TRANSMISSION LINES: ANALYSIS UNDER ANOTHER FOCUS

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Introduction

The subject "Transmission Lines" has been involved by a mystery cloud for the hamradio world (and even for some professionals). The reason for that is because the involved concepts are not well presented, letting some degree of speculation and discussions of the type "in my opinion", generating polemics.

In the texts on transmission lines, a generator is said as 'matched to the line' when its output impedance is equal to **Zo**, the line surge impedance. This is not a real match when we remember that, in the well-behaved cases[1], it is matched to the load when it transfers the maximum possible power to the load, that is, its output impedance is the complex conjugate[2] of the impedance seen on the load. In the general case, this impedance is not equal to **Zo** and, therefore, we will consider that a generator is matched to a line when the impedance seen at the lower end of the line (resulting from the load impedance at its upper end) is matched with that of the generator and **Zo** is merely a parameter of the line itself.

For us, here, 'matched to the line' and 'matched to **Zo'** are two completely different things and must be well understood because they will be used for now on in the present article.

The 'matched to the line' is more coherent with the following situation: suppose we have a generator connected to a black box (may be there is a line inside the box, but we do not know). We ask somebody to Adjust the impedance of the generator to match the black box input. He cannot adjust it to **Zo** because he was not informed about the black box details. He will adjust things to get the greatest power transfer between the generator and the box and this will occur when the generator is matched to the impedance seen at the box input.

We will not present here any derivation or concept already presented in other texts.

As 'return loss' and 'line loss' are independent things, we will divide the text into two parts, ideal lines and lossy lines.

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[1] Linear and time independent circuits, as transmission normal lines are.
[2] Or equal if there are no reactance involved.

Ideal Lines

To simplify things, we will consider for the time being that the line is ideal (no loss) and the load at the line upper end is purely resistive[3].

Suppose a generator connected to a line (**Zo**) and the latter to a load **Ri = Zo**, as in Figure 1.

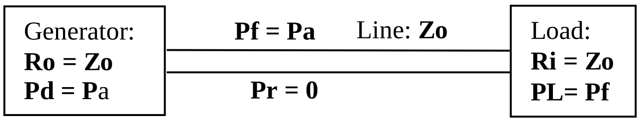

Figure 1

As the load impedance is equal to **Zo**, the reflected power is null and the impedance seen by the generator is **Zo**. This delivers a power **Pd** equal to the maximum available power **Pa** entirely to the line and the forward power **Pf** is equal to **Pa**. Then the power **PL** delivered by the line to the load is also **Pa**. This is the simple case of total match.

Now suppose that all those conditions are kept, but the load impedance now is **Ri = Z ≠ Zo**, as in Figure 2.

We have now a reflected power **Pr** (not zero) that goes in the direction of the generator. Supposing we use an ideal coupler (if necessary) for matching it with the line (not to **Zo**), that is, all the maximum available power is still delivered to the line.

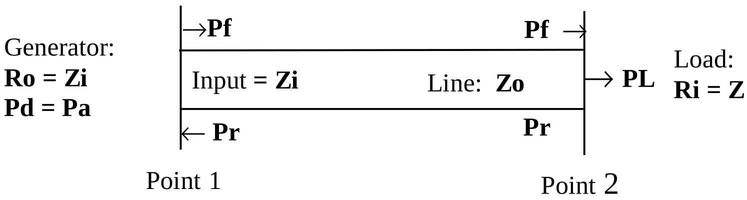

Figure 2

Remembering that, in any not dissipative point of a circuit, the arriving power is equal to the leaving one (by the energy conservation law), we can analyze what happens at the Points 1 and 2 of the figure (they are respectively the two ends of the line, that of the generator and that of the line).

[3] **This does not lead us to any loss of generality, but only simplifies the discussions.**

At the Point 1, the arriving power is **Pr + Pa** and the leaving power is **Pf**, so **Pf = Pa + Pr (I).** At Point 2, the arriving power is **Pf** and the leaving one is **PL + Pr**, so **Pf = PL + Pr (II)**.

Comparing **(I)** and **(II)**, we have **PL + Pr = Pa + Pr**, or **PL = Pa**, independently of the reflection coefficient, as we have not mentioned it yet.

This means that, with a generator matched to the line, all of its power is dissipated on the load, no matter as great is the mismatch between line and load.

As all involved power are positive numbers (squared voltages divided by positive impedances or squared currents multiplied by positive impedances), from **(I)**, we can see that the power **Pf** is greater than the available power **Pa**. This also can be seen so:

Pf = PL + Pr and $\mathbf{Pr = |\rho|^2 . Pf}$

Thus, as **PL = Pa**, we may write:

$\mathbf{Pf - |\rho|^2 . Pf = Pa}$ or $\mathbf{Pf = Pa / (1 - |\rho|^2)}$

As $\mathbf{|\rho|^2 \leq 1}$, then $\mathbf{Pf \geq Pa}$.

With the standing wave ratio = **Swr** and as, by definition, $\mathbf{|\rho|^2 = (Swr - 1) / (Swr + 1)}$, we may also write the following:

$\mathbf{Pf = Pa . (Swr + 1)^2 / (4 . Swr)}$

A question arises immediately: is not it a power creation from nothing?

The answer is NO, because the forward power is fed not only by the generated power, but also by the reflected one; the excess of power at Point 2 that is not delivered to the load, just **Pr**, will contribute to **Pf** at Point 1, as in Figure 2.

We may say that there is a power equal to **Pa** (the maximum available power) going upwards on the line in the direction of the load and being dissipated on the latter, plus a circulating power **Pr**. The forward part of this circulating power sums with the power **Pa** as **Pf** and the back power is just **Pr** (it is a mesh analysis) as in Figure 3.

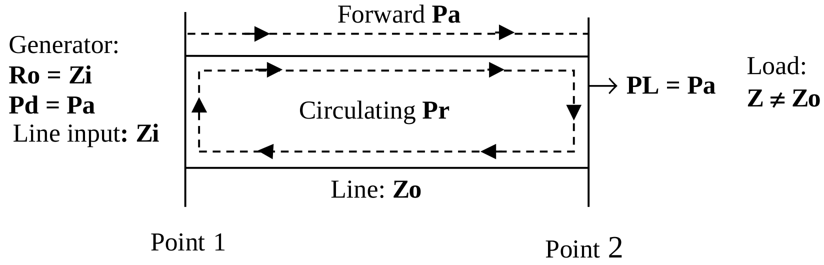

Figure 3

Later, we will show a similar situation in case of pipes with liquids.

This shows that the reflected power itself is the reason of the efficiency decrease when there is a mismatch between a lossless line and the load, as all available power is delivered to it.

This is in perfect agreement with the fact that, if all power is delivered (nothing is given back) by the generator to a system composed by an ideal element (line) and a dissipative element (load), this power can only be dissipated on the load (due conservation of energy), nothing being said about reflections.

When we do not have a 'match to the line' condition in the line generator end, but, instead, a 'match to **Zo'** situation, we have indeed a mismatch at the generator and **this** is the real reason for the loss that, although called 'reflection loss', is a loss internal to the generator.

Ideal lines are only lossless impedance transformers, with the reflected power being only used to adjust and match the involved impedances. **Zo**, although having impedance dimension, is only a line parameter.

Lossy Lines

In the real world, however, the presence of reflected waves increases the voltage/current peaks in some points of the line (standing waves with peaks and valleys) and these peaks increase losses[4]. Thus, it is the **line loss** responsible for the losses in a mismatched line and **not** the reflection itself, as many people commonly think it.

As a simple and well-known example, we have the case of a resonant 50Ω antenna fed with a half wavelength long 300Ω line. The impedance seen by the generator is also 50Ω due the line length, but we have a 6:1 mismatch at the line antenna end. Even with that big reflection occurring, on this line little loss will be noted. We see that, in spite of the difference of the generator (50Ω) and line (300Ω), the reflected power does not mean loss and no 'reflection loss' will occur. This is because the generator is really matched to the line input impedance and not to its surge impedance (when nothing is said about power transfer).

The loss of a transmission line, when the transmitter is matched to it (not with **Zo**), that means, due only to the inherent line loss increased by the presence of **VSWR = R**, is given by:

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[4]Due the quadratic behavior of the power, the increase of the losses in the peaks is greater than the decrease in the valleys and then the global loss is greater.

$$\mathbf{At\ (dB) = L \cdot A / 100 - 10 \cdot \log \{4 \cdot R /[(R + 1)^2 - (R - 1)^2 \cdot 10^{(-L \cdot A / 500)}]\}}$$

Where **L** is the line length **in feet**, **A** the line specific attenuation in **dB/100 feet** at the working frequency, **log** is the decimal logarithm and **R** the VSWR (the **R** of the ratio **R:1**). The numeric constants are due the units chosen for the length and specific attenuation of the cable.

We see clearly that, if the specific attenuation **A = 0dB** (no attenuation on the line), the total cable attenuation **At = 0 dB**, that is, there is no attenuation ***independently of the VSWR***. Conversely, if the VSWR **R = 1** (no reflection), the total attenuation is only equal to the attenuation of the **L** length line.

'Matching to Zo'

If the line is lossless and the generator is 'matched to the line' (not to **Zo**), we see that, even existing a reflected power, there is no **return loss**. The latter is important, however, when there is a mismatch between the line and the load and we have the 'match to **Zo**' condition.

The reflected power sees the generator impedance **Zo** when it arrives to the lower end of the line and, therefore, it is totally transferred to the generator itself that **dissipates** it.

The forward power is the same of the perfect match case, but the transferred power to the load is the forward power less the reflected one.

So, we have less power at the load and this difference is dissipated on the generator. Now we have the so-called 'return loss'. When we have an ideal coupler at the generator output and we get a 'match to the line' condition, the coupler nullifies that return loss, even with a great mismatch at the load. That is why the expression 'return loss' is not much convenient and it is one of the reasons of the bad understanding about transmission lines.

Case of pipes with liquids

Suppose we have a pipe as in Figure 4. If, for exemple, 10 l/s of water enter from the left, independently of the pipe shape, 10 l/s will come out to the right. In the central part of the pipe, thicker, the flow is also the same 10 l/s.

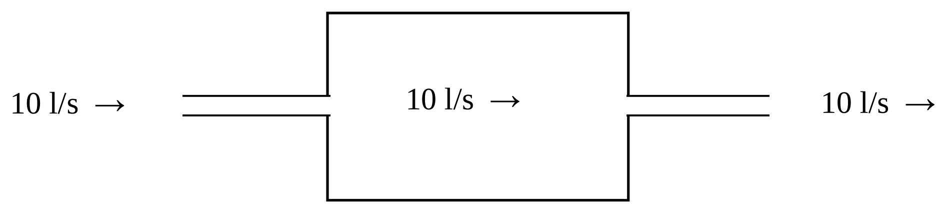

FIGURE 4

Does exist a way to create a system entering only 10 l/s, coming out only 10 l/s, but in an internal branch we have, say, 12 l/s circulating with no other external water source? Yes, it is possible as in Figure 5.

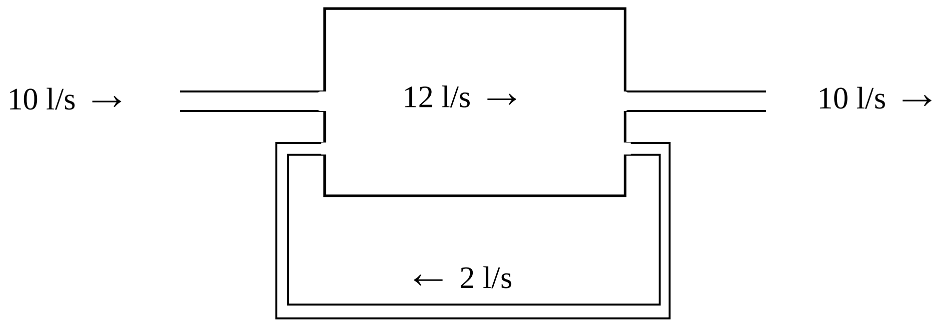

FIGURE 5

In the thiner pipe the flow is 2 l/s due the pressure made by the water to the right and the negative pressure at the left due the speed of the water. So, in the thicker pipe the flow is 12 l/s, 10 l/s coming from the externa source and 2 l/s from the thiner pipe. The source of this greater flow is part from itself, that means, there is a circulating 2 l/s flow. So, we got na internal greater flow without create water in any place. The same happens to the power on transmission lines: a forward power can be greater than the generated one without creating power from nothing. The only difference is that, in the water case, due the friction, the returning flow cannot use the same pipe of the forward one. The reflected power can return through the same lina as both waves do not interact.

Mechanism of impedance match by the cable

In a impedance transformer with primary and secondary, the impedance transformation ratio is $\mathbf{n^2}$, where **n** is the turns ratio. In the case of transmission lines, the process is diferente. Suppose a resistive load **R** (only for simplicity, as this does not change the considerations). By Ohm law, the ratio between the voltage and current on that load is **V/I = R**, something that must be satisfied. But the ratio between the forward voltage **Vf** and the forward current **If**, of the forward waves that travel on the cable is **Zo**. As the top end of the cable is connected to **R**, something maus happen to solve this problem.

Suppose that **Zo** is greater than **R**.

We have:

Vf/If = Zo

V/I = R

For the first ratio, that is greater than the second, to have the value of the later, it is necessary to decrease the numerator and increase the denominator. So:

(Vf – Vr)/(If +Ir) = Zo

with **Vr** being a voltage with opposite sign to **Vf** and **Ir** current with the same sign as **If**. From the electromagnetic wave theory, if we change the sign of only one of the variables that composse the power, the direction of the wave inverts. Thus, new waves are created traveling back in the direction of the generator (thats why they are called reflected waves), so that the resulting voltage and current at the end of the cable are respectively **Vf – Vr = V** and **If + Id = I**. This makes the ratio between voltage and current now as being equal to **R**. The cable reflects at the generator end na impedance depending on its parameters as length, velociti fator, frequency and **Zo** itself.

For the case where **Zo** is samller than **R**, things are similar with the summation occurring in the numerator and the subtraction in the denominator.

The process of impedance transformation by a line is, therefore, based on the existence of standing waves on it.

Conclusions

When we have a transmitter with fixed output impedance, with no coupler and connected to an ideal line, it is advisable to match the line to the antenna due the return loss. With a coupler, or a transmitter with variable output impedance, the VSWR is irrelevant for those lines. Indeed the line adjusts to the antenna via the reflection and leaves to the transmitter the problem of the loss decrease.

In the real world, when lines have losses that increase with the VSWR, we must keep the latter as little as possible in any situation, but couplers are still useful to cancel the return loss[5].

Another reason for keeping the VSWR the lowest as possible is the decrease of the maximum power on a cable with standing waves[4].

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[5] We see that the expression 'return loss' is not very convenient because the coupler, at the line generator end, is able to cancel the return loss without affecting the return power (reflected) on the line that depends only on the mismatch condition at the line antenna end.
This article does not intend to change the expression 'return loss' in the literature as it is well accepted, but call the attention of the reader about its concept.

The line, indeed, is simply an impedance transformer, reflecting to the generator the load impedance transformed by the line. If the line is ideal, it is simply a lossless impedance transformer.

A common transformer with primary and secondary uses the magnetic properties involved in the windings ratio to execute such a transformation. The transmission line uses the reflection to execute it, nothing having to do with losses.

I believe that this focusing of the problem (involving the fact that the forward power is greater than the generated one in the lossless case) is a novel one; at least I have never seen it explicitly in the literature.

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[4] **The maximum power specified by cable manufacturers corresponds to the condition of VSWR = 1:1; for a VSWR of n:1, the maximum power is the specified divided by n.**