ON POWER TRANSFER and THE CONJUGATE MATCH

Getting power from the transmitter into the antenna is not rocket science, it's pretty simple physics, yet most hams have no idea what it's all about. This writing is an attempt to diminish that lack of very significant knowledge and is absolutely worth the effort it takes to understand it. So TAKE THE TIME TO UNDERSTAND THIS! STUDY THE DIAGRAM BELOW along with the explaination that follows.

The symbol * stands for multiplication: A * B = A x B = A "times" B so 3 * 2 = 6. The symbol ^ stands for exponentiation. Q^B means Q raised to the B power. B=2 for almost all the equations below. Q^2 is the square of Q, meaning you multiply Q times itself: Q^2 = Q*Q.

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-----------                                    ANT
|   TX    |(input)       FEEDLINE      (output)|L|
|100 watts|==|T|===============================|O| Za = R + j X
|   (%)   |    Zo = Ro  (ohms)   and   A (dB)  |A|
-----------                                    |D|
           line loss factor:   F=10^(-A/10)

| Po --->> (=FWD)            Pi = F * Po --->>  |
|                                   Vi --->>  |
|                                   Ii --->>  |
|                                             |
|             reflection coefficient p        |
|           p = (Vr/Vi) = (Ir/Ii) = SQRT(Pr/Pi) |
|                  so that p^2 = Pr/Pi         |
|                                             |
|                   Vr = p * Vi     <<--- Vr   |
|                   Ir = p * Ii     <<--- Ir   |
|                                             | -->>> pwr into Load (ant)
| <<--- Pb (=REF)                    <<--- Pr  | Pa = Pi - Pr
| Pb = F * Pr      q = F * p        Pr=(p^2)*Pi | Pa = (1-(p^2))*Pi
|                                             |
|  SWR@TX = (1+q)/(1-q)                SWR@LOAD = (1+p)/(1-p)

           NET POWER INTO FEEDLINE = FWD - REF = Po - Pb
      NET = FWD - REF = 100 - F*(p^2)*Pi = 100*(1 - [(F*p)^2])

>>>>>>>>>>>>>>>>>>  TRANSFER (%) = Pa/NET   <<<<<<<<<<<<<<<<<<<<<<<<<


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PART 1 ... Explanation and an Example

For the moment and for the sake of not having to redraw everything, ignore the |T| appearing in the feedline. |T| applies to Part 2. So in Part 1 the feedline is solid from TX to LOAD.

In the above diagram, TX is a 100 watt (max) transmitter matched to the line Zo. We use 100 so that we can just as easily interpret percent (%) power as we go thru the calculations. Then if you run any other power you can multiply that power times the % numbers calculated here and get results relating to your situation.

The feedline connects the transmitter (TX) to the ANT (=LOAD).
The feedline ends at the input terminals to the antenna. Zo = Ro + j0 is the impedance of the feedline (X=0 or no reactance). Ro is a pure resistance. Real feedlines have very small values of X in the frequency range of amateur operations. This small value is effectively negligible and we do so here ... ignore it ... X=0. The loss of the feedline is A (dB) taken to be a non-negative number, A is thus greater than or equal to 0.
F is the FACTOR you multiply the line input (TX) power by to obtain the amount of power arriving at the output of the feedline ... the power loss here is the major loss of the system. Reducing this value is thus very significant in the antenna system performance and efficiency.

The antenna (LOAD) has an impedance Za = R + jX which is MEASURED AT THE INPUT TERMINALS OF THE ANTENNA ... NOT measured at the TX (input/shack) end of the feedline. Feedlines are impedance transformers .. Za is transformed down the feedline to a new value Zs seen at the input (shack) end of the line.

So Po is the forward (FWD) power out from the TX. It travels left to right in the diagram, from TX to LOAD (ANT). Pi is the amount of power that is left after travelling the feedline to the antenna terminals.

>>>>> NOT ALL OF THE INCIDENT POWER Pi goes into the antenna! <<<<<<<

The only time all of Pi goes into the load is when the load equals the line impedance Zo (=Ro) and this RARELY occurs in the common ham use of antennas. It does for tuned monoband antennas ... some of the time.

The power incident on the antenna terminals (LOAD) at the feedline output is Pi and splits into two components: Pr and Pa. Pr is the power reflected back towards the input (transmitter / shack) and Pa is the power tranferred into the antenna. We want to maximimze this power, Pa. Thus, Pi = Pr + Pa

Pr travels back down the feedline and suffers another loss (called the mismatch loss.) This loss is always there on a lossy feedline that is not terminated in its line impedance Zo (=Ro). The power arriving back at the input (TX) is Pb and is the reflected power (REF). The NET power entering the system, meaning the ACTUAL power the transmitter is putting out is equal to NET = FWD - PWR.

Thus NET = FWD - REF is the actual power entering the transmission line from the transmitter. It is less than 100 watts which is the max power available from this transmitter.

You can look at it this way. When you key down, the transmitter doesn't know what is at the end of the feedline and it puts out 100 watts.
When the power Pi gets to the load and discovers the load is NOT Zo in value, then some of that power is reflected (Pr) back towards the transmitter.
The power Pr thus experiences attenuation A (db) during the trip to

the input of the line and becomes Pb and the transmitter discovers not all of the 100 watts is being used, so the output power is reduced to the NET power output, always equal to Forward (FWD) power minus Reflected (REF) power.

IT IS TOTAL MYTH THAT THE RETURNED POWER Pb "enters" THE TRANSMITTER AND "burns up your finals". If there is one thing this writing hopes to accomplish it is refutation of this absolutely absurd concept that has been propagated over and over for eons.

What percentage of the incident power Pi is reflected? This amount is determined by three paramters: the feedline impedance Zo, the antenna resistance (R) and antenna reactance (X). Zo and R are dissipation paramters where the power is acutally "burned" up or radiated.
X is a indicates the power stored in the system from cycle to cyle.
Stored energy does not contribute to radiation, thus you don't want that. The only way to avoid this is to have X = 0 .. a condition known as RESONANCE ! Antenna resonance (X=0) is generally not the case for an antenna operated in the ham bands or across the ham bands.

The REFLECTION COEFFICIENT at the LOAD represents the amount of voltage (or current) that is reflected at the load. This number is p in the above diagram. p is the MOST IMPORTANT parameter on the page!
p is determined solely by the values of Zo, R and X. Zo does not change with frequency, but R and X do. So p also varies from frequency to frequency. Note that the reflected voltage (Vi) and reflected current (Ii) both have the same reflection coefficient (in magnitude). The reflection of power behaves according to p^2 however, which is obtained very simply from Pr = Vr * Ir = (p * Vi) * (p * Ii) = (p^2) * (Vi * Ii) = (p^2)*Pi

Note that the amount of power entering the load or antenna is given simply by: Pa = Pi - Pr. What isn't reflected of the incident power Pi goes into the antenna (Pa). You always want to maximize Pa of course.

For a given frequency and physical antenna the parameters F and p TOTALLY determine all other parameters, they are the root values here.
F varies only if A (dB) varies. You change the loss of the feedline.
p varies only if you change any one of the following: Zo (feedline)
R (antenna resistance) or X (antenna reactance), also recognized as the antenna impedance Za.

NOTHING YOU CAN DO IN THE SHACK OR OUT ON THE LINE WITH A TUNER WILL CHANGE p !!!!

So, F and p are the parameters that control the whole system at a given frequency.

We are now ready to compute the one number that determines what percentage of the NET power entering the system goes into the antenna. Expressed in percentage it is simply:

TRANSFER RATIO (%) = 100 * (Pa/NET) = 100 * (Pa/(FWD -REF)).

THE TRANSFER RATIO DOES NOT CHANGE for a given frequency and physical antenna!

NO TUNER IS EVER GOING TO CHANGE THIS VALUE! It is the ULTIMATE value (in %) of the power you will ever get into the antenna! This parameter is the one to focus on in the evaluation of power transfer efficiency, which you want to maximize of course. Take your measurements then calculate the TRANSFER RATIO to determine the maximum possible power you will ever be able to get into the ANTENNA! This is the FOCUS or CENTRAL parameter that you want to know as quickly as you can.

To illustrate all this, we take an example ....

Let the feedline impedance be Zo = 50. This number is only used in determining p, which we will not detail here, but the formula is this:

p = SQRT((Zo-R)^2 + X^2))/SQRT((Zo+R)^2 + X^2), where SQRT means take the square root of ....)

Let A = 0.5 dB. Then F = 10^(-0.5/10) = 10^(-0.05) = 0.8913

Let the antenna impedance be measured as Za = 100 + j200, meaning R = 100 ohms and X =200 ohms. Knowing Zo, R and X we can compute p.

p = 0.824621   p^2 = 0.679999   q = F * p = 0.734984

We now have:

SWR@ANT = (1+p)/(1-p) = 1.827621/(1-0.824621) = 4.70
SWR@INPUT (in shack) = (1+q)/(1-q) = 1.734984/0.265016 = 2.77
So loss A on the line has reduced the SWR at the input (shack end) of the feedline.

FWD = 100 watts (%)
Pi = 100 * F = 89.13 watts (%)
Pr = (p^2)*Pi = 0.67999 * 89.13 = 60.61 watts (%)
Pa = Pi - Pr = 89.13 -60.61 = 28.52 watts (%)
Pb = REF = F * Pr = 0.8913 * 60.61 = 54.02 watts (%)
NET = FWD - REF = 100 - 54.02 = 45.98 watts (%)
and finally ..

TRANSFER RATIO (%) = Pa/NET = 100*(28.52/45.98) = 62.03 %

The TRANSFER RATIO states the maximum power you will EVER be able to get into this antenna is 62.03% of the transmitter power.

But right now the power going into the antenna is only 28.52 watts (%) so you better do something to change that!

What are you going to do? Well, to make a difference from what we know at this point the only choices are changes in A, Zo, R and X. This means that you are going to have to change the feedline, the antenna or both. But which to choose? There are indeed things you can do. You can lower A (db) and reduce X as close to 0 (resonance) as you can!

However after you have done all the work, other than lower A, X is going change somewhat on you when you change frequency and certainly when you change bands.

In this specific example we have 89.13 watts arriving at the antenna, of which 60.61 is reflected and 54.02 arrives back at the TX shutting its NET power out to 100 - 54.02 = 45.98 watts.

To clarify ... It is not the POWER Pb that "shuts down" the TX; it is the IMPEDANCE Zs of the feedline that is causes the transmitter to limit its NET output. Recall, Zs is the impedance derived from the antenna or load impedance Za and transformed into Zs at the shack/input end by the feedline parameters. (Complex number calculations)
We have not computed that value Zs = Rs + jXs. It can be done without much difficulty but is not needed here. The major player in the transformation of Za at the load to Zs in the shack is the line attenuation A (dB). Zs is the impedance an antenna tuner matches in the shack.

This set of computations is very easy and simple. It only involves square root, square and the computation of F from A. ALL of these parameters are found on the simple everyday calculator except for F = 10^(-A/10) which all scientific calculators and most spreadsheets can do. There is no excuse here that "the math's too hard!".
Don't be LAZY!

There is another way of improving the power transfer to the antenna, the CONJUGATE MATCH, which is accomplished by most ANTENNA "tuners". These are better termed "SYSTEM TUNERS".

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Part 2: The CONJUGATE MATCH.

We now put the "tuner" |T| back in the feedline as shown in the diagram above. It is typically placed in the shack at the output of the transmitter. It can actually be placed anywhere along the feedline, including at the antenna input itself.

The first thing the tuner has to do is TUNE. The second thing it has to do is MATCH. Tuning means RESONATING the system (X=0)
After that the only thing remaining is to take the resulting impedance Rs and the power it contains and transform (MATCH) it into Rt = Zo = Ro at the input of the tuner where the SWR will now be 1 to 1.
SWR@SHACK = 1|1 and you GRIN from ear to ear ... 100 watts going out now!
The full transmitter power is entering the line as NET power.

The required steps are TUNING (resonance X=0 in the system) and MATCHING (transforming the resulting line Rs into Zo which is what the transmitter needs in order to put out full power). It is always assumed that the feedline Zo is matched to the TX output. Otherwise you will have to locate the tuner AT the TX.

When the tuner is properly tuned an interesting thing occurs (for lossless lines) If you cut the feedline anywhere between the TX and the LOAD and measure the impedance Zb looking back towards the TX and Zf looking forward to the LOAD you will find they are COMPLEX CONJUGATES (hence the term CONJUGATE MATCH), i.e., if Zb = Rb + jXb and Zf = Rf +jXf we find that Xb = -Xf, the reactances are opposites ... put the line back together and they cancel ... X=0, resonance. If you apply this fact right at the antenna terminal you find the feedline Xb cancels the antenna Xf=Xa and the antenna is also tuned/resonated.

The only thing left is for the tuner to now transform the power in the shack Rs into power in Ro (=Zo).

With the tuner in line doing it's job we find the following calculations apply ...

FWD = Po = 100/(1-(q^2)) ... watts (%) and we find FWD > 100
How can that be? Under the conditions of the conjugate match, the power returned is ADDED to the output of the transmitter. So we get FWD = Po + Pb and this difference or increase brings the max power transferred to the antenna (Pa) equal to the TRANSFER RATIO which is the best you can possibly do for the given antenna system at the working frequency. THIS is what the conjugate match accomplishes!

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So,  FWD = 100/(1 - (q^2)) = 100/(1 - (F*p)^2) ... watts (%)
           Pi = F * FWD  ... watts (%)
           Pr = (p^2)*Pi  ... watts (%)
           Pa = Pi - Pr  ... watts (%)
     REF = Pb = F * Pr ... watts (%)
     NET = FWD - REF = 100 ... watts (%)
     TRANSFER RATIO = 100*(Pa/NET) = 100(Pa/100) = Pa ... watts (%)
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TX is now putting out full power (100 watts), shack SWR is 1|1, and everyone is probably happy. But still the MAX power you will ever get even under the CONJUGATE MATCH is the TRANSFER RATIO. The conjugate match simply transforms the shack impedance Zs into Zo and the transmitter puts out full power. In the process, the antenna system is resonant and maximum power transfer occurs. Thus using a tuner is far better than having to physically adjust the system to improve the results every time you change frequency, which no one wants to have to do. [There is one manufacturer that comes close to doing this however, where the physical parameters of the antenna are changed in real time as frequency is changed. But it is a limited process.]

The conjugate match brings the antenna power up to the maximum possible as calculated by the TRANSFER RATIO. If you want to improve antenna power over that you will have to make changes to the feedline or to the antenna, or both.

Example: We apply the conjugate match now to the example just examined.

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F = 0.8913         p = 0.824621      q = 0.734984

SWR@ANT = (1+p)/(1-p) = 4.7  .....  NO CHANGE !!!

FWD = 100/(1-(q^2))= 100/(1-0.540201) = 217.5  ... watts (%)
Pi = FWD * F = 217.5 * 0.8913 = 193.9 ... watts (%)
Pr = (p^2)*Pi = 193.9 * 0.680 = 131.85  ... watts (%)
REF = Pb = F * Pr = 131.85 * 0.8913 = 117.5 ... watts
NET = FWD - REF = 217.5 -117.5 = 100 ... watts (%)
Pa = Pi - Pr = 193.9 -131.9 = 62 ... watts (%)

TRANSFER RATIO (%) = 100(Pa/NET) = 100(Pa/100) = Pa = 62 %
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It's that simple!!!

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