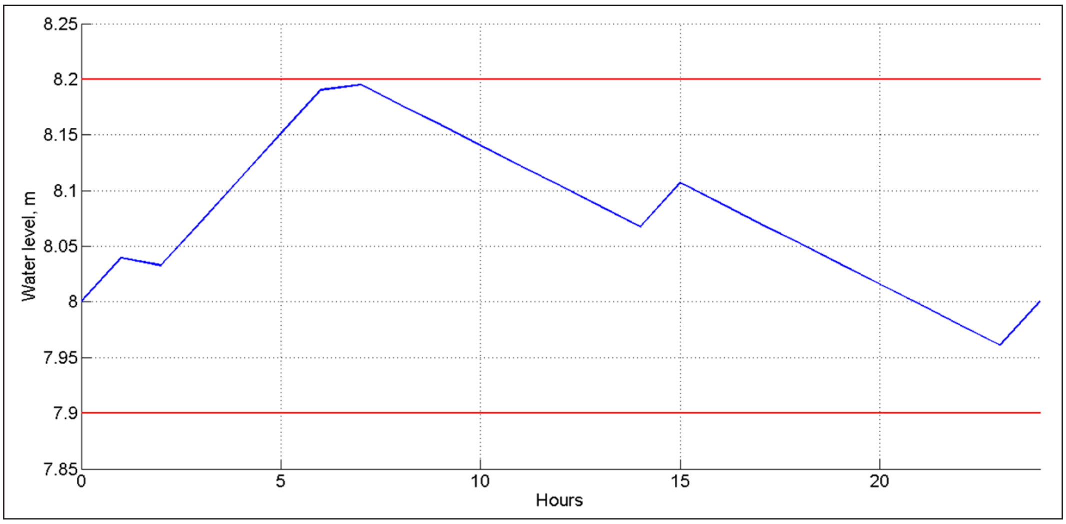

Fig. 11. Water level fluctuations in the water reservoir of HPP

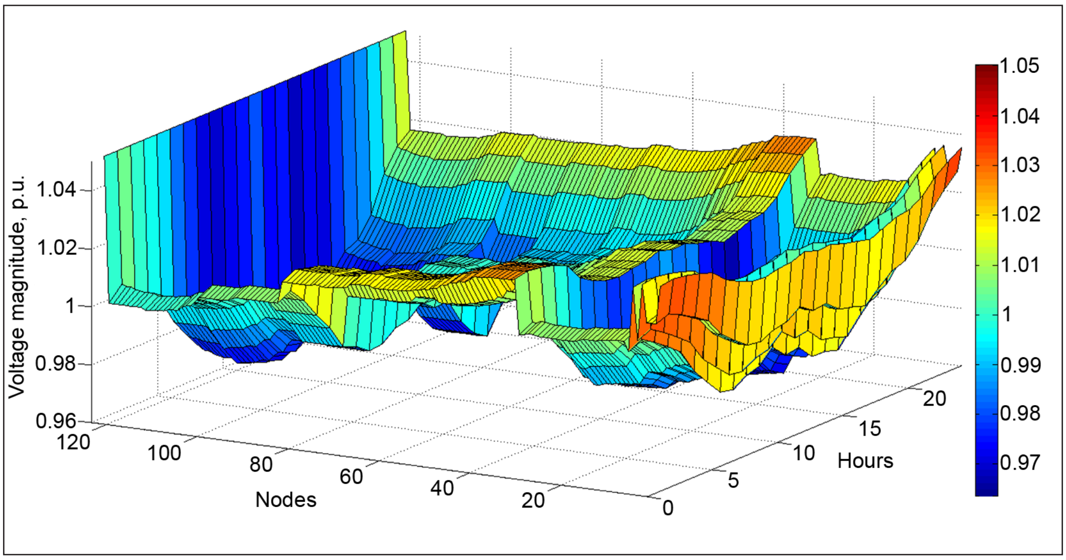

Fig. 12. Changes of voltages at all nodes of the network during a day (24 hour period)

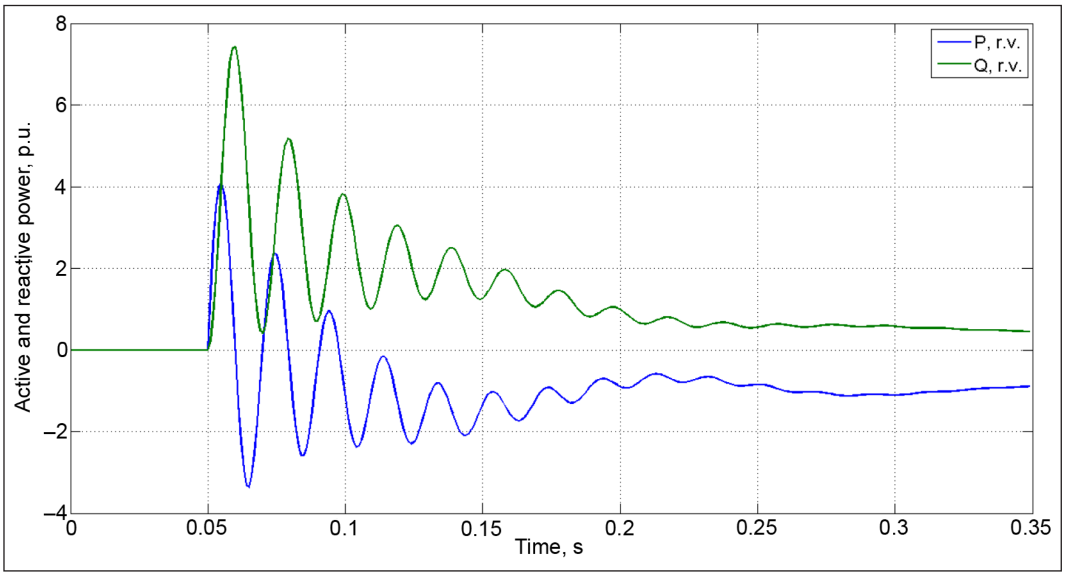

Fig. 13. Changes of the active and reactive power of the asynchronous generator (start at 16 o'clock)

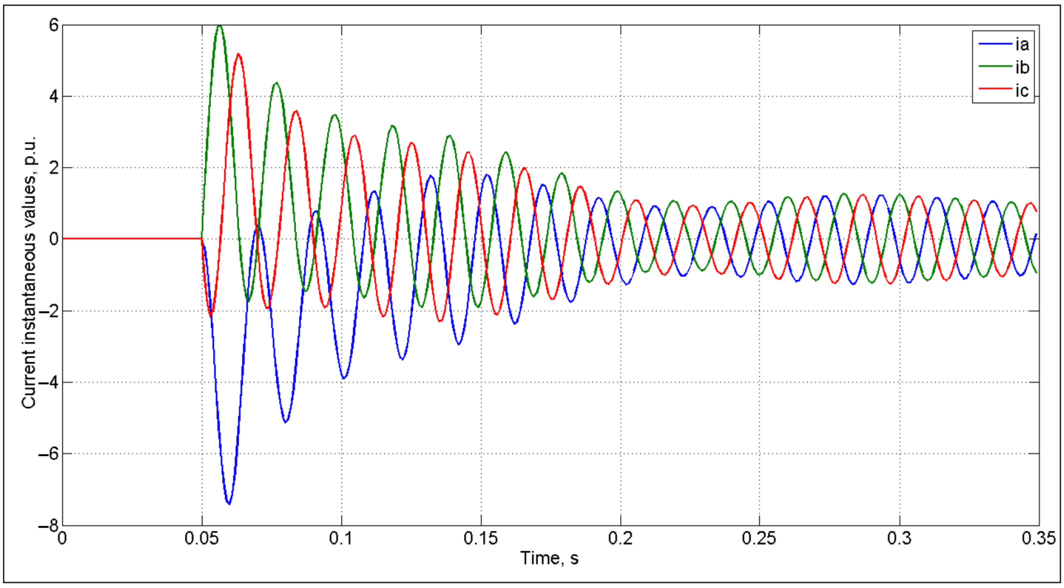

Fig. 14. Changes of momentary values of currents of the asynchronous generator (start at 16 o'clock)

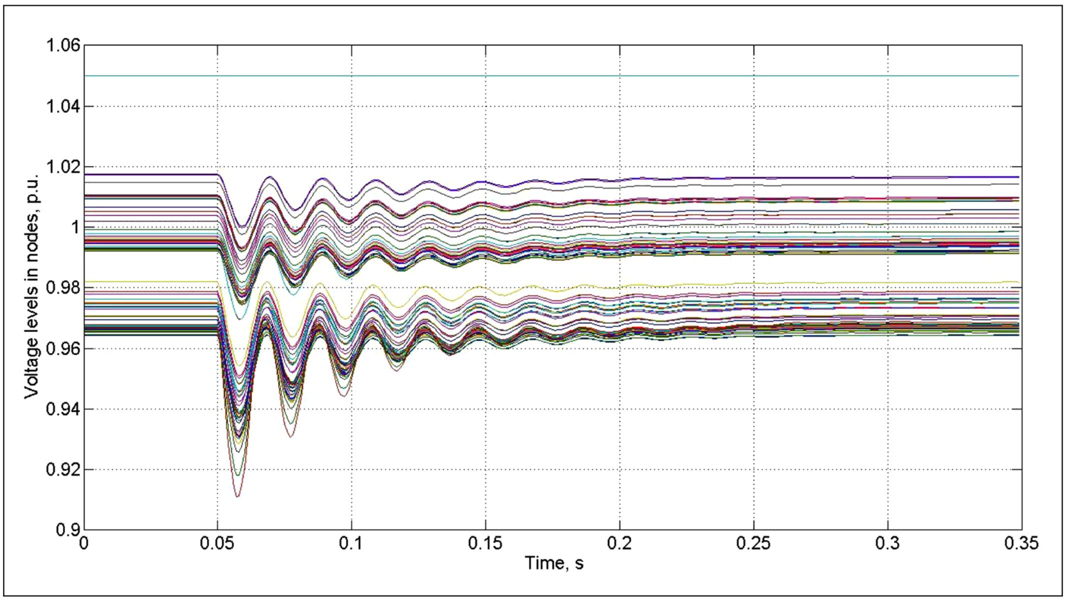

Fig. 15. Changes of voltage in network nodes (start at 16 o'clock)

voltages at all nodes of the network during a day (24-hour period).

Figures 13, 14 and 15 represent startup of the 250 kW HPP generator (at 16 o'clock) and show the results of calculations obtained in the transient process simulation module.

The results represent the case of asynchronous generator connection to the grid with synchronization ($M_{sl} < 0$ – generator mode ($M_{sl} = -1\,512\ N \cdot m$), *slip* = −0.025). This connection technique is usually used in real life, especially for generators with big power. Before connection to the grid, water gate doors of HPP are opened and water pushes blades that in their turn make the rotor to rotate. At the moment when rotation of the asynchronous machine exceeds network's frequency value by 2.5–5%, synchronization of the machine begins and it is connected to the grid.

In case of connection with synchronization (slip value −0.025), oscillations of electrical parameters in the grid appear for the time period 0.15 second, that is small enough for not operating of relay protection. Moreover, voltage level drop during starts does not exceed the allowed level defined in the standard EN50160 "Voltage Characteristics of Electricity Supplied by Public Electricity Networks".

Calculations shown in the paper give an idea of possible model usage in real life. The aforementioned results show if the potentially planned HPP could be connected to the exact place in the network. Simulations of different regimes with different electricity prices, water inflows as well as load in nodes can be performed before making investments in the construction of a new power plant. By this can be identified if the HPP can operate with or without a negative effect on the network and in case of the negative effect simulations can help to answer the question how the potential negative effect can be mitigated. This, in its turn, will allow the personal of DSO to make the decision on possibility of generator connection to some node in the network, as well as decide on the maximal allowed power of generator.

CONCLUSIONS

The model for distributed generation operation optimization and assessment of the impact on the distribution network was developed. The model includes the module for finding an optimal HPP generation plan for 24-hour period that allows one to simulate generation of HPP with high precision using real life conditions – under electrical energy price and water inflow uncertainty. The developed module allows forecasting power flows in the distribution network where HPP is installed. The second module of the model has been developed for full scale calculations of transient processes. The model allows one to see values of currents and voltages occurring during transient processes at a very short time frame after generator start – 0–0.3 seconds. Both modules together offer a tool for extensive evaluation and planning of HPP projects from the technical and economical side.

The model presented in the paper has significant value for distribution system operators as it can be used for coordination of HPP development and relay protection devices installed in the grid. The significance of the model for DSOs is also described by the possibility to use results of the model for evaluation of HPP effect on power quality parameters in the grid as DSO is responsible for major power quality parameters. At the moment Latvian DSO is not capable to make measurements of voltage and current changes in such a small time interval (0–0.2 seconds) with high precision as it is very complicated. The reason is that Latvian DSO is interested in the developed model as it allows evaluating the effect of the generator on network. The model is also important for developers of projects of small scale HPPs as well as it allows evaluating the effect of HPP connection on the grid before making investments in HPP construction. In case of construction of a new HPP and having different connection options, the developed model allows to choose the best location for construction of a power plant as it can help to choose such place in the grid that needs no or needs less investments to the grid in comparison to other possible locations. In case of reconstruction of the existing power plant (by improvement of generation capacities) or having plans to operate in the power market, the developed model makes it possible to evaluate further impact of HPP to the grid and identify the need for network improvement. So, it allows both DSO and the HPP owner to evaluate possibilities for improvement and plan their investments.

Taking into account that the developed models have been created in the Matlab environment, they can be used by a wide number of professionals and the models have almost unlimited opportunities for improvement and development of functionality. For example, the models can be accomplished with a separate module for evaluation of HPP operation on relay protection of the grid.

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MAŽOS GALIOS HE ĮJUNGIMO Į PASKIRSTYMO TINKLĄ ĮTAKA VERTINANT ELEKTROS ENERGIJOS GENERAVIMO OPTIMIZAVIMĄ

Santrauka

Straipsnyje pateikti pagrindiniai dviejų metų SmartGrids ERA-NET projekto „Efficient identification of opportunities for Distributed Generation based on Smart Grid Technology (SmartGen)“ įgyvendinimo Latvijoje tikslai ir pasiekimai. Pasiūlyti pagrindiniai hidroelektrinių (HE) eksploatacijos sąlygų optimizavimo principai naudojant prognozuojamas elektros energijos kainas ir vandens debitų vertes bei asinchroninio generatoriaus prijungimo prie skirstomojo elektros tinklo įtakos vertinimas atsižvelgiant į jo techninius parametrus.

Sukurtas modelis įvertina pačius svarbiausius HE techninius parametrus ir skirstomąjį elektros tinklą, leidžiantį atlikti HE elektros energijos gamybos prognozavimą ir jo įtaką tinklui naudojant priklausančius nuo laiko dinamikos ir nuolatinius įvesties parametrus. Mažos galios HE matematinis modelis sukurtas HE elektros gamybos ir pereinamųjų procesų vertinimui.

Straipsnyje pateiktas analizuojamojo atvejo aprašymas ir rezultatai siekiant patikrinti ir įvertinti matematinį modelį. Pasirinkto atvejo analizė atlikta naudojant realius skirstomojo elektros tinklo, dirbančio kartu su HE, duomenis. Modeliuoti skirtingi elektros energijos gamybos ir apkrovos scenarijai. Modeliavimas atliktas programinio paketo MATLAB aplinkoje.

Išvystytas modelis gali būti naudojamas HE ir skirstomojo tinklo darbo režimų tyrimui bei pritaikytas kitų tipų elektrinių eksploatacijos vertinimui.

Raktažodžiai: paskirstyta generacija, dinaminis programavimas, hidroelektrinių gaminama elektros energija, matematinis modelis, optimizavimas, elektros paskirstymas, išmanieji tinklai

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ОЦЕНКА ВЛИЯНИЯ ПОДКЛЮЧЕНИЯ ГЕНЕРАТОРА МАЛОЙ ГЭС В СУЩЕСТВУЮЩУЮ РАСПРЕДЕЛИТЕЛЬНУЮ СЕТЬ В УСЛОВИЯХ ОПТИМИЗАЦИИ ГЕНЕРАЦИИ

Резюме

В статье представлены основные цели и достижения в Латвии проекта „Efficient identification of opportunities for Distributed Generation based on Smart Grid Technology (SmartGen)“, в рамках научной программы SmartGrids ERA-NET.

Целью представленного исследования является разработка модели малой гидроэлектростанции (ГЭС) с учетом оптимизации выработки электроэнергии при прогнозированной её цене и величине притока дебита воды. В работе также оценено влияние подключения асинхронного генератора к существующей сети, принимая во внимание и учитывая основные технические ограничения.

Для моделирования малой ГЭС и учета переходных процессов была разработана математическая модель в среде Matlab. Разработанная модель включает в себя важнейшие технические параметры ГЭС и сети, что позволяет произвести прогноз генерации ГЭС и оценить её влияние на распределительную сеть, используя переменные и постоянные во времени параметры.

В статье также представлены описание и результаты тестировании предложенной математической модели на примере реальной распределительной сети с подключением малой ГЭС. Тестирование осуществлялось для разных сценариев генерации и нагрузки.

Разработанная модель может быть применена для оптимизации работы широкого диапазона ГЭС на рынке электроэнергии, при оценке и анализе распределительной сети, а также может быть адаптирована для моделирования других типов электростанций использующих асинхронные генераторы.

Ключевые слова: распределённая генерация, динамическое программирование, гидроэлектрогенерация, математическая модель, оптимизация, распределение электроэнергии, интеллектуальные сети