on; the line 2401-2280 is turned on and the line 2401-2402 is turned off; the line 2401-2280 is turned off and the line 2401-2402 is turned on. Analysis shows that network configuration influences the occurrence of resonances. When the line 2401-2402 is turned off, the resonances occur close to the 6, 8, 9, 12, 14-th and 21-st harmonics. When the line 2401-2280 is turned off, resonances in the network in relation to the node 2401 occur approximately on the harmonics 12.5 and 18.6.

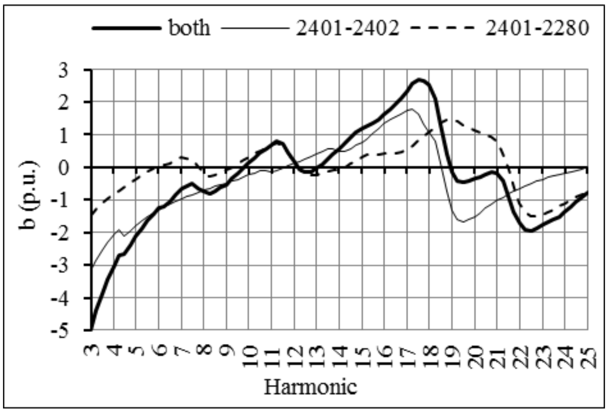

Fig. 3. Frequency response of susceptance for node 2401.

B. Analysis of Resonance Modes in the 110 kV Network Node

Figure 4 illustrates the frequency responses of input admittance, susceptance and conductance of the 110 kV network node. Taksimo railway substation is connected to this node. The substation gains power through the autotransformer from the 220 kV 1000 km long electric network that powers other substations of the railway.

To analyze the resonant modes in a 220 kV network, we used the scheme network of East Siberia, which has 542 nodes with voltages from 10 to 500 kV. The nodes include the following: 27 nodes with generators, 300 nodes with active-inductive and asynchronous load, 81 nodes with large non-linear loads (including railway substations and aluminum plant), 98 nodes with shunt reactors and capacitors, 6 nodes with equivalent circuits of electric network containing non-linear loads. The scheme has 682 connecting link, including power lines, transformers, autotransformers and series compensators.

In the node where Taksimo substation is connected to the network the harmonic factors $K_{U(h)}$ were measured. They were used to model the modes of the electric network. For example, the measured value of $K_{U(5)}$ turned out to be equal 2.57%. After modeling the mode of the 5-th harmonic, the calculated $K_{U(5)}$ value in the node turned out to be close to the measured value and amounted to 2.30%. The calculations showed that at the 5-th harmonic in the connection node of the Taksimo railway substation there is the mode close to the resonance one. The susceptance curve (Figure 4) suggests that conductance turns positive from negative and thereby illustrating series resonance circuits on harmonics 4.5, 6.6, and 8.5. Susceptance turns negative from positive thereby illustrating parallel resonance modes on harmonics 4.9, 7.1 and 10.9. The mentioned harmonics are interharmonics. If currents of the mentioned harmonics are not present in the electric network, then resonance circuits on those harmonics do not constitute any danger.

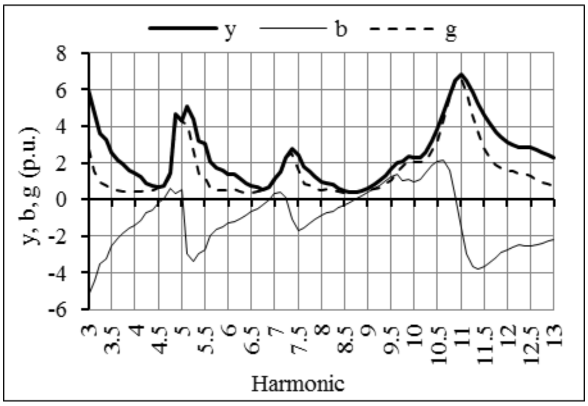

Fig. 4. Frequency responses on the 3-13-th harmonics at the Taksimo railway substation.

C. Analysis of Resonance Modes in the 220 kV Network

Figure 5 illustrates values calculated with the use of HARMONICS software: current, susceptance, admittance and harmonic factor for the 5-th harmonic in nodes of the 220 kV networks.

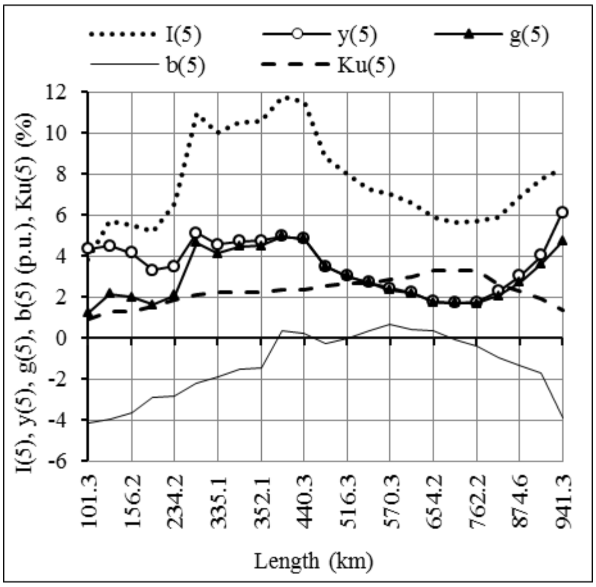

Fig. 5. Parameters of nodes and mode of 220 kV network on the 5-th harmonic

This network powers 23 substations from Slyudyanka (~101.3 km in Fig. 5) to Chita (~941.3 km in Fig. 5). Those two substations are some 840 km far from each other. The curves in the figure show that resonance modes occur on the interval from 400 to 700 km. Susceptance in this area changes its sign four times. In the analyzed area, two series resonance circuits and two parallel resonance circuits occur on the 5-th harmonic. As susceptance falls, admittance also decreases and becomes equal to conductance. Despite the 5-th current harmonic decreases, $K_{U(5)}$ increases, this may be due to the resonance mode in the electric network. Measurements performed on substations confirmed high $K_{U(5)}$. At

Novoilyinsky substation (~516.3 km in Fig. 5) $K_{U(5)}$ totaled 2.07%. Value $K_{U(5)}$ amounted to 2.27% at Kizha substation (~544.3 km in Fig. 5). Both values exceed the limit value 1.5% [14].

D. Analysis of the Resonance Modes that Occurs when the Capacitor Bank is Turned on

The capacitor bank is located at the substation Tataurovo, which belongs to the power supply organization. The capacitor bank has a capacity of 50 Mvar. It is turned on by the operator command. The capacitor bank is designed to maintain the voltage at the fundamental frequency that meets regulatory requirements.

Figure 6 illustrates the $K_{U(h)}$ value measured in phases B and C at the Tataurovo railway substation before and after turning on the capacitor bank. The capacitor bank was turned on the 19-th minute. The curves suggest that values $K_{U(3)}$ and $K_{U(5)}$ increased after turning on the capacitor bank.

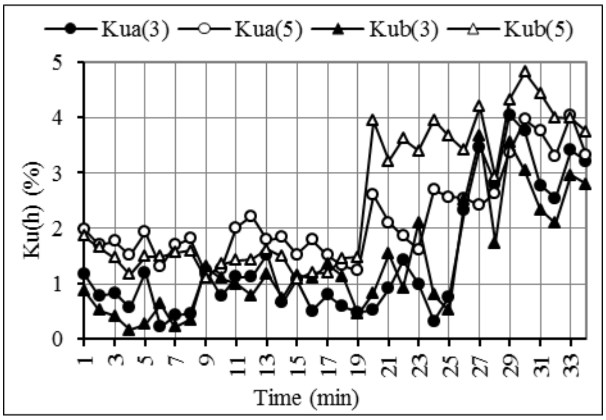

Fig. 6. $K_{U(h)}$ at Tataurovo railway substation.

HARMONICS software helped analyze how the capacitor bank affects the parameters of the network and mode of Tataurovo railway substation. Calculation results for phase A are given in Table II.

Table II. - Parameters of the electric network and mode in the node connection of Tataurovo railway substation

Parameter	*Harmonic*	
	3	5
I(h) (A)	7.8143	14.9198
g(h)CB (S)	0.0	0.0
g(h)NW (S)	0.0046	0.0092
g(h)CB+NW (S)	0.0046	0.0092
b(h)CB (S)	0.0076	0.0127
b(h)NW (S)	-0.0116	-0.0125
b(h)CB+NW (S)	-0.0039	0.0003
y(h)CB+NW (S)	0.0060	0.0092
$K_{U(h)}$ (%) (without CB)	1.14	1.75
$K_{U(h)}$ (%) (with CB)	2.36	2.96
K_L (%)	1.5	1.5

The notations used in the table are: I(h) - the current of the *h*-th harmonic in the electric network node; g(h)CB - the conductance of the capacitor bank; g(h)NW - the input conductance of the electric network node; g(h)CB+NW - the sum of conductance of the capacitor bank and input conductance of the electric network node; b(h)CB - the susceptance of the capacitor bank; b(h)NW - the input susceptance of the electric network node; b(h)CB+NW - the sum of susceptance of the capacitor bank and input susceptance of the electric node; y(h)CB+NW - the admittance of the capacitor bank and electric network node.

The table shows the calculated of $K_{U(h)}$ values in the network node before and after turning on the capacitor bank; K_L is the standard value of the *h*-th harmonic factor. As seen from the table, before the capacitor bank turning on, input susceptance of the network node on the 3-rd and 5-th harmonics was inductive (negative). After the capacitor bank turning on, susceptance of the 5-th harmonic turned positive, which suggests the occurrence of the resonance mode between the 3-rd and 5-th harmonics. As susceptance turned positive from negative, a series resonance occurred. The values of $K_{U(3)}$ and $K_{U(5)}$ increased and significantly exceeded the K_L .

4. Conclusion

Resonance modes in electrical networks occur randomly by various changes in the network configuration and load powers, as well as turning on capacitor banks and and passive harmonic filters.

Resonant circuits and modes in high voltage electrical networks can be determined and analyzed using special software. Resonance modes are one of the reasons for the high values of voltage and current harmonics. This knowledge is very important due to the widespread availability of digital equipment that is sensitive to low quality voltage.

Special software can be used in the operation of electric networks for predicting resonance modes at various harmonics during power quality control.

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