

INBUILT MINIATURE INLINE VSWR METER AND ANTENNA ANALYSER FOR HANDHELD RADIO TRANSCEIVERS

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Abstract

This paper discusses an inbuilt miniature inline voltage standing wave ratio (VSWR) meter and antenna analyser for handheld radio transceivers. Most high-end and special purpose handheld radios include a VSWR meter inside that measures the antenna parameters all the time while transmitting. Such a feature helps mitigate inadequate antennas, loss of power and sensitivity, overload of the final stage of the transmitter, excessive heat dissipation and battery energy wasting. Most such meters measure VSWR only and knowledge of this parameter is sufficient in most scenarios.

The current article presents a simple to build, high efficiency and compact, yet sophisticated computer controlled VSWR meter that also measures other parameters of the antenna besides the VSWR. The meter capabilities are equal to or better than professional or specialized antenna analysers while being extremely small in size and low in complexity. The proposed device is capable of measuring complex antenna impedance and additionally revealing the value and sign of the antenna reactance, i.e. whether it is capacitive or inductive.

Key words: VSWR meter, handheld radio antenna analyser

Introduction. This paper discusses an inbuilt miniature inline voltage standing wave ratio (VSWR) meter and antenna analyser for handheld radio transceivers.

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Voltage standing wave ratio (VSWR) meter, also known for short – SWR meter, evaluates the voltage standing wave ratio of a radio transmitter antenna. The meter is placed between the transmitter final stage and the antenna. The device measures the impedance mismatch between the load (antenna) and the transmitter final stage [1, 2]. Such a device is useful in evaluating some of the antenna parameters such as its impedance match to the desired one (usually 50 ohms). If there is a mismatch, the user may tune the antenna to achieve better match [3, 4]. Many high-end and professional radios include a permanently inbuilt VSWR meter in their circuit. This helps without further effort to know the antenna mismatch during the time of use. If the antenna malfunctions, the meter will signal the user and they may wish to repair the antenna or replace it.

Classic VSWR meter with lumped elements. There are two main categories of VSWR meters: directional and lumped elements ones [5]. The directional meters are bulky for VHF and lower frequencies and due to lack of volume in hand-held radios this type of VSWR meter is seldom used for such frequencies [6]. The lumped elements variant is also called VSWR bridge (see Fig. 1). The bridge consists of three transformers or in some cases two transformers. All transformers have voltage transformation ratio of k . Their impedance transformation ratio is k^2 .

When the antenna impedance has the desired value (usually 50 ohms active impedance and zero ohms reactive impedance) the bridge is balanced. In the situation of mismatch the bridge will measure VSWR value that is greater than 1:1. The standard variant of the bridge will show only the VSWR of the antenna and the user will not be able to conclude anything further about the antenna impedance. Here is how this type of meter works.

To evaluate the voltage standing wave ratio of a radio transmitter the meter is placed between the transmitter final stage and antenna. The meter measures the impedance mismatch between the load (antenna) and transmitter final stage.

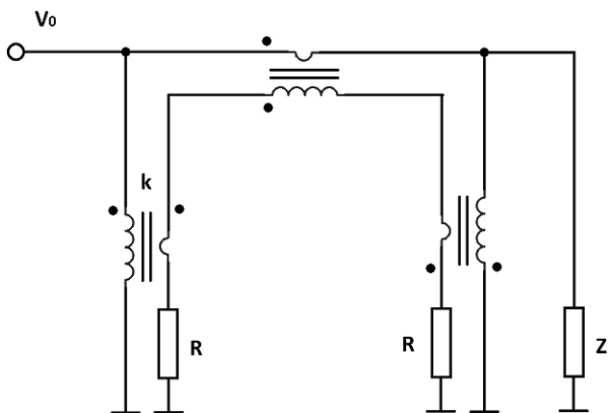


Fig. 1. VSWR bridge schematic diagram

Such a device is useful in evaluating some of the antenna parameters such as its impedance match to the desired one (usually 50 ohms).

The outer current loop of the circuit from Fig. 1 has input voltage (modulus) from the final stage of the transmitter v_0 and antenna load Z . The left and right transformers introduce very high impedance and can be neglected (approximated as open circuits). The top transformer introduces minor impedance and can also be neglected (approximated to zero impedance). Thus the entire analysis can be focused on the inner current loop of the schematic. The inner current loop of the circuit from Fig. 1 is shown in Fig. 2. The secondary windings of the left and right transformers along with the primary one of the top transformer have only a single turn. The secondary winding of the top transformer and the primary windings of the other two transformers have as many windings as possible without degrading the Q-factor of the transformer or entering a self-resonant mode of operation. All three transformers are exactly the same. The current flowing in this inner loop is:

$$\dot{I}_R = \frac{v_0}{Zk}.$$

The load impedance (the antenna impedance) is:

$$Z = a + jb.$$

The voltage across each of the resistors is:

$$\dot{U}_R = \dot{I}_R R = \frac{v_0}{k} \frac{R}{Z}.$$

The resistance R of the resistors is equal to the characteristic impedance Z_0 of the load or in other words to the desired resistance of the antenna (in most cases 50 ohms). In the above equation v_0/k is a real number. For convenience we substitute this number with:

$$\frac{v_0}{k} = c.$$

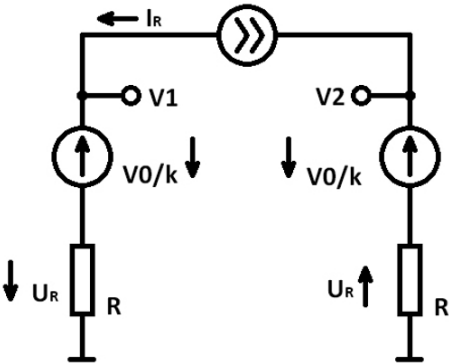


Fig. 2. Equivalent schematic diagram of the inner current loop

It follows that:

$$\dot{U}_R = c \frac{R}{Z}, \quad |\dot{U}_R| = u_R.$$

For the voltages $\dot{V}_1$ and $\dot{V}_2$ we have (see Fig. 2):

$$\begin{aligned} \dot{V}_1 &= c + \dot{U}_R = c + c \frac{R}{Z} = c \left(1 + \frac{R}{Z} \right), & |\dot{V}_1| &= v_1, \\ \dot{V}_2 &= c - \dot{U}_R = c - c \frac{R}{Z} = c \left(1 - \frac{R}{Z} \right), & |\dot{V}_2| &= v_2. \end{aligned}$$

With this schematic we have two options: to measure v_1 and v_2 or v_1 and u_R . When measuring high frequency voltages the easiest way is to measure maximum values. We need to recall that a maximum value of a sinusoidal voltage is equal to its effective value (modulus) multiplied by square root of two. To calculate the modulus value of a voltage we need to measure its maximum value and divide it by square root of two.

Option 1. We measure v_1 and v_2 (see Fig. 2):

$$\begin{aligned} v_1^2 &= c^2 \left| 1 + \frac{R}{Z} \right|^2 = \frac{c^2}{z^2} |Z + R|^2 \Rightarrow v_1 = \frac{c}{z} |Z + R|, \\ v_2^2 &= c^2 \left| 1 - \frac{R}{Z} \right|^2 = \frac{c^2}{z^2} |Z - R|^2 \Rightarrow v_2 = \frac{c}{z} |Z - R|. \end{aligned}$$

Let us recall the definition of the reflection coefficient Γ :

$$\Gamma = \frac{Z - Z_0}{Z + Z_0} = \frac{Z - R}{Z + R} \Rightarrow |\Gamma| = \left| \frac{Z - R}{Z + R} \right| = \frac{|Z - R|}{|Z + R|} = \frac{v_2}{v_1}.$$

Using this setup one can calculate in a straightforward way the VSWR. It is necessary to use the definition of VSWR:

$$\text{VSWR} = \frac{1 + |\Gamma|}{1 - |\Gamma|} = \frac{1 + \frac{v_2}{v_1}}{1 - \frac{v_2}{v_1}} = \frac{v_1 + v_2}{v_1 - v_2}.$$

Most VSWR meters do exactly this and continue no further. It is tempting to squeeze more information from these measurements having the same schematic and unchanged setup. The additional data is delivered simply by measuring transmitter voltage maximum value and calculating its modulus v_0 and then enhancing the software of the VSWR meter. By transforming the squared modulus parts of the equations for v_1^2 and v_2^2 we obtain a system of two equations:

$$\begin{cases} v_1^2 = c^2 \left| 1 + \frac{R}{Z} \right|^2 = c^2 \left(1 + \frac{R^2 + 2Ra}{z^2} \right) \\ v_2^2 = c^2 \left| 1 - \frac{R}{Z} \right|^2 = c^2 \left(1 + \frac{R^2 - 2Ra}{z^2} \right) \end{cases} \Rightarrow \begin{cases} z^2 = c^2 \frac{R^2 + 2Ra}{v_1^2 - c^2} \\ z^2 = c^2 \frac{R^2 - 2Ra}{v_2^2 - c^2} \end{cases}.$$

If we add the two equations of the system, the value of the antenna impedance modulus squared is derived as:

$$z^2 = a^2 + b^2 = \frac{2R^2c^2}{v_1^2 + v_2^2 - 2c^2}.$$

If we further subtract the two equations of the system, we derive the real component of the antenna impedance:

$$\frac{R^2 + 2Ra}{v_1^2 - c^2} = \frac{R^2 - 2Ra}{v_2^2 - c^2} \Rightarrow a = \frac{R(v_1^2 - v_2^2)}{2(v_1^2 + v_2^2 - 2c^2)}.$$

And from the equation for the impedance modulus squared we calculate the absolute value of the imaginary part (the reactance) of the antenna impedance:

$$a^2 + b^2 = \frac{2R^2c^2}{v_1^2 + v_2^2 - 2c^2} \Rightarrow b = \pm \sqrt{\frac{2R^2c^2}{v_1^2 + v_2^2 - 2c^2} - a^2}.$$

This is a lot of additional information about the antenna impedance gathered.

Option 2. We measure v_1 and u_R . Another system of two equations is formed:

$$\left| \begin{array}{l} v_1^2 = c^2 \left| 1 + \frac{R}{Z} \right|^2 = c^2 \left(1 + \frac{R^2 + 2Ra}{z^2} \right) \\ u_R^2 = c^2 \left| \frac{R}{Z} \right|^2 = c^2 \frac{R^2}{z^2} \end{array} \right. \Rightarrow \left| \begin{array}{l} z^2 = c^2 \frac{R^2 + 2Ra}{v_1^2 - c^2} \\ z^2 = c^2 \frac{R^2}{u_R^2} \end{array} \right.$$

After subtracting the two equations we get:

$$\frac{R^2 + 2Ra}{v_1^2 - c^2} = \frac{R^2}{u_R^2} \Rightarrow a = \frac{R(v_1^2 - c^2 - u_R^2)}{2u_R^2}.$$

Using the second equation of the system we obtain:

$$b = \pm \sqrt{c^2 \frac{R^2}{u_R^2} - a^2}.$$

Complete complex antenna Z impedance meter with only two transformers. It is possible to alter the lumped circuit in Fig. 1 by adding a capacitor and removing one of the transformers. The newly formed circuit is shown in Fig. 3. This circuit enables us to obtain even more information about the antenna impedance, namely the exact value of the complex antenna impedance.

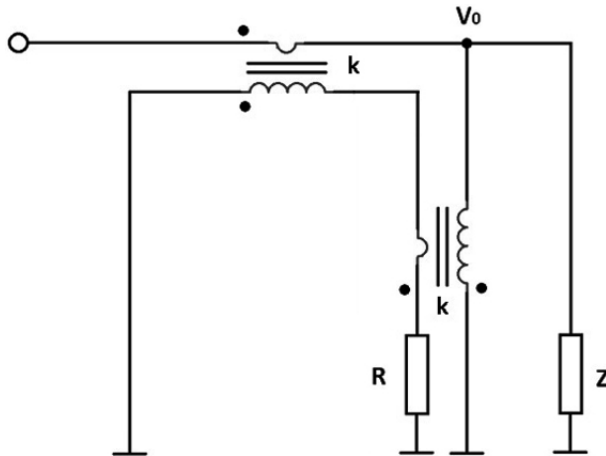


Fig. 3. Improved lumped element antenna analysis circuit

The equivalent circuit of the inner current loop is shown in Fig. 4. We need to obtain the complex antenna impedance with exact values including correct sign of its imaginary part:

$$Z = a + jb.$$

R is the resistance of the resistor in the inner current loop. The inner loop also includes a series capacitor with capacitance C . The capacitor impedance is:

$$X_C = r - j\frac{1}{2\pi fC} = r - jx, \quad x = \frac{1}{2\pi fC}.$$

Here r is the capacitor equivalent series resistance. To obtain the complex

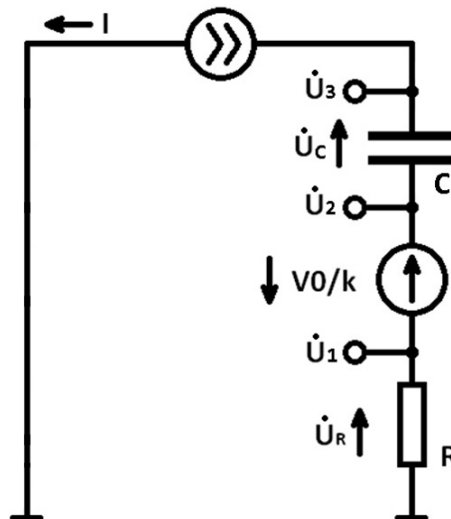


Fig. 4. Equivalent schematic diagram of the inner current loop of the improved circuit

antenna impedance Z we measure the maximum values of the four complex voltages $\dot{U}_0$, $\dot{U}_1$, $\dot{U}_2$, and $\dot{U}_3$, employing high frequency rectifiers. The moduli of these voltages are u_0 , u_1 , u_2 and u_3 , respectively. We are going to use also the squares of these moduli. The square of a voltage modulus is half the square of its maximum value.

The inner loop current is:

$$\dot{I}_{\text{out}} = \frac{u_0}{Z}.$$

We may set the imaginary part of voltage $\dot{U}_0$ to be zero hence $\dot{U}_0 = u_0$. This voltage has zero phase angle. All other voltages will have non-zero phase angles in the general case. As with the classic lumped element VSWR bridge circuit, here the impedance added by the top transformer to the outer loop is negligible. Hence the error in calculating $\dot{I}_{\text{out}}$ is also negligible. This impedance addition error is hundreds of times smaller than the antenna impedance and when appropriate transformers are used, can be neglected. The current in the inner loop is k times smaller and its direction is denoted in Fig. 4. Number k is the voltage transformation ratio of the two transformers, just like in the classic VSWR bridge schematic. The impedance transformation ratio is k^2 . The current in the inner loop in complex form is:

$$\dot{I} = \frac{\dot{I}_{\text{out}}}{k} = \frac{u_0}{Z} \frac{1}{k} = \frac{q}{Z}.$$

We set $q = u_0/k$. This is a real and positive number.

The voltage across the resistor in the inner loop is:

$$\dot{U}_R = \dot{I}R = \frac{q}{Z}R.$$

The voltage across the capacitor in the inner loop is:

$$\dot{U}_C = \dot{I}X_C = \frac{q}{Z}(r - jx).$$

$X_C = r - jx$ is the complex impedance of the capacitor. r is the equivalent series resistance of the capacitor, and x is the imaginary part of its impedance:

$$x = \frac{1}{\omega C} = \frac{1}{2\pi fC}.$$

Here ω is the angular frequency, and f is the frequency of the radio signal entering the measuring device. For the voltages in the inner loop we have:

$$\begin{aligned}\dot{U}_1 &= -\dot{U}_R = -q\frac{R}{Z}, & |\dot{U}_1| &= u_1, \\ \dot{U}_2 &= q - \dot{U}_R = q - q\frac{R}{Z} = q\left(1 - \frac{R}{Z}\right), & |\dot{U}_2| &= u_2, \\ \dot{U}_3 &= q - \dot{U}_R - \dot{U}_C = q - q\frac{R}{Z} - q\frac{r - jx}{Z} = q\left(1 - \frac{Z_1}{Z}\right), & |\dot{U}_3| &= u_3.\end{aligned}$$

For convenience we substitute:

$$Z_1 = R + r - jx = R_1 - jx, \quad z_1^2 = R_1^2 + x^2.$$

Now we evaluate the squares of the voltages moduli u_1 , u_2 , and u_3 . First we obtain the equation for the squared modulus of voltage u_1 :

$$u_1^2 = q^2 \frac{R^2}{z^2}.$$

From this equation we derive the antenna impedance modulus squared:

$$z^2 = q^2 \frac{R^2}{u_1^2}.$$

Second, we find equation for u_2^2 :

$$u_2^2 = q^2 \left| 1 - \frac{R}{Z} \right|^2 = q^2 \left| 1 - \frac{Ra}{z^2} + j \frac{Rb}{z^2} \right|^2 = q^2 \left(1 + \frac{R^2 - 2Ra}{z^2} \right).$$

From this equation we derive the real part of the antenna impedance:

$$a = \frac{R^2 - \left(\frac{u_2^2}{q^2} - 1 \right) z^2}{2R}.$$

Thirdly, we evaluate u_3^2 :

$$\begin{aligned} u_3^2 &= q^2 \left| 1 - \frac{\bar{Z}}{z^2} Z_1 \right|^2 = q^2 \left| 1 - \frac{1}{z^2} (a - jb)(R_1 - jx) \right|^2 \\ &= q^2 \left| 1 - \frac{aR_1 - bx}{z^2} + j \frac{ax + bR_1}{z^2} \right|^2 \\ &= q^2 \left[\left(1 - \frac{aR_1 - bx}{z^2} \right)^2 + \left(\frac{ax + bR_1}{z^2} \right)^2 \right] \\ &= q^2 \left(1 - 2 \frac{aR_1 - bx}{z^2} + \frac{a^2 R_1^2 - 2aR_1bx + b^2 x^2}{z^4} + \frac{a^2 x^2 + 2axbR_1 + b^2 R_1^2}{z^4} \right) \\ &= q^2 \left(1 - 2 \frac{aR_1 - bx}{z^2} + \frac{(R_1^2 + x^2)(a^2 + b^2)}{z^4} \right) \\ &= q^2 \left(1 + \frac{R_1^2 + x^2 - 2R_1a + 2xb}{z^2} \right). \end{aligned}$$

So

$$\left(\frac{u_3^2}{q^2} - 1 \right) z^2 = z_1^2 - 2R_1a + 2xb.$$

Using the last equation we obtain the imaginary part of the antenna impedance:

$$b = \frac{\left(\frac{u_3^2}{q^2} - 1\right) z^2 - z_1^2 + 2R_1 a}{2x}.$$

Conclusion. Introducing compact lumped element VSWR bridge meters in handheld VHF and HF radio transceivers enables the user to measure the antenna parameters all the time and tune their antenna in the field or replace a broken antenna when the latter malfunctions. The lumped element VSWR bridge meter can be transformed into full parameter antenna analyser with only minor modification and extensive software calculations possible in modern microcontroller units.

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