Investigation of the Emission Higher Harmonics into the Generator Grid

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Abstract. The article considers a section of the grid with generator voltage busbars (GRU-10 kV) of one of the hydroelectric power plants HPP-I of a large cascade HPP, which supplies electricity to an aluminium plant via two busbars. It is described that the plant load includes converter units, including: transformers, bridge rectifier blocks and saturation chokes, which are powerful sources of harmonic disturbances. An overview of the developed model and the principles of its construction for studying the influence a powerful non-linear load on the generator is given. Analysis of the results calculations on the model showed that the load of an industrial enterprise creates current and voltage distortions in the electrical s not only of the plant itself, but also in urban grids, and on the busbars of the generator voltage HPP-I. The article analyzes the influence of the current effects of a large industrial enterprise load in asymmetric modes on hydrogenerators by evaluating torsional vibrations and tangential vibrations in generators. It is shown that tangential forces of double frequency (100 Hz) practically do not create significant vibration displacements when the natural frequency of the frontal parts basket is adjusted.

1. Introduction
One of the electromagnetic compatibility (EMC) problems is the presence of higher voltage and current harmonics in electrical grids. The procedure for ensuring EMS is prescribed in the Federal Law on Technical Regulation [1]. The permissible values of higher harmonic voltages in general-purpose grids for different nominal voltages are determined by national standards for the quality of electrical energy [2-6], and the currents values are determined by standards for the emission of interference from distorting loads [7-9]. The standards regulate the distortion coefficients of the sinusoidal voltage and current, and the coefficients of the higher harmonics. In accordance with the law on Electric Power Industry [10], the grid operation in violation of the regulations is not allowed. Compliance with the requirements of the national standard for the quality of electric energy is mandatory for all electric grids. The problem of providing high-quality electricity is relevant for grids of different voltage classes, this is reflected in a significant number of works [11-20].

2. Characteristics of the researched grid
Power-consuming enterprises that have installations with non-linear parameters as part of their consumers are often sources of deterioration in the quality of electricity, which affects the energy
consumption indicators of other consumers connected to the same supply grid, as well as the efficiency of the supply grid itself. Additional influence is exerted on the generating equipment if it is connected near the source of distortion or has a direct connection to grid that feeds the electric receivers.

The research was carried out on the example of an aluminum plant, which is a powerful consumer of electricity. Its equipment operates in an uninterrupted technological cycle with almost constant power consumption. The plant power supply is carried out from the 110/10 kV step-down substation, as well as directly from the 10 kV HPP-I buses via two busbars with a length of more than 1 km.

A single-line simplified diagram of the 10 kV distribution electrical grid of an aluminum plant is shown in Fig.1. Nineteen converter units of type B-TPPD-6.25-900 are connected to three sections of buses IA, 1B and II, which include three-winding transformers of type TDNP 25000/10, two bridge rectifier units for a nominal current of 6250 A and a nominal rectified voltage of 900 V, saturation chokes at the input of converter units, which type is DN-6300/50, for regulating rectified voltage.

![Diagram of aluminum plant power supply](image_url)

**Figure 1.** Simplistic scheme of an aluminium plant power supply.

The other load of the plant, as well as the city load, are powered only from the second section of tires connected to two transformers T1 and T2 with a capacity of 63 MVA each with a higher voltage of 115 kV installed on the S-I. The voltage to transformers is supplied from the taps of two overhead lines -110 kV L-7 and L-8, going to the HPP-II.

The power consumed by the electrolysis load of the plant reaches 125 MW, the city load in total consumes up to 6 MW on the two existing feeders.
The controlled converters of the electrolysis workshop available in the plant's power supply system are a powerful source of harmonic disturbances. Converters introduce distortions of the sinusoidal voltage curves both in the electric grid of the plant itself and in other consumers connected to the electric grids of 10 kV and 110 kV. Higher harmonics create additional losses in the supply grids, make it difficult to perform reactive power compensation using the most efficient capacitor batteries for this purpose, affect the errors of electricity metering systems, and the level of higher harmonics in earth fault currents in the 10 kV grid.

The NERC KSC RAS employees a comprehensive study of the problem higher harmonics in electrical grids of an aluminum plant and a city, in order to find economically sound solutions to improve the quality of electric energy are performed. In particular, the levels of higher harmonics emission into the supply grid from the load of the electrolysis shop connected to the GRU buses were clarified, and their influence on the level of higher harmonics in the voltage was estimated.

3. Model of a powerful non-linear load influence

The model for analysis of the powerful nonlinear load influence was made in the Matlab Simulink environment using the "Power System" block as demonstration development modules, including the "Synchronous generator powered by hydraulic turbine with excitement and governor systems" modules. The generated model is shown in Figure 2.

![Model of the power supply of an aluminum plant from the generator voltage tires of a hydroelectric power plant.](image)

The presented model takes into account the configuration section circuit for switching on HPP-I generators, including a hydro turbine, a hydro generator, a control system, a load of own needs, a busbar and a load of aluminum plant receivers, as well as a source of current and voltage distortion. The connection of the generator voltage grid with the 110 kV grid through a 45 MVA transformer, the equivalent system parameters and the grid load are also taken into account to simulate the redistribution of energy flows through the power transformer both to the 110 kV grid and from the 110 kV (for example, when one of the generators is put into repair). In the presented model, due to the great complexity and large volume of calculations in an extensive grid with the need to take into account the
presence of asymmetry and higher harmonics, a simplification is adopted – the separation of the complete switching circuit for all HPP generators on generator voltage buses.

The appearance of higher harmonics is taken into account by an external source with parameters determined by the composition of harmonics and their power (relative amplitude and internal resistance). The harmonic sources power was determined by comparing the harmonic registration data on the busbar near plant receivers and on the generator voltage buses.

In the hydrogenerator model are used a synchronous machine module from examples of the "Power System" block in generation mode. The electrical part of machine is represented by a spatial model of the sixth order and the mechanical part is similar to the block of a simplified synchronous machine. The model takes into account the stator dynamics, the field and the damping system. The model equivalent scheme is presented in the rotor structure.

Symbols used:
d, q - d and q are indices of the longitudinal and transverse axes;
s - stator index;
l, m - indices of the scattering and magnetization inductance;
f, k - index of the field and the damping winding.

The electrical diagram of the model is shown in Figure 3.

The electrical model of the generator includes following equations with respect to voltage drops and flow couplings in the d and q axes:

\[ U_q = R_s \cdot i_q + \frac{d}{dt} \varphi_q - \omega_s \varphi_q, \quad \varphi_q = L_s \cdot i_q + L_{mq} \cdot (i_d + i_{kd}), \]
\[ U_q = R_s \cdot i_q + \frac{d}{dt} \varphi_q - \omega_s \varphi_d, \quad \varphi_d = L_s \cdot i_q + L_{md} \cdot (i_d + i_{kd}), \]
\[ U'_{id} = R_{id} \cdot i_{id} + \frac{d}{dt} \varphi_{id}, \quad \varphi_{id} = L_{id} \cdot i_{id} + L_{md} \cdot (i_d + i_{kd}), \]
\[ U'_{kd} = R_{kd} \cdot i_{kd} + \frac{d}{dt} \varphi_{kd}, \quad \varphi_{kd} = L_{kd} \cdot i_{kd} + L_{md} \cdot (i_d + i_{kd}), \]
\[ U'_{kq1} = R_{kq1} \cdot i_{kq1} + \frac{d}{dt} \varphi_{kq1}, \quad \varphi_{kq1} = L_{kq1} \cdot i_{kq1} + L_{mq1} \cdot i_q, \]
\[ U'_{kq2} = R_{kq2} \cdot i_{kq2} + \frac{d}{dt} \varphi_{kq2}, \quad \varphi_{kq2} = L_{kq2} \cdot i_{kq2} + L_{mq2} \cdot i_q. \]

The main parameters of the model are defined in International System of Units (SI). In the field of determining the machine parameters, rotor type, poles number, winding type, nominal number of revolutions are indicated. The nominal parameters of the machine are specified: power, line voltage, frequency, rated stator current, reactance.

The stator parameters indicate resistance \( R_s \), the scattering inductance \( L_s \) in the d-and q-axes, the magnetization inductance \( L_{md} \) and \( L_{mq} \), etc. The mechanical parameters include inertia coefficient \( J \).
(kg·m²), friction factor $F$ (N·m·s), and pairs of pole $p$. At the same time, it is possible to take into account the rotor magnetic saturation and stator (it was not taken into account in this task).

Since the modelling tasks do not include studies of the starting processes, regulating and operating turbine conditions and control systems, the module of the hydraulic turbine and control system is taken from developments of Matlab Simulink practically unchanged. The adjustment is made in terms of the power source under consideration and operating frequency.

The busbar model (and later power transmission lines) is made in traditional way – by P-cells, taking into account the parameters in a straight sequence. Due to inclusion of relatively short transmission elements (units of kilometers), the zero sequence influence of busbar and power lines is not taken into account.

The model of a two-winding transformer is also traditional and therefore is not given here. The model is made in a three-phase formulation with galvanic isolation between the windings and considering the neutral modes of grid, that is, on the 110 kV side, the windings are connected according to "star" scheme with a grounded neutral, and the windings on the 10 kV side are included in a "triangle" with an isolated neutral. The model takes into account the grid capacity and the generator to the ground.

In the future, when analyzing the developed measures effectiveness, the model is transformed to corresponding changes in the scheme, that is, with the inclusion of additional modules of power transformers and power transmission lines.

During the research, two variants of modeling the source of harmonic distortion are considered. The first option is an independent model, which is represented by a branch with a harmonic source connected in parallel to the load resistance. In this case, intensity of the harmonics generated in grid depends on shunt action of load, i.e. part of harmonic current branches off into the load. This leads to a significant increase in the equivalent harmonic source power and distorts the physics of their occurrence.

The second option takes into account fact that the source of harmonics is load itself, the nonlinearity of its dynamic parameters, the phase distribution unevenness, etc. In this case, it is advisable to accept harmonic source resistance equal to load resistance, which allows you to exclude the offshoot of distortion energy into the load. In a real grid, some of receivers are a source of distortion and harmonics, and other part actually has a damping effect. Since it is not possible to unambiguously distinguish the active load parameters generating harmonics and other distortions in the model, concept of equivalent parameters of the distortion source, i.e. the harmonic source power, is used in future. Moreover, with division of equivalent power for each of significant harmonics.

4. Registration of the harmonic composition voltage
The quality control of the simulation of distortion emission into the 10 kV HPP-I supply grid from the plant load side (1-A and 1-B RU-10 kV PS-I) was performed for the mode of separate operation GRU-10 kV buses, since in this mode, due to the absence of the shunt effect of a passive load, there is no alignment of the harmonic voltage spectrum on the GRU buses. The power supply scheme is shown in Figure 4.

The sources power of higher harmonics is estimated based on data of recording the composition of voltage harmonics on the busbars from the 10 kV aluminum plant buses (1 and 2) and voltage harmonic composition on 10 kV GRU buses (3) when they operate in the combined mode. The connection points of devices for registration are shown in Figure 4.

The initial data of harmonic compositions are given in Table 1.

From the data in Table 1, it can be seen that the main harmonic distortion source is plant load (1-A RU-10 kV PS-I) connected to the F-6 busbar (except for 11th and 19th harmonics). The plant load (1-B RU-10 kV PS-I), connected in this case to the busbar from F-3, is either passive or generates harmonic distortions of a small magnitude, i.e., when the buses are combined in GRU-10 kV, it is actually damping.
Figure 4. Power supply scheme for estimating the emission of higher harmonics and distortions to 10 kV grid feeding the aluminium plant.

Table 1. Harmonic composition of voltage on GRU-10 kV HPP-I buses and 10 kV aluminium plant buses.

| Harmonic number      | 7    | 11   | 13    | 15    | 17    | 19    | 21    | 23    | 25    |
|----------------------|------|------|-------|-------|-------|-------|-------|-------|-------|
| Busbar from the feeder 6 | 1,39 | -    | 4,04  | 6,23  | 0,37  | -     | 0,37  | 1,45  | 1,57  |
| Busbar from the feeder 3 | 0,79 | -    | 0,97  | 1,63  | -     | 0,27  | -     | 0,69  | 0,25  |
| GRU-10               | 0,81 | 0,35 | 2,17  | 2,67  | -     | -     | -     | 0,65  | 0,76  |

The estimation of equivalent power harmonic is performed without taking into account the phase shifts of harmonic components, considering the busbars resistance. The calculations results are summarized in Table 2.
Table 2. Characteristics of higher harmonics sources on the plant load side.

| Harmonic number | The equivalent power of the harmonic source, kVA |
|-----------------|-----------------------------------------------|
| Load on the feeder 6 (1-A RU-10 kV PS-I) | 4,5 27,3 68,1 0,3 2,1 2,1 |
| Load on the feeder 3 (1-B RU-10 kV PS-I) | 0,3 4,2 5,1 - - 0,3 |

The obtained characteristics are included in the model for calculating the harmonic distortion emission, which is used in the study of developed technical measures effectiveness. When analyzing harmonic distortion emission for separate operation modes of the GRU-10 kV HPP-I bus systems, the most powerful distortion source from the aluminum plant load (1-A RU-10 kV PS-I) connected to the F-6 busbar is considered.

5. Technical measures to reduce the emission of distortions to the supply grid
The conducted studies have shown that the direct galvanic connection of powerful load of the aluminum plant with supply grid (GRU-10 kV HPP-I) has a negative impact on operating conditions of hydro generators, which is manifested in increased consumption of their resources. The reason for acceleration of equipment wear is presence of systematic intensive shock actions with sharp changes in the load current, as well as increased emission of currents accompanying transients. In addition, the aluminum plant generates higher harmonics that reach and exceed the permissible levels according to GOST 32144-2013 [2]. Therefore, the main goal of technical measures development is to significantly reduce the emission of shock currents, higher harmonics and currents accompanying transients into the generator voltage grid.

The use of filter-compensating devices (FCD) is an inefficient measure, since they must provide power flows of tens of MVA. In addition, the harmonic source has a high power and compensation of shock effects and transient currents with an amplitude of up to 1.6 kA cannot be obtained from a FCD.

One of possible measures to improve operating modes of HPP-I electrical equipment is the rejection of the plant's power supply system directly from the 10 kV GRU-10 kV buses by busbars means (Figures 1 and 4). Let's consider an alternative option related to transfer of power to the busbars load F-3 and F-6 through power grid.

This will require the installation of two additional 110/10 kV power transformers connected to the GRU-10 kV buses, and construction of a 110 kV power line from the HPP-I to the RU-10 kV plant. In proposed version, the connection through busbars F3 and F-6 are taken into reserve.

6. Conclusion
According to level of experimental registrations of the higher harmonics emission into generator grid, the equivalent capacities of harmonic sources are determined. The equivalent distortion power at the 11th and 13th harmonics is 27 kVA and 68 kVA, respectively. The equivalent sources power of the 23rd and 25th harmonics is 2.1 kVA each. The obtained characteristics are used in analysis of effectiveness of technical measures to reduce emission of distortion in the 10 kV HPP-I supply grid.

Analysis of resistance system influence connected to the GRU-10 kV HPP-I showed that the direction of energy flows through the installed power transformers of 40 MVA does not have a damping effect on higher harmonics emission into the supply grid from the aluminum plant load.

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