Antenna System Impedance Matching Analysis Using Stubs
by F.M. Griffee, N4FG (EE Ret)

Introduction

In previous articles, I have referred to stub matching. This article shall address that subject and also compare experienced results with hybrid matching. Hybrid matching refers to the use of actual inductive and capacitive variables instead of transmission line segments.

Through my readings, it appears very little is included regarding stub matching details. Indeed, it usually starts and ends by using the Smith Chart or other graphical technique. In this day and age, graphic use can be replaced by the equations used to derive the graphics. Quite clearly, programs that can be derived today can include both if desired. My efforts will concentrate on the more simplified approach of using given equations within the program. But I shall not include quarter wave transformers since they primarily require resistive terminations and will be addressed in future articles.

As a beginning, I shall use the excellent work of Cebik (Ref 5) where he derives an equation set that allows calculation not only for the line surge impedance Zo match, but also to a second line Zo that may be used from the stub line attachment point on to the source generator (our transceivers). Since our transceivers of today are designed to be terminated in a Zo very close to 50 Ohms resistive, I shall begin with that value. However, there are situations where 50 Ohms or close to that value, cannot be reached. In some cases, a balun must be used.

I shall conduct experimental measurements to substantiate the theory. Measured results using the MFJ-259B HF/VHF SWR Analyzer and the Autek Research RX Vector Analyst Model VA1 will be included.

It is well recognized that series or parallel stub matching can be employed. Generally speaking however, it is preferred that parallel stub matching be used. The reason for this is straightforward because the parallel equivalent impedance reactive component can be easily cancelled, leaving the desired Zo of the particular transmission line terminated by an equal Zo. This is obviously seen as Zo matching that is apart from the actual load impedance seen at any particular point on the transmission line or at the antenna apex point itself. Since the parallel equivalent of the impedance seen along the transmission line and at the antenna apex must be known, I have included the determination of it within my transmission line program upgrade, ZiZLCA30.EXE (available in the download section in the *antenneX* Guest Rooms at: http://www.antennex.com/guests.html (get yourself a login on that page and enter the Guest Rooms).

The Stub Matching Program Equations

I have received permission from LB Cebik to use his derived equations and repeat them at this point for clarity. They are used in my program using my Borland C++ Compiler. I recently discovered this compiler is offered as a free download at the Web Site address:

http://community.borland.com/article/0,1410,20633.html.

Cebik did write a program in BASIC but it requires the GWBASIC interpreter that loads it, then runs the program using the appropriate command keys. The user must use function keys to perform the required commands for "load" and "run". I decided to write a program (stubs6.exe) using my C++ compiler since it arrives at a self-execute result, allowing a simple mouse icon and click to run it. The Cebik BASIC program and listing is, however available at:

http://www.cebik.com/mu/mu3a.html

The Cebik equations follow.

$$R_T = \frac{Z_m^2\left(1-\left|\rho_L\right|^2\right)}{Z_F\left(\left|\rho_L\right|^2-1\right)+2Z_m\left(\left|\rho_L\right|^2+1\right)} \tag{1}$$

where R_T is the series impedance resistive value seen at the point where Z_F, the parallel equivalent of the impedance along the line that equals the line surge impedance, Zo (the small reactive value of Zo is assumed zero for all practical purposes). The parallel equivalent impedance resistive value at a point on the transmission line is

$$Z_F = \frac{R_T^2 + X_T^2}{R_T} \tag{2}$$

The length of transmission line, l_r, is found after a great deal of work to equal

$$l_r = \tan^{-1}\left[\frac{\frac{X_L}{Z_o^2} \pm \sqrt{\frac{X_L^2}{Z_o^2} - \left(\frac{X_L^2}{Z_o^2} + \frac{R_L^2}{Z_o^2} - \frac{R_L}{R_{in}}\right)\left(1 - \frac{R_L}{R_{in}}\right)}}{\left(\frac{X_L^2}{Z_o^2} + \frac{R_L^2}{Z_o^2} - \frac{R_L}{R_{in}}\right)}\right] \tag{3}$$

Equation (3) may appear complicated but once entered into a program becomes transparent to the user. But I must admit that going through the derivation process, I experienced the usual complexity and ease of making mistakes along the way. Eventually, however, I am able to reach the desired result. Note that there are two answers since the square root radical includes a choice of + or – sign. The better choice is obvious after conducting the calculation using the given program but both solutions can be provided. There are always conditions with this type of equation. If the quantity within the square root radical is less than 0 or negative, then there is no solution and a new value of Zo, R_{in} , or both must be chosen. Examples of using the program that includes these equations will follow later.

The value for R_{in} is exactly equal to the desired value of R_T or the surge impedance, Zo, of the line at the point on the line, l_r feet distant from the antenna apex. It merely requires the user to enter the value of Zo, R_{in}, R_L, and X_L. The values for R_L, and X_L are those at the antenna apex. If an antenna includes a known transmission line and length, and the source impedance is known by measurement or modeling using EZNEC or NEC-WIN Plus+, then the values of R_L, and X_L can be easily determined by using my program ZiZLCa30.EXE (or ZiZLCa29.EXE) or other similar program (but I do not know of any program that is similar to my ZiZLCa#.EXE programs although there are some that can derive a result assuming lossless lines).

The Cebik equation derivations do assume lossless line characteristics but quite frankly, the assumption is definitely acceptable for all practical purposes, many of which are given in his excellent article on the subject (Ref 5). But my programs do assume line losses and therefore I can decide whether I want the lossless to be considered inconsequential. Or I can compare the results between assuming losses are negligible to that when losses are included.

The remaining needed equations are parallel equivalent reactance, X_p , the reactance X_{in} , and the stub length, l_s .

The equation for X_{in} is

$$X_{in} = \frac{X_L\left(1-\tan^2\left(l_r\right)\right)+\left(Z_o-\left(\frac{R_L^2+X_L^2}{Z_o}\right)\right)\tan\left(l_r\right)}{\left(1-\left(\frac{X_L}{Z_o}\right)\tan\left(l_r\right)\right)^2+\left(\left(\frac{R_L}{Z_o}\right)\tan\left(l_r\right)\right)^2} \tag{4}$$

The parallel equivalent reactance of X_{in} is easily found from

$$X_p = \frac{R_{in}^2+X_{in}^2}{X_{in}} \tag{5}$$

at point l_r where

$$R_{in} = \frac{R_L\left(1+\tan^2\left(l_r\right)\right)}{\left(1-\left(\frac{X_L}{Z_o}\right)\tan\left(l_r\right)\right)^2+\left(\left(\frac{R_L}{Z_o}\right)\tan\left(l_r\right)\right)^2} \tag{6}$$

and is the value the stub reactance (assumes zero losses), must equal in magnitude but be opposite in sign so there will be cancellation.

Again, I must admit that it is an arduous task to arrive at all of the above equations but I am able to reach them after experiencing mistake corrections and a final complete derivation process. My derivation merely substantiates that I did things correctly after being done by Cebik.

The equations are then used in my program but I split various variable and entities into discrete steps so I could keep track of ratios and especially the parentheses through the equation flow.

Last but not least are the equations for the stub lengths. There are two choices, one for a short circuit and one for open circuit termination.

They are:

$$l_s = \tan^{-1}\left(\frac{X_{in}}{Z_o}\right) \tag{7}$$

for a short circuit stub termination assuming zero loss, and

$$l_o = \cot^{-1}\left(\frac{X_{in}}{Z_o}\right) \tag{8}$$

for an open circuit stub termination, again, assuming zero loss.

Normally, a short-circuit stub termination is used but after reaching microwave frequencies, problems with open circuit stub terminations no longer exist since they are very short. But this area is beyond the scope of this article and will not be pursued further.

At VHF and UHF, there can be problems with open circuit stub termination since the stub may tend to radiate or be too unwieldy regarding construction properties. At HF frequencies, actual capacitance and inductive elements can be used at various points along a given length of transmission line. This relates directly to the popular L-network matching designs.

Stub design and examples using my program, Stub6

The name of my program, STUB6.EXE, is the sixth iteration after much manipulation and error correcting. An example equal to that of Cebik's BASIC program named "Stubtune," follows (in **Table 1**) where Rin = 50 Ohms, the Zo = 450 Ohms, f = 28.5 MHz, ZL = 141.36 – j693.56 Ohms, and the velocity factor of the coaxial cable equals 0.66 while that for the 450 ohm line equals 0.95. In all cases, I have assumed the stub and transmission line Zo are equal, and that the same type of line is used for both.

The velocity of light used in these examples for determining wavelength is taken from that of the National Institute of Technology and Standards (NITS) data and is equal to

$$VOL := 299.792458 10^{6} \cdot 3.28083333 \text{ ft/sec}$$

where meters are converted to feet by the factor 3.28083333 ft/mtr.

```
f ...........................................= 28.5000 MHz
The velocity factor, vf .....................= 0.9500
Surge line impedance, Zo1 ...................= 450.0000 Ohms
Surge line impedance, Zo2 ...................= 50.0000 Ohms
OPTION A
Stub point series Zs ........................= 41.0997 -j 19.1259 Ohms
Stub point equivalent parallel Zp of Zs.....= 50.0000 -j 107.4451 Ohms
Line from antenna apex to stub, foot length = 5.0385 ft
Short circuit stub, foot length ............= 1.2230 ft
Short circuit stub, degree lengh ...........= 13.4289 degrees
Open circuit stub, foot length .............= 9.4194 ft
Open circuit stub, degree length ...........= 103.4289 degrees
Short cirduit stub, Zsc .....................= 0.0000  +j 107.4451 Ohms
Open circuit stub, Zoc ......................= 0.0000  +j 107.4451 Ohms
OPTION B
Stub point series Zs ........................= 41.0997 +j 19.1259 Ohms
Stub point equivalent parallel Zp of Zs ....= 50.0000 +j 107.4451 Ohms
Line from antenna apex to stub, foot length = 5.4855 ft
Short circuit stub, foot length ............= 15.1698 ft
Short circuit stub, degree lengh ...........= 166.5711 degrees
Open circuit stub, foot length .............= 6.9734 ft
Open circuit stub, degree length ...........= 76.5711 degrees
Short circuit stub, Zsc .....................= 0.0000  -j 107.4451 Ohms
Open circuit stub, Zoc ......................= 0.0000  -j 107.4451 Ohms
```

Table 1 – Results from my program analysis of the example.

Table 1 provides the results that agree with the Cebik BASIC program, STUBTUNE.BAS. The 50-Ohm coaxial cable line then is handled separately from the stub point to the transceiver. This line characteristic data is then followed regarding losses and other data such as the velocity factor. The data for two options are given where option A uses a positive sign, and option B uses a negative choice for the previously mentioned square root radical.

A second example (shown in **Table 2**) is used to illustrate the experience of a situation where the Zo of the line must be changed since no solution is otherwise possible.

The frequency in this example is 14.175 MHz, Zo1 = 400 Ohms, Zo2 = 200 Ohms, the vf = 0.90 for the ladder type line, and the antenna apex impedance ZL = 129-j313 Ohms.

```
f ........................................= 14.1750 MHz
The velocity factor, vf ..................= 0.9000
Surge line impedance, Zo1 ................= 400.0000 Ohms
Surge line impedance, Zo2 ................= 200.0000 Ohms
OPTION A
Stub point series Zs .....................= 88.5039 -j 99.3370 Ohms
Stub point equivalent parallel Zp of Zs.....= 200.000 -j 178.1892 Ohms
Line from antenna apex to stub, foot length = 3.9847 ft
Short circuit stub, foot length ............= 4.1653 ft
Short circuit stub, degree lengh ...........= 24.0117 degrees
Open circuit stub, foot length .............= 19.7775 ft
Open circuit stub, degree length ...........= 114.0117 degrees
Short cirduit stub, Zsc ...................= 0.0000  +j 178.1892 Ohms
Open circuit stub, Zoc ....................= 0.0000  +j 178.1892 Ohms
OPTION B
Stub point series Zs .....................= 88.5039 +j 99.3370 Ohms
Stub point equivalent parallel Zp of Zs ....= 200.000 +j 178.1892 Ohms
Line from antenna apex to stub, foot length = 9.0469 ft
Short circuit stub, foot length ............= 27.0591 ft
Short circuit stub, degree lengh ...........= 155.9883 degrees
Open circuit stub, foot length .............= 11.4469 ft
Open circuit stub, degree length ...........= 65.9883 degrees
Short circuit stub, Zsc ...................= 0.0000  -j 178.1892 Ohms
Open circuit stub, Zoc ....................= 0.0000  -j 178.1892 Ohms
```

Table 2 – Second example using stub matching and my program.

Again, note that surge impedance for the length of line and stub are equal. The value for Zo2 is the surge impedance for the line going from the stub point to the transceiver. The stub and line surge impedance values are set to be equal in my program. They are not set as a variable. A 4:1 Balun would be a good choice for this example and allows the use of coaxial cable from that point on towards the source generator.

A third example will address impedance for a 2-meter antenna design. The load impedance, ZL = 18 – j45 Ohms, the line Zo = 450 Ohms with a velocity factor of 0.90, and the frequency = 146 MHz.

```
f .........................................= 146.0000 MHz
The velocity factor, vf ...................= 0.9000
Surge line impedance, Zo1 .................= 450.0000 Ohms
Surge line impedance, Zo2 .................= 50.0000 Ohms
OPTION A
Stub point series Zs ......................= 17.8721 -j 23.9623 Ohms
Stub point equivalent parallel Zp of Zs....= 50.0000 -j 37.2921 Ohms
Line from antenna apex to stub, foot length = 0.0449 ft
Short circuit stub, foot length ...........= 0.0798 ft
Short circuit stub, degree lengh ..........= 4.7374 degrees
Open circuit stub, foot length ............= 1.5956 ft
Open circuit stub, degree length ..........= 94.7374 degrees
Short cirduit stub, Zsc ...................= 0.0000  +j 37.2921 Ohms
Open circuit stub, Zoc ....................= 0.0000  +j 37.2921 Ohms
OPTION B
Stub point series Zs ......................= 17.8721 +j 23.9623 Ohms
Stub point equivalent parallel Zp of Zs ...= 50.0000 +j 37.2921 Ohms
Line from antenna apex to stub, foot length = 0.1477 ft
Short circuit stub, foot length ...........= 2.9518 ft
Short circuit stub, degree lengh ..........= 175.2626 degrees
Open circuit stub, foot length ............= 1.4360 ft
Open circuit stub, degree length ..........= 85.2626 degrees
Short circuit stub, Zsc ...................= 0.0000  -j 37.2921 Ohms
Open circuit stub, Zoc ....................= 0.0000  -j 37.2921 Ohms
```

Table 3 – Third example of stub matching design.

Table 3 illustrates a situation where an open circuit terminated stub might be more practical since the short circuit terminated stub requires a very small value of inductance of about 0.04 uH. The open circuit stub termination choice shows a capacitive value of approximately 58 pf. But its length is nearly a half wavelength and may produce serious radiation problems. The short circuit stub length on the other hand, is approximately one inch.

The bandwidth is another factor to consider but is beyond the scope of this article and will be considered for future articles.

Experimental results

I chose the 20-meter band for my experimental analysis and to my great pleasure, found the theory was almost perfectly on target. The frequency for this experiment is 14.175 MHz, the load impedance 107 – j 284 Ohms, the velocity factor of the line 0.90, and Zo is 404.9706 – j0.5997 or essentially 405 Ohms.

I shall repeat the theoretical analysis for these data for clarity since the load impedance has changed. See **Table 4**.

```
f .........................................= 14.1750 MHz
The velocity factor, vf ...................= 0.9000
Surge line impedance, Zo1 .................= 405.0000 Ohms
Surge line impedance, Zo2 .................= 200.0000 Ohms
OPTION A
Stub point series Zs ......................= 74.7696 -j 96.7648 Ohms
Stub point equivalent parallel Zp of Zs.....= 200.000 -j 154.5389 Ohms
Line from antenna apex to stub, foot length = 3.8947 ft
Short circuit stub, foot length ............= 3.6230 ft
Short circuit stub, degree lengh ...........= 20.8857 degrees
Open circuit stub, foot length .............= 19.2352 ft
Open circuit stub, degree length ...........= 110.8857 degrees
Short cirduit stub, Zsc ....................= 0.0000  +j 154.5389 Ohms
Open circuit stub, Zoc .....................= 0.0000  +j 154.5389 Ohms
OPTION B
Stub point series Zs ......................= 74.7696 +j 96.7648 Ohms
Stub point equivalent parallel Zp of Zs ....= 200.000 +j 154.5389 Ohms
Line from antenna apex to stub, foot length = 8.7058 ft
Short circuit stub, foot length ............= 27.6014 ft
Short circuit stub, degree lengh ...........= 159.1143 degrees
Open circuit stub, foot length .............= 11.9892 ft
Open circuit stub, degree length ...........= 69.1143 degrees
Short circuit stub, Zsc ....................= 0.0000  -j 154.5389 Ohms
Open circuit stub, Zoc .....................= 0.0000  -j 154.5389 Ohms
```

Table 4 – Theoretical prediction for stub matching using recent data

Table 4 predicts what can be expected during the stub matching process. Two lengths of my ladder line with a Zo very close to 400 Ohms is used. The lengths are taken from previous experimental analysis where the line length from my antenna system line feed point equals 4 feet and 8.5 inches, and the second length for the stub is 4 feet and 1.5 inches. I did not trim these lengths since I was curious to see how close they would come to the theoretical results. The length from the load shows to be predicted as 3.8947 feet while the stub length is predicted to be 3.6230 feet. The results were quite surprising to me!

The measured series impedance at the stub attachment point was 74 – j105 Ohms, and after attaching the stub with a short circuit termination, the impedance became equal to 244 + j44 Ohms. This is very close to the desired 200 Ohms value.

I did not trim the line or stub lengths but no doubt could have brought the desired bandwidth characteristics closer to the center of the band.

My Guianella 4:1 current balun was added at this point and the input impedance measured 88 + j14 Ohms. This would recommend a line Zo of 75 Ohms but I continued with 50-Ohm coax since I did not have any 75-Ohm line. Nevertheless, the success path continues!

The SWR at my TS870S transceiver measured 2.7 at 14.000, 1.45 at 14.175, and 1.16 at 14.350 MHz. I then found the SWR minimum of 1.02 at 14.290 MHz. The acceptable 2:1 SWR was found at 14.120 MHz.

Therefore, some fine-tuning is obviously required but this is not the point. The theoretical approach predicted data very close to what is actually needed to arrive at the desired result. Some fine-tuning therefore can be conducted to bring the desired characteristics towards the target values.

An additional modified program, my ZiZLCA30.EXE, is used and allows the prediction of an acceptable value for Zo. Indeed, the stub and line length can be found directly by varying the line length. But this is not quite as fast when comparing its analysis against the Cebik equation approach. However, the two approaches can be compared to determine possible differences that may occur. The modification merely displays the parallel equivalent impedance along the transmission line as its length is varied incrementally. Any impedance value along the line is found very quickly while the incremental length is being varied.

A second experimental measurement is conducted at 7.150 MHz. After determining the approximate apex impedance (892.6+j1839.95 Ohms), it is found that the point along the line is equal to 33.26 feet. Since the line length is 44 feet long, a series capacitor is used to effectively shorten the line length. This can be termed a hybrid stub match. A series variable capacitor is adjusted until a value of 28 – j25 Ohms is found. This value corresponds closely to the value found using my program ZiZLCA30.EXE (34.7764 – j24.4656 Ohms). The four foot stub terminated in a short circuit that was used for the 20 meter experiment was used rather than cutting a new one to the predicted required length of about three feet. I was curious to see if there would be a great deal of difference in the results before trimming the stub length. Surprisingly, the resulting impedance became equal to 45 + j7 Ohms with a resulting SWR equal to 1.15. I then decided to try adjusting the series variable capacitor after learning that the SWR at 7.0000 MHz was 2.45, and 2.59 at 7.3000 MHz. The SWR could be reduced to 1.14 at 7.0000 and 1.14 at 7.3000 MHz by slightly varying the series variable capacitor.

Once again, the second experiment illustrates that theory can predict the needed design quite accurately. Again, varying the line length to the stub point and the stub length itself results in very good agreement with theoretical predictions.

L-network design comparison using ZPIM3

I decided to compare the stub matching design with the use of my program, ZPIM3. The results, as expected, are similar but then the stub matching must be integrated into the L-network design process. This is not done. However, the results show two choices when using ZPIM3: One with two inductors where one is in series and the other at the output as a shunt element, and the second choice shows a series capacitance and an output shunt inductance. The same Zo and load impedance values are used. I chose the result that includes a series input capacitance, and output shunt inductance. The predicted values were C = 33.3267 pf, and L = 2.2044 uH. Of course, parallel equivalency is used for the load impedance when designing the L-network.

These results may be considered somewhat simplified but are direct impedance matching techniques that work. In future articles, I shall include more analysis including the popular quarter wave transformer approach. But be aware that the ZPIM3 impedance matching addresses the series load value rather than a parallel load impedance value.

Conclusions

Theoretical and actual measured in-field results show excellent agreement. The results are very encouraging where measurements illustrate how theoretical analysis can support the stub matching design. This allows a very good approximation towards what is required towards obtaining the impedance match component values or needed line length data.

Like measuring the conjugate impedance however, it is difficult to measure the parallel equivalent of the series impedance. However, the indication for the conjugate impedance match is a minimum SWR with respect to 50 Ohms resistive with respect to the source generator. Of course it is recognized that stub line tuning can be simulated using capacitive and inductive elements

The value of a supporting program to find the series impedance that is paralleled with a value of the parallel equivalent impedance is found to be of great value. This is accomplished in my program ZiZLCA30.EXE, STUB6.EXE, and Cebik's program, STUBTUNE.BAS.

The Cebik equations are shown to be very supportive and include flexibility towards arriving at a transmission line from a given stub point that would be more desirable in many cases. **–30-**

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Again the programs described in this article are available in the download section in the *antenneX* Guest Rooms at: http://www.antennex.com/guests.html
If you don't already have a login to the Guest Rooms, you can get yourself a login on that page and then enter the Guest Rooms. Be sure to bookmark the Guest Rooms and make a record of your login for future visits.

BRIEF BIOGRAPHY OF THE AUTHOR
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After graduating from the Orono, Maine High School, I joined the Navy for a three-year tour to get my service requirements completed. I was extended one year due to the Korean situation near the end of my three-year tour of duty. My service time was then nearly four years or from 1948 to 1952. I served as a Radio Operator for the Navy during the entire tour of duty.

After leaving the Navy, I went back to school at the University of Maine and received an engineering degree in Electrical Engineering in 1956, with a minor in power distribution and mathematics. From that point on, I worked with various companies as electronics engineer, specializing in navigational aids, communications, and computer systems at various levels of responsibility until retiring in 1988.

My amateur radio interests started in 1945 and I got my first license in 1948 as W1QWV. At that time, the FCC required issuance of a new call sign when moving to new districts. So I received K2UUU when moving to New Jersey in 1956, and then W4IYB when moving to Virginia in 1965. My present call was issued to me after application in 1968. My interests in amateur radio have been experimental projects but more specifically in the antenna and transmission systems. However, I did design and build a complete amateur radio station in 1967, which was a very interesting project, especially regarding the receiver and transmitter.

To date, my interests are still primarily antenna systems, which include antenna tuners (impedance matching networks), antennas, and transmission line characteristics. My primary amateur radio mode of interest is still CW. I turned 76 in October 2004.

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