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FREQUENCY DEPENDENCE OF RADIO WAVE SURFACE IMPEDANCE OF CENTRAL YAKUTIA PERMAFROSTBASED ON RESULTS OF NUMERICAL MODELING

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Abstract

The results of numerical modeling of frequency dependence of permafrost surface impedance in a band of 1 Hz to 1000 MHz are shown for typical geoelectric sections (GESs) of Central Yakutia. Particular qualities of frequency dependence are represented by oscillation values in a wide frequency band. The role the bias and conduction currents play is marked. Two main bilayer models of permafrost are discussed: weak-inductive and strong-inductive models. Additional three-six layer models are considered along with indication of their particular qualities and conformity with natural sections. An example of models' comparison with radio impedance sounding data is given. One marks the significance the phase curves of radio impedance sounding possess when used for determination of GES type under condition of approximate automatic interpretation.

Keywords: Numerical modeling, permafrost zone, Central Yakutia, wide frequency band, models' comparison.

I. Introduction

Sharp difference (by a factor of 10 or more)in specific electrical resistance (SER) of horizontal layers appears to bea particular feature of geoelectric section in permafrost zone. The difference is caused by a much higher SER value of a horizon of icy frozen mellow sediments (1000-30000 Ohm×m) in comparison with SER values of either underlying horizons of frozen and thawed bedrocks (100-3000 Ohm m), or bridging horizon of seasonally thawed mellow sediments (20-100 Ohm×m). At the same time, values of relative permittivity for permafrost are quite stable (7-12 units) with small differences. The condition of the SER sharp difference makes it possible to apply effective high-frequency electrical prospecting techniques of geophysics, in particular, the method of surface impedance frequency sounding [I] in a radio wave band (radio comparison and direction finding) [XIII; X]; generally known as radio impedance sounding. It allows using steady alternating electromagnetic field and conducting removed measurements from the surface of environment under investigation. The latest is of great importance while exploring permafrost zone when it has bad conditions of grounding. Besides the dramatic change in the SER values of known horizons, the permafrost zone has several structural features greatly affecting surface impedance. Thus, while conducting regional research on the territory of Yakutia in a frequency band 10…900 kHz, numerous radio impedance soundings have established a presence of thin conductive layer in the permafrost zone [VIII]. Manifestations of the phenomenon were observed in different parts of frequency band. They demonstrated both substantial phase shift between electric and magnetic horizontal components of the field (45-80^{o}) and increased slope steep (> 26^{o}) of frequency dependence asymptote of impedance module in logarithmic scale [VI].

II. Methodical Features

To increase, facilitate and automate approximate interpretation accuracy of electromagnetic sounding of permafrost zones in radio wave band, it becomes necessary to answer a question of how main geoelectric parameters of a environment being studied influence the frequency dependence of surface impedance. As far as natural permafrost zones, when appear together with underlying environment, represent horizontal-multilayer structures in a scale of detector lines (from 5 to 20 m) used for radio impedance sounding, it is sufficient to apply fundamental Tikhonov-Cagniard's magnetotelluric model for considering the frequency dependence of the surface impedance. We assume that horizontal layers lack the property of magnetism and in the considered local plan have isotropic electrical properties. Different ice content in frozen mellow sediments and in bedrocks leads to wide band of SER variation in layers from 200 to 20000 Ohm×m, that is considered as important fact for modeling. Iciness influence on absolute permittivity is not that significant, and relative permittivity of layers can be assumed equal to 10 units. For bilayer models, in simple cases, one can apply an analytical approach to analyze the influence of lamination. However, generally, laminated models – when taking into consideration perception complexity of physical consequences of lamination influence expressed through multilink recurrence formulas, and when studying patterns of influence of main horizons' parameters on surface impedance of permafrost zone – requireapplying of numerical modeling. This refers to computation of surface impedance of laminated environment sorting out variants of layers parameters allowable changing on the basis of developed models of geoelectric construction and typical geoelectric sections (GESs) of the permafrost. Frozen bedrocks (FBR) are taken for datum for permafrost modeling. The FBR capacity is determined by a depth of ground freezing; for Central Yakutia the capacity index is 200-300 meters below the surface. The known example of a thawed zone horizon, which changes its impedance frequency dependence at frequencies below 30 kHz, is thawed bedrocks

(TBR) with the SER index band of 100…1000 Ohm×m. The horizon of frozen mellow sediments (FMS), overlapping FBR, is complicated in its structure, heterogeneous for different areas of Central Yakutia and is understudied in respect of geoelectricity. In certain areas, the FMS capacity index reaches a 150 meters value. Seasonally thawed layer (STL) of mellow sediments is easily available for study and is always present during warm seasons. The STL capacity index for this region is 2 m. It makes a significant impact on surface impedance throughout the entire frequency band. Besides the specified horizons, the modeling FMS zone of permafrost included intermediate layers: a thin conductive layer (TCL) and a thin poorly-conductive layer (TPCL). A priori, these layers are supposed to have local distribution. They are intended to model objects that perturb expected frequency dependence of impedance.

Generally, for permafrost modeling the approach taking into consideration the importance of layers influence has been used: from the upper layer – to the lower one, with limitation of skin-layer thickness. Thus, influence of those layers has been revealed, occurrence depth of which is simultaneously located within the active part of the underlying permafrost and is less than skin-layer thickness for this frequency [VIII].

Electromagnetic field, penetrating the ground and depending on field's frequency and electrical properties of rocks, causes conduction currents, defined by SER values of rocks, and bias currents, defined by the absolute permittivity values. The first Maxwell's equation postulates the well-known ratio of bias and conduction currents density

$$\left|\frac{j_{bias}}{j_{cond}}\right| = \left|\frac{\omega\varepsilon_a E}{\sigma E}\right| = \frac{\omega\varepsilon}{\sigma} \quad , \tag{1}$$

Where σ is ground conductivity, ε – relative permittivity. The $|j_{bias} / j_{cond}|$ ratio is a parameter that defines environment's electrical properties for alternating field with constant frequency. If condition $\sigma / \omega >> \varepsilon$ holds true, then conduction currents prevail in environment, and the environment itself becomes close to conductor. On the other hand, when the $\sigma / \omega << \varepsilon$ ratio holds – bias currents come to prevail, environment's properties are close to insulator.

Surface impedance of homogeneous isotropic non-magnetic ground, as a complex quantity, can be represented by a well-known formula [IV]

$$Z = \frac{120\pi}{\sqrt[4]{(\omega\varepsilon)^2 + \sigma^2}} e^{i0.5arctg(\omega\varepsilon/\sigma)} \tag{2}$$

Here, the module of the surface impedance is

$$|Z| = \frac{120\pi}{\sqrt[4]{\varepsilon^2 + (\sigma/\omega)^2}} \tag{3}$$

and its argument or phase is presented by

$$\arg Z = 0.5\, arctg\,(\omega\varepsilon / \sigma) \,. \tag{4}$$

Correlation between bias and conduction currents in expressions (2-4) determines the nature of their frequency dependence.

Substituting expression (1) in (4), we get that

$$\frac{\omega\varepsilon}{\sigma} = tg(2\arg Z) \,. \tag{5}$$

This implies that if conduction currents prevail in homogeneous environment, then $\arg\delta \geq 42^\circ$, **and if bias currents – then** $\arg\delta \leq 3^\circ$**.**

Numerical modeling is conducted – using parameters of typical GESs, known by results of electrical prospecting at constant current – to investigate the impact made by laminated permafrost upon surface impedance. Module and argument (phase) of laminated permafrost models' surface impedance have been calculated using (3, 4) expressions taking into consideration a correction factor that estimates layers influence by a well-known recurrence relation [XIII]. Computations are made considering bias currents. Values are derived for alternatives network in a frequency band 1 Hz – 1000 MHz. Varying GES parameters and taking into consideration electrical properties of frozen and thawed bedrocks, primary patters of frequency dependence changing are established [VIII; IX].

III. Results and Discussion

Radio impedance sounding uses a field of removed radio stations in a frequency band of 10-1000 kHz. To better represent frequency dependence of surface impedance, varying conduction-to-bias currents ratio in this band, it has been required to significantly extend the frequency band. The modeling of frequency dependence of permafrost's surface impedance – conducted in the wider band from 1 Hz to 1000 MHz – allowed obtaining complete frequency curves that led to ambiguous results.

Complete curves of surface impedance frequency dependence of permafrost denote more or less oscillation pronounced of impedance's module and phase values along corresponding values for homogeneous half-space with electrical parameters of one of the layers. The layer is determined by its decisive role within the limits of skin-layers' thickness for a frequency given. Oscillations are brought about by overlay of fields and emerge when different current types – bias or conductivity – prevail in neighboring layers.

In his work, Bulgakov (1962) explains the emergence of oscillations of surface impedance by interference of a direct and layer boundary reflected fields. He noted, that «surface impedance of bilayer environment shows oscillating properties at those frequencies on which bias currents outweigh conduction ones in the upper layer».

The statement requires certain clarification. At first, emerging of oscillations of surface impedance of bilayer environment simultaneously requires a) bias currents prevailing in the upper layer and b) conduction currents outweigh in the bottom layer. In the second, surface impedance is subjected to oscillations also at those frequencies on which conduction currents prevail in the upper layer, and bias currents – in the bottom one layer.

Traditionally, one describes simple models of permafrost's geoelectrical construction by two types of bilayer models: weak-inductive and strong inductive models. These names, originating from the theory of radio wave propagation, are analogous to terms referring to argument of complex impedance which are being used in the electric circuit theory, [XI]. Models correspond to sections with conduction currents predominance in one of the layers (inductivity analogue) and with bias currents outweighing in the other (electrical capacity analogue).

Having bilayer permafrost presented as electric circuit with distributed parameters, we obtain a series connection of either inductivity orelectrical capacity, or vice versa. By capacity, we mean poorly conductive horizon of frozen mellow sediments, by inductivity – STL conductive horizon, or FBR relatively conductive horizon. Similarly to resonance in serial electrical circuit we obtain in first approximation two models of the permafrost zone. These bilayer models are considered as a basis for the following interpretation of frequency dependencies of module and argument of the laminated permafrost surface impedance.

<u>Weak-inductive bilayer model</u> (conductor on insulator) induces normal or low slope of frequency dependence curve of a module of surface impedance at low and average frequencies. Further frequency increasing makes the module value of the surface impedance with oscillation approach a curve corresponding to the upper layer (Figure 1).

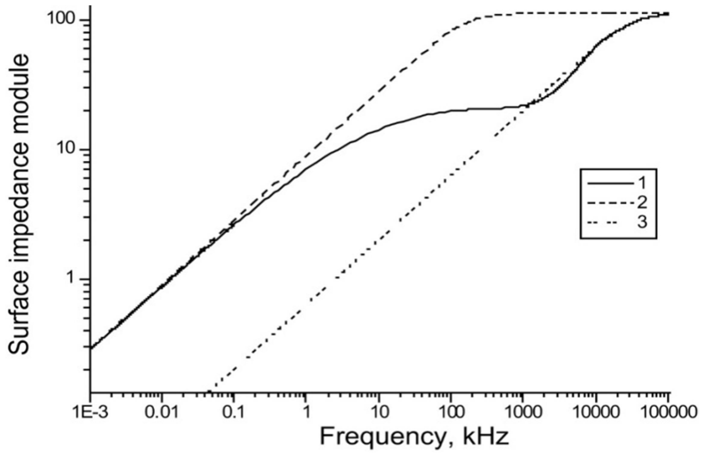

Fig. 1: Frequency dependences of the surface impedance module:

1 is for weak-inductive model ($\rho_1 = 50\,Ohm \cdot m$, $h_1 = 1\,m$, $\rho_2 = 10{,}000\,Ohm \cdot m$); 2 is for homogeneous half-space with $\rho = 10{,}000\,Ohm \cdot m$; 3 is for homogeneous half-space with $\rho = 50\,Ohm \cdot m$

Its' argument value first decreases from 45^o to 0^o along with frequency's amplifying, and then, increasing with oscillation, approaches the upper layer curve and remains oscillating around it with low amplitude.

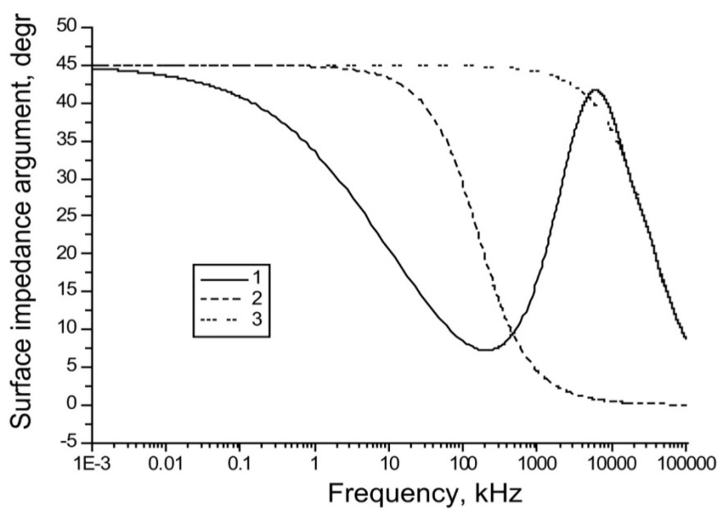

Fig. 2: Frequency dependences of the surface impedance argument:

1 is for weak-inductive model ($\rho_1 = 50\,Ohm\cdot m$, $h_1 = 1\,m$, $\rho_2 = 10{,}000\,Ohm\cdot m$); 2 is for homogeneous half-space with $\rho = 10{,}000\,Ohm\cdot m$; 3 is for homogeneous half-space with $\rho = 50\,Ohm\cdot m$

The shapes of frequency dependencies are caused by a) outweighing of conduction currents in the upper layer with a low capacity in comparison with thickness of skin-layer, and b) by bias currents predominance in the bottom layer. In nature, the model complies with potent FMS horizon, overlapped by a thin layer of thawed mellow sediments with low SER value. The weak-inductive model is acceptable in the band of average and high frequencies (> 300 kHz), for which the skin-layer thickness does not exceed the capacity of structurally homogeneous FMS.

Strong-inductive bilayer model (insulator on conductor) at frequencies < 1000 kHz reveals increased slope steepness of frequency dependence curve of surface impedance (>27°) module and argument, both of which are continuously growing from 45° to 90° with increase of low and average frequencies. These forms represent entries, which at high frequencies turn into oscillations of values along the curves corresponding to the upper layer (Figures 3, 4).

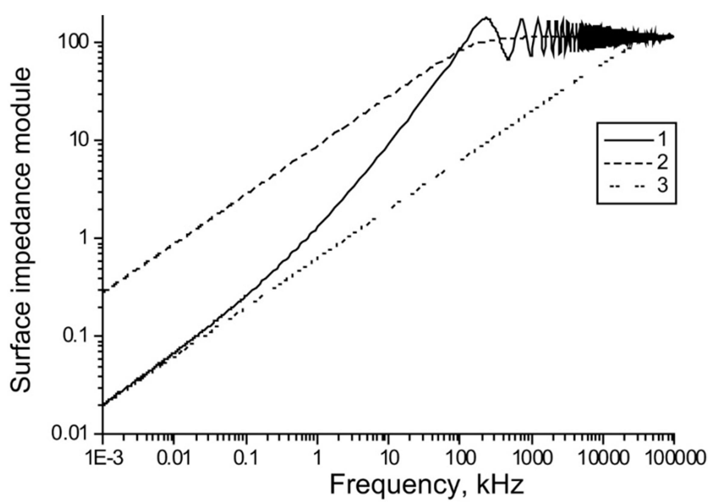

Fig. 3: Frequency dependences of the surface impedance module:

1 is for strong-inductive model ($\rho_1 = 10{,}000\,Ohm\cdot m$, $h_1 = 1\,m$, $\rho_2 = 50\,Ohm\cdot m$); 2 is for homogeneous half-space with $\rho = 10000\,Ом\cdot м$; 3 is for homogeneous half-space with $\rho = 50\,Ohm\cdot m$

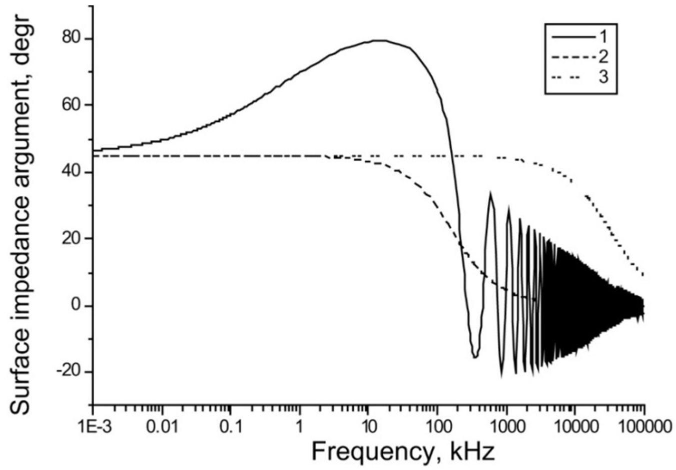

Fig. 4: Frequency dependences of the surface impedance argument:

1 is for strong-inductive model ($\rho_1 = 10{,}000\, Ohm \cdot m$, $h_1 = 1\, m$, $\rho_2 = 50\, Ohm \cdot m$); 2 is for homogeneous half-space with $\rho = 10000\, Ом \cdot м$; 3 is for homogeneous half-space with $\rho = 50\, Ohm \cdot m$

Such forms of frequency dependencies of module and argument of surface impedance appear to be a considerable manifestation of oscillation. At low frequencies, these forms represent oscillation maximums stretched over frequency scale. One can observe smooth oscillations when bias currents slightly prevail over conduction ones in the upper layer, and in the bottom layer – conduction currents outweigh. Strong-inductive model tends to have a greater scope of oscillation amplitude. As field frequency increases, oscillations become more vivid due to their period reduction. Under greater capacity values of the upper layer (> 20 m) oscillations shift toward low-frequency area, and their amplitude rises (Figures 3, 4). The model predicts existence of a much more conductive layer under homogeneous permafrost in absence of seasonal thawing. Depending on frequency, conductive horizon can be represented by any of the following. For low frequencies (<30 kHz) – it is a sub permafrost horizon of thawed bedrocks. For average and high frequencies (>30 kHz) –by potent inter permafrost thawed, aquifer, micro fine or salted horizon in mellow sediments. Strong-inductive model can be implemented through the entire frequency band: with capacity of the upper poorly-conductive layer >20 m at frequencies <300 kHz, and with the upper layer capacity of <20 m – at frequencies >300kHz. This model corresponds more to widespread natural GESs of permafrost zones, than weak-inductive does (in absence of STL or at its low capacity values). When field frequency increases to values indicating bias currents predominance in the upper layer and excluding the bottom layer's influence, oscillations of impedance's module and argument become to damp and they approach horizontal asymptote. According to

(3, 4), asymptotic value of impedance's module will equal $120\pi / \sqrt{\varepsilon}$; argument's asymptotic value – 0^o.

Implementation of numerical approach has revealed the following patterns common for both types of bilayer oscillation models.

1. Either enlargement of occurrence depth of the bottom layer, or conductivity reduction of the layers' contrast band, leads to frequency drop of oscillation occurrence as well as to oscillation period decrease.

2. Either the bottom layer's occurrence depth reduction, or conductivity enlargement of layers' contrast band, results in magnifying of oscillation amplitude scope.

3. Longitudinal h/ρ conductivity, lowering values of impedance's module, is assumed to be the parameter that determines the influence of the upper conductive layer. The impact, referring to the upper poorly-conductive layer, is determined by its longitudinal $h \cdot \rho$ resistivity that amplifies values of impedance's module.

Next, three-six layer models, which are based on considered bilayer oscillation models, approach natural permafrost zones.

Three-layer modelrepresents bilayer strong-inductive model supplemented with overhead thin conductive layer with capacity of 0.5-2 meters and SER value equal to 20-100 Ohm×m. The model characterizes main horizon of frozen bedrocks, overlapped by frozen mellow sediments with seasonally thawed surface that corresponds to the most common types of GES of permafrost. Supplementing an overhead conductive layer reduces oscillations' amplitude caused by dominance of different current types in STL, FMS and FBR (curves' label«1» on figures 5, 6).

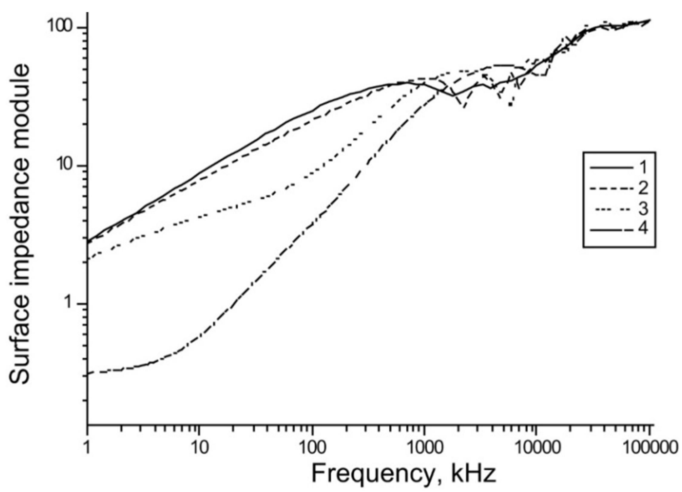

Fig. 5: Frequency dependences of the surface impedance module:

1 is for three-layer model; 2 are for four-layer model; 3 are for five-layer model; 4 is for six-layer model.

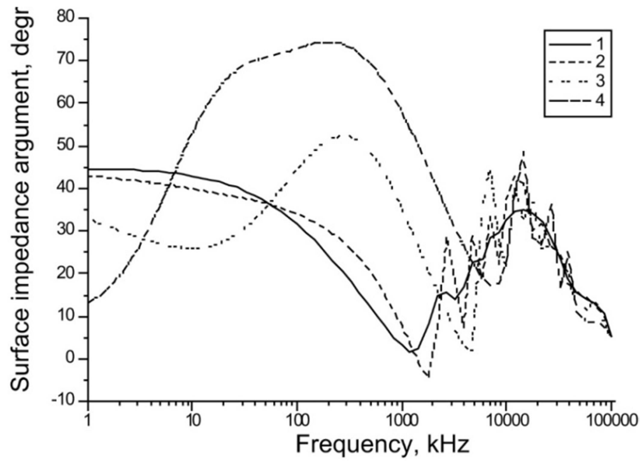

Fig. 6: Frequency dependences of the surface impedance argument:

1 is for three-layer model; 2 are for four-layer model; 3 are for five-layer model; 4 are for six-layer model.

Increase of STL longitudinal conductivity results in reduction of oscillations' amplitude. It occurs due to the fact that STL longitudinal conductivity compensates the impact made by FMS longitudinal resistivity on impedance of FBR datum. If

$$\frac{h_1}{\rho_1} = \frac{h_2}{\rho_3}$$

equation holds true, then we obtain an almost complete compensation.

Four-layer model conforms to permafrost with a mellow sediments base surface that intrudes a thin conductive layer (TCL). In this case, TCL can be represented by cryogenic residuum or by microfine sediments. TCL intrusion amplifies amplitude of both modules' oscillation and surface impedance's argument (curves' label «2» on figures 5, 6).

Five-layer model is formed by TCL intrusion in FMS of three-layer model. This is consistent with the presence of either microfine sediments or aquifer, or cryopeg in FMS [V]. Conductive layer intrusion on a depth, less than that at which FBR horizon is located, leads to large amplification of both amplitude and period of oscillations of surface impedance's module and argument at average frequencies (curves' label «3» on figures 5, 6).

There is another five-layer model that differs from the previous one by the fact that instead of a thin conductive layer, mellow sediments intrude thin poorly-conductive layer (TPCL) that conforms to a presence of either strong icy sediments or pure ice layer in FMS. TPCL intrusion increases FMS effective resistance, i.e. SER contrast band in comparison with FBR, as well as contribution of bias currents. On the other hand, TPCL intrusion with SER value of tens of thousands of Ohm×m makes its underlying horizon behave as conductive layer. It as well leads to scope amplification of oscillations amplitude, but in a less degree than TCL intrusion does. Besides, five-layer model can as well reflect a situation when intermediate layer in FMS is formed by frequency dispersion of electrical conductivity [II] as result of presence of thin layers of ice.

Six-layer model represents permafrost with FMS intrusion that encompasses double-level TCLs (taliks, cryopegs). Superposition of oscillations that lead to substantial phase shifts in a band of low and average frequencies is a typical feature of six-layer models (curves' label «4» on figures 5, 6).

As both formulas, describing homogeneous half-space (3), and numerical modeling results of laminated environments, frequency dependence of surface impedance's argument, rather than of module, is mainly characterized by proportion of bias and conduction environment currents. Thus, interpretation of phase data at radio impedance sounding gains particular importance. Phase frequency curves of the surface impedance have completely different shapes in a frequency band, used in radio impedance sounding, for different types of permafrost GES (Figure 6). Consequently, analyzing shapes of phase frequency curves enables us to determine the GES type of permafrost. This way the information the surface impedance's argument contains is valuable for determining GES type, and the module's data – for estimating SER values of the permafrost's main horizons.

Comparison of the models described along with radio impedance sounding results at frequencies 25-864 kHz, derived near the city of Yakutsk, can serve as an example. Permafrost's capacity of about 300 m allows neglecting the impact the subpermafrost horizon makes. For proper sounding data interpretation, bilayer strong-inductive model had been initially applied as considered to be more suitable subject to phase data; then, it has been replaced by a more reasonable five-layer model (Figures 7, 8).

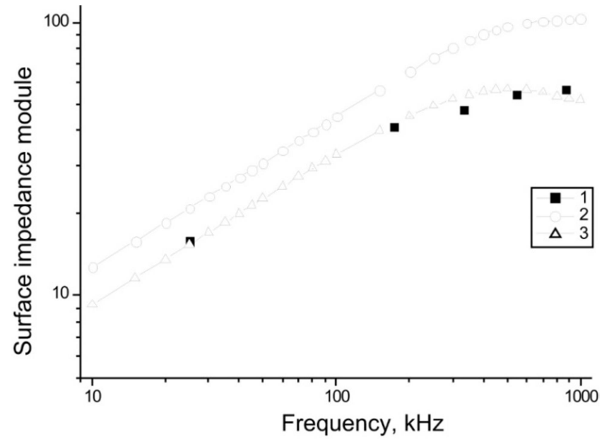

Fig. 7: Frequency dependences of the surface impedance module:

1 is for two-layer model; 2 are for five-layer model; 3 are radio impedance sounding data.

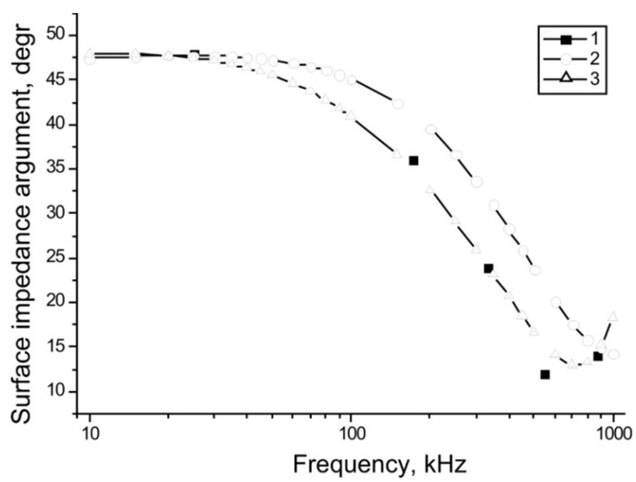

Fig. 8: Frequency dependences of the surface impedance argument:

1 is for two-layer model; 2 are for five-layer model; 3 are radio impedance sounding data.

As figures show, frequency dependencies of module and argument of surface impedance, calculated during data interpretation for five-layer model with TCL intrusion in FMS, are in the good agreement with radio impedance sounding data.

IV. Conclusion

The extent of oscillations along homogeneous half-space values with electrical parameters, related to the main layer, determines the shape the frequency curves of module and argument (phase) of permafrost's surface impedance take. The oscillations are caused by predominance of bias currents in one of the permafrost's main layers, and of conduction currents – in the other. Depending on these horizons' mutual location, one differs GESs with weak- or strong-inductive properties.

Main bilayer models (weak-inductive and strong-inductive correspondingly) proposed are able to describe any GESs of the permafrost in respect with the impact the overlapping and underlying layers have within the limits of the skin-layer thickness.

Measurement data of argument (phase) of surface impedance is of great importance at radio impedance sounding of permafrost in a frequency band of 10…1000 kHz. Phase data has considerable interpretation abilities that allow efficient determination of the GES type.

Manifestation of TCL effect in permafrost can be explained by areas of half-period occurrence of oscillation of impedance' argument and module values, caused by bias currents predominance in the horizon of FMS, and by conduction currents outweighing in the underlying horizon.

Long half-period occurrences of oscillation of impedance's argument (phase) let us interpret their areas, that correspond to the operating band of radio impedance sounding, to determine GES type of permafrost. This can be used for approximate automate interpretation of phase data of radio impedance sounding.

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