The struggle for the range of telephone communication before the invention of the audion Lee de Forest

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Abstract. The increase in the range of laying telephone lines at the beginning of the 20th century raised the issue of high-quality telephone signal transmission for scientists and engineers. The innovative technology for solving the problem was based on the "Heaviside condition". AT&T engineer George Campbell, who received a patent for the design of load coils, was engaged in this task. He demonstrated that a telephone line loaded with coils can transmit clear voice signals twice as far as unloaded telephone lines. At about the same time, Columbia University professor Michael Pupin dealt with this problem, who also received a patent for a similar concept in priority over Campbell's application. As a result, load coils became known as "Pupin coils". Ironically, Campbell lost the patent priority battle. The proposed innovation eliminated time delays and distortions in the signal, thereby significantly increasing the transmission speed.

1 Introduction

The operation of long-distance telephone lines, at the beginning of the 20th century, revealed a number of their shortcomings, among which the main thing was noted - the low quality of human speech transmission [1]. The arising problem required its quick solution. New cable designs were needed that were fundamentally different from the existing ones, especially telegraph cables. The difference between them was determined by the highest frequency of transmitted signals. If a telegraph signal required no more than 100 Hz, then for a satisfactory transmission of the sounds of human speech it was necessary at least 3000 Hz. With increasing frequency, there is a rapid attenuation of the signal transmitted along the line. Devices that were previously used on telephone lines did not meet the new requirements. Lee de Forest's audion had not yet been invented, so it was necessary to look for other approaches for improving the telephone lines.

2 Oliver Heaviside theory

On the 3rd of March, 1885, Bell Telephone Company established a subsidiary company AT&T (American Telephone and Telegraph Company), whose task was to provide

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commercial services for the implementation of long-distance telephone communications. In the same year, AT&T began building long-distance telephone lines. In 1892, a two-wire telephone line was laid at a distance of 900 miles (1,445 km) between New York and Chicago (Illinois). To reduce the attenuation of the transmitted electrical signal in this telephone line, a rather thick copper wire with a diameter of more than 1/8 inch (3.2 mm) and a weight of about 900 pounds (408 kg) per linear mile (1.609 km) had to be used. It was that limit the length of the telephone line at which the telephone conversation was possible without distortion and using any special devices in it.

The arisen problem was the distribution of inductance between the conductors and the distributions between the conductors. As for the telegraph signal, it had a relatively low frequency spectrum. The telephone signal was relatively broadband and high-frequency, as a result of which they could not understand each other's speech in significant attenuation of the high-frequency components.

The English physicist Oliver Heaviside (05.18.1850–03.02.1925), who at one time, from 1870 to 1874, worked as the telegraph operator of the Great Northern Telegraph Company station, became interested in finding the problem of transmitting an electrical signal without distortion through a cable line in the city of Newcastle on the northeast coast of the UK. A telegraph cable was laid to Denmark from this station. During this period of time, he took part in the experiments conducted by his brother on two-way telegraphic communication, at first, in the laboratory, and then between Newcastle and Sunderland (the city on the North Sea coast at the mouth of the Wear River).

Oliver's brother was a divisional engineer at the British Post Office in Newcastle upon Tyne. His aunt, by the way, was married to Sir Charles Wheatstone, a pioneer of electrical telegraphy. All this formed a scientific atmosphere around the young Oliver and stimulated his interest in transmitting electrical signals by wire.

In 1874, due to deafness, he had to quit his job and began to study the theory of electricity independently. Thanks to the research, regardless of the English physicist J. G. Poynting (09.09.1852–30.03.1914) and the Russian scientist Nikolai Alekseevich Umov (01.23.1846–05.01.1915), O. Heaviside (Fig. 1) constructed the theory of electric signal transmission in telegraph lines, which was generalized for telephone lines.

Fig. 1. Oliver Heaviside.

He derived the so-called "telegraph equations" to describe the propagation of electromagnetic waves through a two-wire line communication cable:

$$\frac{\partial U}{\partial x} = -L_x \frac{\partial I}{\partial t} - IR_x, \qquad \frac{\partial I}{\partial x} = -C_x \frac{\partial U}{\partial t} - UG_x, \tag{1}$$

where *U(x, t)* and *I(x, t)* are the voltage and current in the line; *L* and *C* are linear (per unit length) inductance and capacitance, depending on the cross section of the wires, the distance between them and the properties of the filling medium; *R* and *G* are linear resistance and conductivity, taking into account leakage currents.

System (1) was called *telegraph equations* (the French name *"l'équation des télégraphistes"* was proposed by A. Poincare in 1897). Telegraph equations in the form of (1) are a mathematical model of a *real* line in which energy is dissipated by the active elements R and G.

Heaviside received accurate analytical solutions to equations (1), which allowed us to study the technical problems encountered in the practical operation of wire lines.

In 1887, he showed that the attenuation coefficient in the cable communication line will be minimal, if the conditions $\frac{R}{L} = \frac{G}{C}$ or $R \cdot C = G \cdot L$ are met (where the main electrical parameters: R is the active resistance, L is the inductance, C is capacitance and G is the insulation conductivity per unit line length).

The energy loss in the communication line, characterized by the attenuation coefficient α, will be minimal when $\alpha_{min} = \sqrt{R \cdot G}$.

The indicated optimal ratio of all four primary electrical parameters of the cable is called the Heaviside condition and is true when the minimum attenuation coefficient is observed. Thus, the fulfillment of this Heaviside condition eliminates distortion of the waveform, since all the frequency components of the complex signal are equally attenuated and move at the same speed $v = 1/\sqrt{L \cdot C}$, which is equal to the phase velocity in an ideal line. At the receiving end of the line, a copy of the sent signal is obtained, reduced in amplitude by αL times. The impedance of a non-distorting line coincides with the impedance of an ideal line without loss.

The inconsistency of the line and the load leads to the appearance of reflected waves, the number of which increases rapidly due to multiple reflections from the ends of the line. Reproduction and superimposition of re-reflected signals leads to their chaotization and creates interference that prevents the registration of a useful signal. It is a disturbance of the line impedance and the transmitting / receiving equipment that interferes with the transmission of electrical signals. In this regard, in order to build power lines without distortion, it is necessary to comply with the conditions of Heaviside [2].

In 1893, Heaviside formulated a practical approach to fulfilling the conditions of optimal ratio of all four basic electrical parameters of a cable: "... The condition of communication on a wire line without distortion can be fulfilled in the case of a significant increase in the inductance of the line " [3]. To fulfill this condition, he proposed to include focuses inductors in the communication line at a certain and equal distance from each other.

3 Researches by George Campbell

Telephone communications, during this period of time, was still at the beginning of its development and was carried out over short distances. As soon as the distance between the telephone subscriptions began to increase, the problem of distortion of the telephone electrical signal arose. At this time in the engineering department of Bell, research was in full swing to find a solution to the problem.

The theory of O. Heaviside was not understood by all specialists in the field of telephony [4]. One of the proponents of this theory was John Stone Stone (24.09.1869-20.05.1943), a researcher at the Bell Telephone Company. John Stone attracted attention at the world's fair in Paris (1889), where he helped with the installation of AT&T exhibits. He brilliantly performed the duties of an engineer and had excellent qualities of a diplomat. This made him a notable person for Bell Co. Because of this, he after completing his studies at Johns Hopkins University in 1890, was invited as an engineer of the experimental Department of the research and Development Laboratory (RDL) Bell Telephone Company in Boston.

Stone was acquainted with Heaviside and corresponded with him until the end of 1891. Heaviside not only answered his letters, but also provided the requested assistance on matters related to the development of long-distance telephone lines.

Stone tried to apply Heaviside's ideas to real telephone lines. In 1896, he invented the bimetallic iron-copper cable. His cable increased the inductance of the line due to the iron content. The following year, stone received a U.S. patent for the use of bimetallic wire consisting in a section of copper and iron for telephone lines, in order to facilitate the matching of cable and overhead line impedances, Fig. 2. Note that iron cables were used to transmit a telephone signal until 1896.

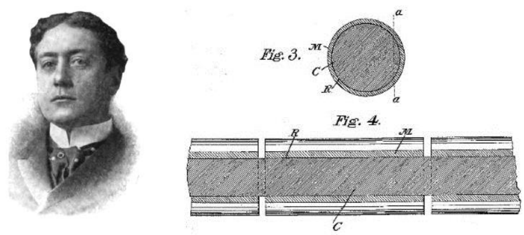

Fig. 2. John Stone Stone (1905) and the design of his bimetallic iron-copper cable (C is the central conductive core, M is the paramagnetic sheath, and R is the gasket with high resistance). Patent US578275 dated March 2, 1897.

In October 1897, John Stone brought George Ashley Campbell (11.27.1870–10.11.1954) to his research as a research engineer at RDL Bell Telephone Co. (later AT&T) in Boston, when Campbell returned from Europe. Prior to this, G. Campbell studied physics and mathematics at Harvard University, where in 1893 he received a master's degree and was awarded a scholarship, which allowed him to continue postgraduate education in Europe for 3 years, Fig. 2.

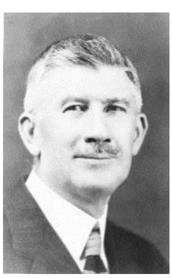

Fig. 3. George Ashley Campbell. July 17, 1935.

John Stone invited the company's management to continue research on ways to improve the quality of the telephone line using a bimetallic iron-copper cable to determine the extent to which the bimetallic line provides improved signal transmission and meets the requirements of Heaviside theory. These works, according to the plan of Stone, should have been done by Campbell.

However, having not received support in the implementation of his idea, Stone left Bell Co. in 1899.

The Director of the Mechanical Dept., Hammond V. Hayes, responsible for research and development, instructed Campbell to choose research in the direction that seemed promising [5].

Due to the relatively high cost of producing bimetallic long lines and the limited budget of the project, Campbell decided to use a less expensive artificial line. Such a line can be built of several separate capacitors and inductors in an iterative scheme and this does not require a large laboratory. His idea was to set the inductance of discrete coils or "load coils" at periodic intervals along the actual telephone line or cable. He realized that they should behave like a normal line, but with a higher self-induction in a wide frequency range. This should have led to greater efficiency.

Campbell began to develop load coils, which, according to Heaviside's theory, was supposed to improve the quality of the telephone conversation. In the last days of the 19th century, G. Campbell made the necessary inductive elements. These were the first "load coils" suitable for practical purposes, Fig. 4.

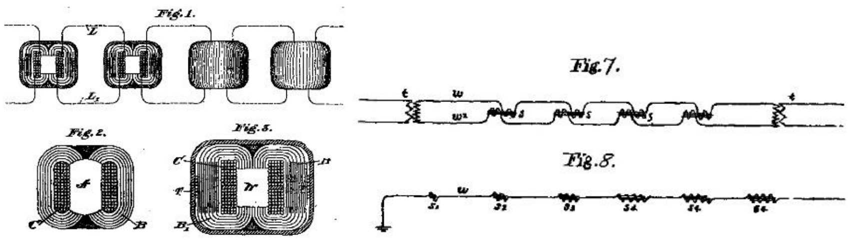

Fig. 4. Load coils of G. Campbell design and their inclusion in the telephone line. Patent GB190016290. 1900.

Upon Campbell's request, Hayes ordered the three reels of cable that had previously been used for testing in Pittsburgh to be delivered to the Boston lab to test the load on a standard commercial telephone cable. Campbell prepared the specifications for the coils to be used and ordered 400 coils from a local manufacturing company.

While waiting for the delivery of coils (June 1899), he derived a theoretical equation for the loaded line, which became known as the “Campbell’s equation”:

$$Cosh(P' \cdot d) = Cosh(P \cdot d) + \frac{Z}{2 \cdot Z_0} Sinh(P \cdot d), \quad (2)$$

where d is the distance between the centers of the coils, Z and Z_0 are the impedance of the loaded and unloaded lines, P and P' are the propagation constants (coefficients) of the unloaded and loaded lines.

The obtained equation (2) was transcendental and its final solution was not obtained. In this regard, Campbell presented the solution to the equation in the form of graphs, from which you can find the optimal values of the inductors and the distance between them. Campbell and his assistant, Edwin H. Colpitts, used the result for numerical calculations in the range of expected loading conditions on standard cables.

Soon, a few months before the end of the 19th century, the necessary inductive elements were manufactured. And, already on September 6, 1899 in Boston, G. Campbell and his assistant conducted the first tests of a telephone cable with load coils over a distance of 46 miles. The cable used for the experiments was called the Pittsburgh Cable, since before that it had been tested in Pittsburgh. In the same year, a telephone line between Philadelphia and Chicago was put into commercial use (678 miles or 1,222 km).

In 1900, G. Campbell received a British patent for the design of load coils and the scheme for their inclusion in the telephone line. The patent GB190016290 was entitled: “Improvements in and connected with Electric Circuits for the Transmission of Energy by Variable Currents”. Later, these studies became part of his doctoral dissertation (PhD), which G. Campbell defended at Harvard in 1901 [6].

4 Pupinization of telephone lines

Scientists in other research centers, in particular, Columbia University, also dealt with the problem of increasing the range of transmission of telegraphic and telephone messages via communication cables. Here, these issues were dealt with by a university graduate Mikhail Pupin (Fig. 5), who returned from abroad on his home ground. After graduation, he spent two years in Cambridge and four years in Berlin. In 1889, in Berlin, he defended his doctoral dissertation "Osmotic pressure and its relationship with free energy" under the leadership of Hermann Ludwig Ferdinand von Helmholtz (08.31.1821-08.09.1894). After protection, Pupin returned to Columbia University and entered the newly formed faculty of electrical engineering [7].

Fig. 5. Michael Idvorski Pupin.

Mikhail Pupin thought about the problem with the phone during his scientific internship in Europe, when he wrote in his memoirs: “I found this solution during the summer holidays of 1894, which I spent in Switzerland. I think this is my general decision - Lagrange can find application in telephony” [8]. In the same year, he received patent US519346 for "Telegraphy and Telephony Device," in which *LC* filters are included in each wire to match the electrical resistance of the source of the electrical signal and the communication line, Fig. 6. The inclusion of such filters increased the inductance of the lines and reduced the attenuation of the electrical signal.

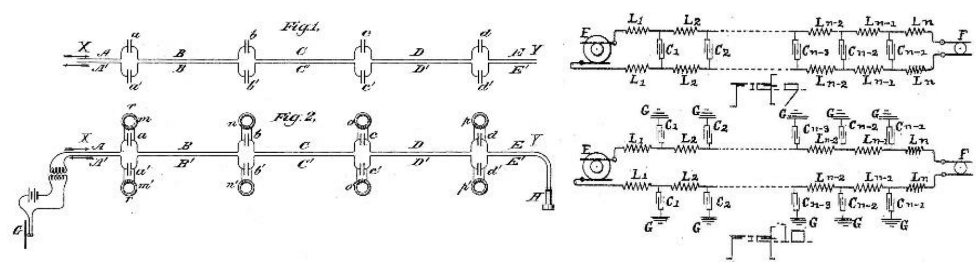

Fig. 6. The inclusion of load coils in a telephone line according to Pupin's patents US519346 (left) and US652231 (right).

It should be noted that in patent US519346 inductors are included in each wire of the communication line. In patent US652231, an inductor included in parallel lines was wound on a single core. Each coil of this type is wound on a separate toroidal core, while in its main patent US 652231, the windings of the inductors included in parallel lines are wound on a separate core.

In 1900, M. Pupin, starting from a similar mechanical Lagrange problem (oscillations of a stretched string, the mass of which increased with the help of balls suspended from the string at certain distances), derived an equation for determining the optimal distance between toroidal inductors and gave a calculation of such coils, Fig. 7.

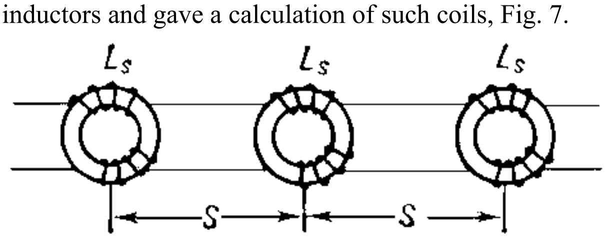

Fig. 7. Scheme of including inductors in a telephone line according to M. Pupin.

M. Pupin suggested periodically including coils with an inductance approximately two orders of magnitude higher than the inductance of the subscriber line itself. Soon, he first made a load inductor suitable for practical use on telephone lines.

The distance between two adjacent coils was called pupinization step (0.3 - 2 km). The presence of coils improves the signal transmission in the range of telephone frequencies (0.3 - 3.4 kHz), but at higher frequencies, the signal transmission is significantly worse, so on telephone lines using high-frequency technologies, Pupin coils are not installed.

If the increase of self-inductance of a telephone line is made using special inductors, these include the elements called "Pupin coil" (their inductance mH 1 - 140), and the line with load coils, in honor of Pupin's called pupinization. The installation of the coil line is called "pupinization". Pupinization line consists of several series-connected units.

Michael Pupin obtained a patent (Fig. 8) for his load inductor, which was called: “Art of reducing attenuation of electrical waves” with a priority of May 28, 1900.

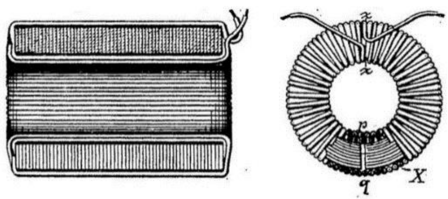

Fig. 8. The design of the load coil M. Pupin. Patent US652231 priority June 19, 1900.

AT&T was puzzled when it learned of Michael Pupin's patent for an inductor to increase the self-induction of a telephone line. The matter is that registration of the patent of G. Campbell's due to bureaucratic delays at AT&T was implemented with a delay. The primacy in the patent dispute belonged to M. Pupin. It should be noted that the patents of G. Campbell and M. Pupin are very different from each other, both in the design of the load coils, and in the schemes of their inclusion in the telephone line.

In 1900, AT&T, anticipating problems with patent claims by Pupin, bought for $455,000 the rights to all of his patents related to long-distance telephony. This allowed the company to monopolize the technology under two patents that were needed to build telephone lines over long distances. AT&T, despite this, continued to improve such technologies under the leadership of G. Campbell.

The most significant consequences of the dispute over load technologies was that Bell deliberately chose the path of development of knowledge-intensive technologies and more aggressive search for patents.

In 1901, AT&T built the longest telephone line between New York and Denver (1,631 miles or 2,625 km) using the new technology. During this period of time, AT & T conducted research by G. Campbell on the properties of pupinization lines. In 1903, he published some results [9], among which the detected frequency-dependent effect of such lines should be highlighted. This effect is that the Pupin lines have a clearly defined critical frequency, which manifests itself in a sudden change in the attenuation characteristics. Below this frequency, the attenuation is small and depends only on spurious cable losses. If these losses are equal to zero, and the attenuation is below the critical frequency, then it is also equal to zero. If the attenuation is large and above the critical frequency, then it is practically independent of cable losses. The transition to a critical frequency can be very abrupt. The critical frequency is determined by the distance between the coils and corresponds to a wavelength equal to twice the distance between them.

The obtained result explains the fact why it was not possible to get high-quality communication on transcontinental umbilical telephone lines. Such cables can transmit only a limited frequency range, which is their main drawback. To overcome it, other technologies were required, which AT&T did in the future.

5 Conclusions

Pupin coils have found particularly widespread use on local telephone networks in the United States. In subscriber networks of Russia pupinization used infrequently, such as the network of Moscow city telephone network has about 5 % pupinization cables. In this regard, a prerequisite for the use of any xDSL technology (a family of point-to-point subscriber access technologies) on existing subscriber lines is the removal of Pupin coils. This is due to the fact that Pupin coils sharply violate the homogeneity of the copper pair. In this case, a pair of wires practically turns into a low-pass filter, the attenuation of which increases sharply at high frequencies [10].

Currently, in Russia, in the operational control link the pupinization cable of type P-270 is used to ensure long-distance communication, and the cable's coupling halves include the mounted inductors. Pupinization step of this cable is 250 m, the inductance of the coil is 1.3 mH, which allows its use in the range up to 60 kHz.

References

1. Pestrikov V.M., Pestrikova M.V. The struggle for the range of telephone communications at the turn of the XIX-XX centuries. Collection of reports of the Ninth Scientific Readings in Memory of A. S. Popova "Networks and communication lines: past, present, future:" dedicated to the Radio Day - holidays of workers in all communication industries (May 6, 2016). SPb.: Own publishing house, 2016. Pp.53–59. (2016)
2. Maksimychev A.V. Signals in long circuits. Abstract of lectures on physical methods of research, part 2. Educational and methodical manual. Moscow: MFTI. 43 p. (2007)
3. Heaviside O. Electromagnetic theory. London: The Electrician Company. Vol. **1**. 466 p. (1893)
4. Baranov M. I. Oliver Heaviside and his contribution to the world Treasury of science// Electrical Engineering and Electromechanics (Edition Of the national technical University Kharkov Polytechnic Institute) No. 4. P. 5–14 (2005)
5. Dr. George A. Campbell //The Bell System Technical Journal, October 1935. Vol. **14**. No. 4. P. 2–6 (1935)
6. George A. Campbell, 1870-1954. The Bell System Technical Journal, January. Vol. **34**. No. 1. P. 1–4 (1955)
7. Marinčić Aleksandar. Michael Idvorsky Pupin (1854–1935). Microwave Review. June, 2005. P. 2–6 (2005)
8. Klejman И. Mihailo Idvorski Pupin//Przeglad Telekomuni-kacyjny. No 7. P. 372. (1979)
9. George A. Campbell. On loaded lines in telephonic transmission. The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science. March 1903. Series 6. Vol. **5(27)**. P. 313–330 (1903)
10. Website "SvyazKomplekt". Pupin coils as a source of problems. URL: https://skomplekt.com/technology/reflect/reel.htm/ (13.10.2019)