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RADIOFREQUENCY SINGLE PROBE-BASED MEASUREMENTS OF LEVEL/INTERFACE POSITIONS OF LIQUIDS IN TANKS

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Abstract – Methods for the design of radiofrequency single probe-based devices for highly accurate disturbances-independent level/interface position measurements are proposed. These methods are based on the application of several (two or more) measuring channels realized with the use of a single radiofrequency probe that is the section of a TEM transmission line. In particular, realizations of radiofrequency single probe-based devices for the measurement of level, interface positions of substances in tanks, of physical properties of these substances are considered.

Keywords: measurement, radiofrequency, liquid level

1. INTRODUCTION

Radiofrequency (RF) measuring devices are applied effectively for highly accurate determination technological parameters, in particular of liquid level in tanks [1-3]. They are realized on the base of TEM-transmission line (coaxial, two-wire, etc.) sections. RF devices with two measuring channels are used for determination of liquid level independently from electrophysical parameters of monitored liquids [1,3]. As a rule, RF measuring channels of such devices are realized using several (two or more) sensors (probes) depending on the number of informative and influencing non-informative input parameters. Obviously realization of these devices on the base of a single sensor's construction would be more effective.

Design principles of single probe-based RF measuring devices for multiple-channel and disturbances-independent measurements of technological parameters are considered in the paper. They are applied for determination of level of a liquid, interface position of two liquids in tanks, physical properties of a liquid, in particular of its density.

2. DESIGN PRINCIPLES OF A SINGLE PROBE-BASED MEASURING DEVICES

Design principles of simple and reliable RF level measuring devices are considered in the paper. A single RF probe that is uniform TEM transmission line section is used here for realization of two or more measuring channels. These measuring channels have various response functions that are needed for independent and multiple parameters measurements. Joint functional processing of these response functions in an electronic unit of a RF measuring device containing a single RF probe, provides solution of a system of equations corresponding to the dependencies of informative parameters on input values under disturbance-independent measurements or on measured values under multiple-parameter measurements. There is a need in two-parameter measurements under storage of substances in tanks: to measure level of a substance and its physical properties (density, concentration if a substance is the mixture of different substances, etc.).

Electronic switching of such TEM-line end loads is provided for response functions' change of a RF probe. As a result, electromagnetic field energy distribution is changed under this switching. It results in various relationships that describe dependence of the TEM-line section resonant frequency of electromagnetic oscillations (informative parameter) on liquid level in a tank. Measurement of the resonant frequency at two various loads of at least one the section ends gives ability to provide the needed independence from electrophysical parameters or to determine interface position between liquids with different densities in a tank. Switching of three end loads in the TEM-line section results in the systems of three equations relative to two interface positions. Thus, their values can be determined under solution of this system of equations in electronic unit of the measuring device.

3. SWITCHED END LOADS OF TEM-LINE SECTIONS

Schematic position of TEM-line section in a tank with a monitored substance is shown at Fig. 1. Distributions of electric field strength *E*(*z*) along (coordinate *z*) an uniform line section are shown in Fig. 1,a – 1,c: along a quarter-wave line section open at its upper end and short-circuited at its lower end (Fig. 1,a); along similar line section, short-circuited at its upper end and open at its lower end (Fig. 1,b); along half-wave line section, open at both its ends (Fig. 1,c).

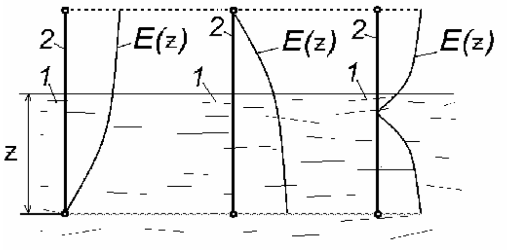

Fig. 1. Distribution of electric field strength along uniform TEM-lines sections
1 – monitored substance, *2* – TEM-line section

Switching of end loads of such a probe can be done by using of diodes connected between the line conductors at its end(s). In particular, quarter-wave line section with switched diodes is described. Here simultaneous switching of the open and short-circuited ends (from the one state to the other one) containing the diodes is realized. Examples of end loads are considered. They contain diodes, diodes connected capacitance or inductance in series or in parallel, etc. (Fig. 2). Such different loads can provide needed various field energy distribution along a line section. Applying opposite potentials to a diode from a voltage source may do electrical connection or disconnection of the line conductors.

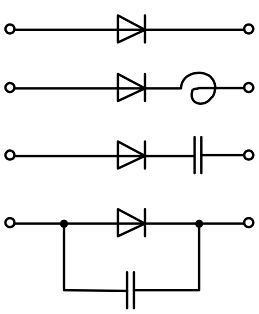

Fig. 2. End loads of TEM-line sections (examples)

Therefore various output characteristics – dependencies of the values of resonant frequency f_r of electromagnetic oscillations (informative parameter of the probe – a TEM-line section) on level of a substance or interface position of two substances in a tank, and also on electrophysical parameters (in particular on dielectric permittivity ε o of a substance) take place in measuring channels of the single probe-based RF device.

4. MEASUREMENT OF LIQUID LEVEL

Measurement of resonant frequency f_r at two various end loads of a line section provides ability to measure level of a substance independently from its electrophysical parameters or to determine interface position of two substances with different densities in a tank. The measured frequencies f_{r1} and f_{r2} are processed jointly in an electronic unit. So level *z* of a substance can be determined independently from its electrophysical parameters. Such processing can be done knowing exact transcendental relationships between f_{r1}, f_{r2} and *z*, ε; however, their use is problematic for determination of *z* and ε through joint processing of f_{r1} and f_{r2}. Using direct approximate relationships between these values, permittivity ε and technological parameters related to it, in particular density of a substance may also be simply found after processing of f_{r1} and f_{r2}. Degree of such approximation is enough for many real measurement tasks providing needed measurement accuracy. For dielectric substances dependence $f_r(z,\ \varepsilon)$ can be described by the following relationship:

$$\frac{f_{r1,r2}}{f_{r1_0,r2_0}} = \frac{1}{\sqrt{1+(\varepsilon-1)\varphi_{1,2}(z,\varepsilon)}} \qquad (1)$$

Here $\varphi_{1,2}(z,\ \varepsilon)$ is the function characterizing distribution of electric field strength along TEM-line section; the distribution is controlled by the choice of loads at the section ends.

For determination of *z* independently from ε the following relationship is received using (1):

$$A_1(z) = A_1(f_{r1}, f_{r2}) = \frac{\dfrac{f_{r1_0}^{\ 2}}{f_{r1}^{\ 2}} - 1}{\dfrac{f_{r2_0}^{\ 2}}{f_{r2}^{\ 2}} - 1} \qquad (2)$$

In this formula f_{r1_0} and f_{r2_0} are initial (at $z = 0$) values of f_{r1} and f_{r2}.

Scheme of RF measuring device for permittivity-independent level measurement is shown in Fig. 3. Here TEM-line section with switched loads is placed vertically in a tank with a monitored liquid. The line section is connected to electronic unit and switching unit. The latter is controlled by signals from electronic unit in order to switch the line section loads over: to open or short-circuit diodes contained in the end loads. Determination of resonant frequencies f_{r1} and f_{r2} at various end loads of the line section and joint functional processing of f_{r1} and f_{r2} according to (1) is realized in the electronic unit.

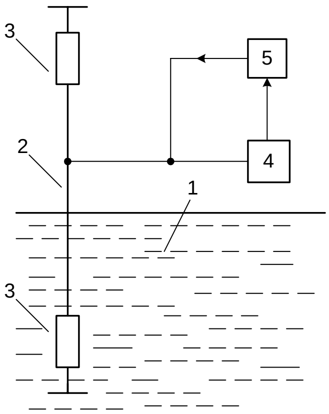

Fig. 3. Scheme of RF measuring device with switched end loads of TEM-line section

1 – monitored substance, *2* – TEM-line section, *3* – end load, *4* – electronic unit, *5* – switching unit

Diagrams corresponding to the dependencies of $f_{r1}(z,\varepsilon)/f_{r1_0}$ and $f_{r2}(z,\varepsilon)/f_{r2_0}$ on *z/l* are shown in Fig. 4 (*l* is the length of the line section) by the lines *1* and *2* correspondently.

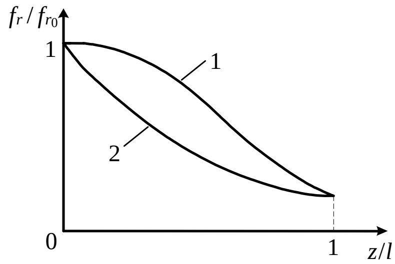

Fig. 4. Resonant frequency versus level of a substance

Fig. 5 illustrates example of RF single probe-based measuring device for dielectric permittivity-independent level determination. Here quarter-wave coaxial line section with switched end loads is used as a RF probe. Two measuring channels are realized by simultaneous switching of both end loads: the line section is open at its upper end and short-circuited at its power end in the first measuring channel; in the second measuring channel the loads are just the opposite ones.

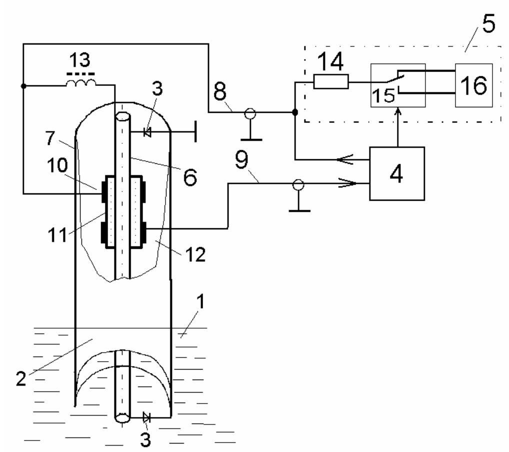

Fig. 5. Scheme of RF level measuring device

1 – monitored substance, *2* – TEM-line section, *3* – end load, *4* – electronic unit, *5* – switching unit, *6* – inner conductor, *7* – outer conductor, *8* and *9* – transmission lines, *10* – coupling element, *11* – isolator, *12* – coupling element, *13* – choke, *14* – resistance, *15* – electronic switch, *16* – voltage supply

RF signal from oscillator within electronic unit *4* comes by transmission line *8* through coupling element *10* (electric capacitance) to inner conductor *6* of the coaxial line *2*. Its outer conductor *7* is connected to the cable screen. On both ends of the coaxial line *2* between its inner and outer conductors are oppositely connected diodes *3*. These diodes are fed by control voltage of switching unit *5*. Diode *3* at the upper end is short-circuited and diode *3* at the lower end is open, or vise versa, depending on the polarity of the control voltage. Thus such a line section is characterized by different functions $f_{r1}(z, \varepsilon)$ and $f_{r2}(z, \varepsilon)$. It is equivalent to two quarter-wave TEM-line sections that are short-circuited at the lower end and the upper end, accordingly.

Resonant frequencies of such quarter-wave line sections are determined via coupling element *12* (similar to the coupling element *10*) and transmission line *9* connected to the electronic unit *4*. Coupling elements *10* and *12* are placed on the isolator 11 coating the inner conductor 6 of the coaxial line *2*. Choke *13* is present at the scheme; it prevents from coming through of RF signals from electronic unit *4* to the outer conductor *7* of the coaxial line *2*. Influence of transmission line *8* on resonant frequencies of the line section 2 is thus excluded.

Switching unit *5* provides control of diodes 3 that is the change of the line end loads in order to have different distributions of electric field strength along the TEM-line section. In the switching unit *5* voltages of different polarities (+ 5V, – 5V) come from voltage supply *16* to the electronic switch *15* controlled synchronously by the signals of the electronic unit *4*. These signals switch over the channels for measurement of the resonant frequencies $f_{r1}(z, \varepsilon)$ and $f_{r2}(z, \varepsilon)$. From the output of electronic switch *15* controlling signals come to the diodes *3* through current-restricting resistance *14* and provide opening and short-circuiting of the diodes *3*. Ends of the line section *2* are thus short-circuited or opened.

RF measuring devices with the single probe described above can be applied for determination of level or interface position(s) of liquids with any electrophysical parameters. The latter can be changed in arbitrarily any limits. At least one conductor of the line section is dielectrically coated for monitoring of liquids that are non-perfect dielectrics.

Experimental results with these RF measuring devices on the base of coaxial and two-wire transmission lines with switched end loads confirm their reliable operation and provision of highly accurate measurement results.

5. MEASUREMENT OF INTERFACE POSITION BETWEEN TWO LIQUIDS

The considered approach based on the use of TEM-line sections (probes) with switched end loads is also effective for measurement of interface position z between two liquids in a tank. In this case coordinate z is determined independently from electrophysical parameters of both (upper and lower) substances. These parameters are dielectric permittivities ε_1 and ε_2 for dielectric substances in a tank. Three different dependencies of resonant frequencies f_{r1} (z, ε_1, ε_2), f_{r2} (z, ε_1, ε_2) and f_{r3}(z, ε_1, ε_2) are now required (Fig. 6) for determination of z independently from ε_1 and ε_2 and for determination of these permittivities (if needed).

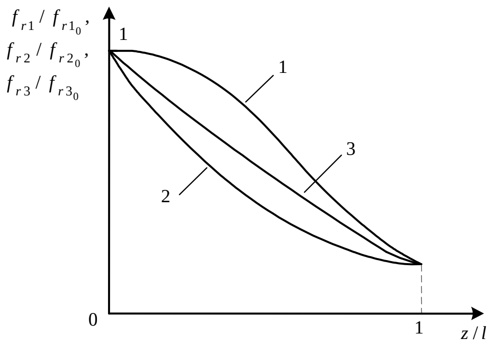

Fig. 6. Resonant frequency versus coordinate of interface position

In Fig. 6 are shown diagrams of three dependencies $f_{r1}(z,\varepsilon)/f_{r1_0}$, $f_{r2}(z,\varepsilon)/f_{r2_0}$ and $f_{r3}(z,\varepsilon)/f_{r3_0}$ on z/l (l is the length of the line section) at some fixed values of ε_1 and ε_2. Here f_{r1_0}, f_{r2_0} and f_{r3_0} are initial (at z = 0) values of f_{r1}, f_{r2} and f_{r3}, accordingly.

The appropriate RF measuring device can be realized using the single TEM-line section with three different switched end loads. First, The line section can be short-circuited at the lower end and opened at the upper end (Fig. 6, line *1*); second, these loads can be at the opposite ends (Fig. 6, line *2*); third, one end can be open but the other can contain now inductive load (Fig. 6, line *3*).

If dielectric substances with dielectric permittivities ε_1 and ε_2 are contained in a tank then the following relationship can be written:

$$\frac{f_{r1,r2,r3}}{f_{r1_0,r2_0,r3_0}} = \frac{1}{\sqrt{1+(\frac{\varepsilon_2}{\varepsilon_1}-1)\varphi_{1,2,3}(z,\varepsilon_1,\varepsilon_2)}} \quad (3)$$

where $\varphi_{1,2,3}(z,\ \varepsilon_1,\ \varepsilon_2)$ is functions of electric field strength distribution along the line section depended on the end loads.

It follow from (3) coordinate z of interface position can be determined independently from ε_1 and ε_2 by the following relationship:

$$A_2(z) = A_2(f_1, f_2, f_3) = \frac{\left(\frac{f_{r1_0}}{f_{r1}}\right)^2 \left(\frac{f_{r2_0}}{f_{r2}}\right)^2 - 1}{\left(\frac{f_{r1_0}}{f_{r1}}\right)^2 \left(\frac{f_{r3_0}}{f_{r3}}\right)^2 - 1} =$$

$$= \frac{\varphi_2(z,\varepsilon_1,\varepsilon_2) - \varphi_1(z,\varepsilon_1,\varepsilon_2)}{\varphi_3(z,\varepsilon_1,\varepsilon_2) - \varphi_1(z,\varepsilon_1,\varepsilon_2)} \quad (4)$$

Fig. 7 illustrates example of RF single probe-based device for realization of the considered approach. Two non-mixed liquids *1* and *2* with different densities may be as the monitored substances. This scheme is realized on the base of coaxial TEM-line section *3* (probe) with inner *5* and outer *6* conductors. Outer tube *7* at its lower end is connected with inner conductor *5* by short-circuiting conductor *4*. End load *8* is switched on between conductor *5*, tube *6* and outer metal tube *7* and is connected to the switching unit *10*.

Switching the diodes themselves may be used as end loads *8* and *9*. They serve as short-circuiting connections (opened diode) or provide the break of the circuit (closed diode). End load *9* contains two diodes. They are needed for the independent control of both end loads. The line section *3* is connected to the electronic unit *11* via coupling elements *12* and *14*. Coupling elements *12* and *14* are placed on the isolator *13* coating the inner conductor 5 of the coaxial line *3*.

RF signals are fed to the line section *3* via coupling element *12* from RF oscillator that is present in the scheme of the electronic unit *11*. RF signals from the line section 3 are fed to the electronic unit *11* through coupling element *14*. In the electronic unit *11* resonant frequencies of the line section with commutated end loads are determined. Switched diodes of end loads *8* and *9* are opened or closed by switching unit *10* according to the control signals of the electronic unit *11*.

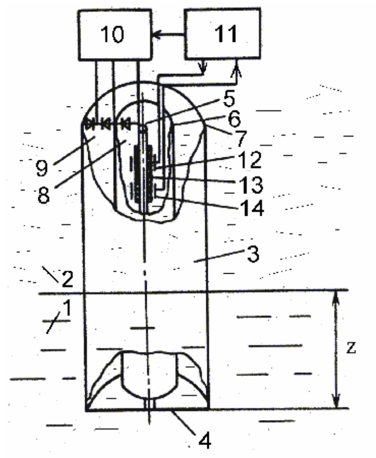

Fig. 7. Scheme of RF interface position measuring device

1 and *2* – monitored liquids, *3* – coaxial TEM-line section, *4* – short-circuiting conductor, *5* – inner conductor, *6* – outer conductor, *7* – outer tube, *8* and *9* – end loads, *10* – switching unit, *11* – electronic unit, *12* – coupling element, *13* – isolator, *14* – coupling element

Measurement process is divided by three stages. At the first stage diodes of end loads *8* and *9* are closed. The line section is excited as half-wave resonator opened at its both ends (small capacitances of the diodes are disregarded). In this case electric field energy is equal to zero at the middle part of the line section and is maximal at its ends. Output characteristic for the U-like TEM-line section is similar to the characteristic of quarter-wave line section (resonator) short-circuited at the lower end (Fig. 6, line *1*). At the second measurement stage diodes *8* and *9* are open. In this case electric field energy is maximal at the middle part of the line section and is minimal at its ends. Output characteristic that is related to this distribution of electric field, for the U-like line section is similar to the characteristic for the quarter-wave line section (resonator) short-circuited at the upper end (Fig. 6, line *2*). At the third stage the diode of the end load *8* is open and the diodes of the end load *9* are closed. In this case the line section is excited as quarter-wave resonator (Fig. 6, line *3*). For the U-like line section distribution of electric field is almost uniform. During three-stage measurement process resonant frequencies f_{r1}, f_{r2} and f_{r3} are determined. Their joint functional processing in the electronic unit provides determination of the coordinate z independently from dielectric permittivities ε_1 and ε_2.

If more than two substances are present in a tank (more than one interface position is between substances), single probe-based approach needs to have appropriate switched loads at the ends of a TEM-line section (probe). The number of these switched loads should be equal to the number of measured and influencing non-measured input parameters under multiple parameter or/and disturbances-independent measurements.

Note that in RF single probe-based measuring devices other informative parameters can also be determined. In particular, phase shift of sounding and propagated through the TEM-line section (probe) electromagnetic waves may serve as the informative parameter.

6. CONCLUSION

Application of only single RF probe for realization of two or more measuring channels is the advantage of the proposed measuring method. This approach can be also used for determination of other technological parameters where the provision of disturbance-independent and multiple parameter measurements is needed.

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