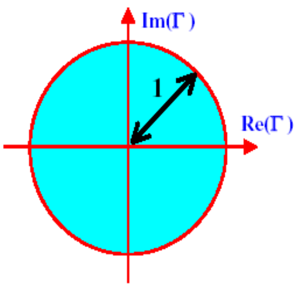
The Smith Chart

- The Smith Chart is simply a graphical calculator for computing impedance as a function of reflection coefficient.
- Many problems can be easily visualized with the Smith Chart
- The Smith chart is one of the most useful graphical tools for high frequency circuit applications. The chart provides a clever way to visualize complex functions.

From a mathematical point of view, the Smith chart is simply a representation of all possible complex impedances with respect to coordinates defined by the reflection coefficient.



The domain of definition of the reflection coefficient is a circle of radius 1 in the complex plane. This is also the domain of the Smith chart.

The goal of the Smith chart is to identify all possible impedances on the domain of existence of the reflection coefficient. To do so, we start from the general definition of line impedance (which is equally applicable to the load impedance)

$$Z(d) = \frac{V(d)}{I(d)} = Z_0 \frac{1+\Gamma(d)}{1-\Gamma(d)}$$

This provides the complex function $Z(d) = f\{\mathrm{Re}(\Gamma), \mathrm{Im}(\Gamma)\}$ that we want to graph. It is obvious that the result would be applicable only to lines with exactly characteristic impedance Z_0.

In order to obtain universal curves, we introduce the concept of normalized impedance

$$z(d) = \frac{Z(d)}{Z_0} = \frac{1+\Gamma(d)}{1-\Gamma(d)}$$

The normalized impedance is represented on the Smith chart by using families of curves that identify the normalized resistance r (real part) and the normalized reactance x (imaginary part)

$$z(d) = \mathrm{Re}(z) + j\,\mathrm{Im}(z) = r + jx$$

Let's represent the reflection coefficient in terms of its coordinates

$$\Gamma(d) = \mathrm{Re}(\Gamma) + j\,\mathrm{Im}(\Gamma)$$

Now we can write

$$r + jx = \frac{1+\mathrm{Re}(\Gamma) + j\,\mathrm{Im}(\Gamma)}{1-\mathrm{Re}(\Gamma) - j\,\mathrm{Im}(\Gamma)}$$

$$= \frac{1-\mathrm{Re}^2(\Gamma) - \mathrm{Im}^2(\Gamma) + j2\,\mathrm{Im}(\Gamma)}{\left(1-\mathrm{Re}(\Gamma)\right)^2 + \mathrm{Im}^2(\Gamma)}$$

The real part gives

Add a quantity equal to zero

$$r = \frac{1 - \mathrm{Re}^2(\Gamma) - \mathrm{Im}^2(\Gamma)}{(1 - \mathrm{Re}(\Gamma))^2 + \mathrm{Im}^2(\Gamma)}$$

$$r(\mathrm{Re}(\Gamma) - 1)^2 + \left(\mathrm{Re}^2(\Gamma) - 1\right) + r\,\mathrm{Im}^2(\Gamma) + \mathrm{Im}^2(\Gamma) + \underbrace{\frac{1}{1+r} - \frac{1}{1+r}}_{=0} = 0$$

$$\left[r(\mathrm{Re}(\Gamma) - 1)^2 + \left(\mathrm{Re}^2(\Gamma) - 1\right) + \frac{1}{1+r}\right] + (1+r)\,\mathrm{Im}^2(\Gamma) = \frac{1}{1+r}$$

$$(1+r)\left[\mathrm{Re}^2(\Gamma) - 2\,\mathrm{Re}(\Gamma)\frac{r}{1+r} + \frac{r^2}{(1+r)^2}\right] + (1+r)\,\mathrm{Im}^2(\Gamma) = \frac{1}{1+r}$$

$$\Rightarrow \quad \left[\mathrm{Re}(\Gamma) - \frac{r}{1+r}\right]^2 + \mathrm{Im}^2(\Gamma) = \left(\frac{1}{1+r}\right)^2$$

Equation of a circle

The imaginary part gives

Multiply by x and add a quantity equal to zero

$$x = \frac{2\,\mathrm{Im}(\Gamma)}{(1 - \mathrm{Re}(\Gamma))^2 + \mathrm{Im}^2(\Gamma)}$$

$$x^2\left[(1 - \mathrm{Re}(\Gamma))^2 + \mathrm{Im}^2(\Gamma)\right] - 2x\,\mathrm{Im}(\Gamma) + \underbrace{1 - 1}_{=0} = 0$$

$$\left[(1 - \mathrm{Re}(\Gamma))^2 + \mathrm{Im}^2(\Gamma)\right] - \frac{2}{x}\mathrm{Im}(\Gamma) + \frac{1}{x^2} = \frac{1}{x^2}$$

$$(1 - \mathrm{Re}(\Gamma))^2 + \left[\mathrm{Im}^2(\Gamma) - \frac{2}{x}\mathrm{Im}(\Gamma) + \frac{1}{x^2}\right] = \frac{1}{x^2}$$

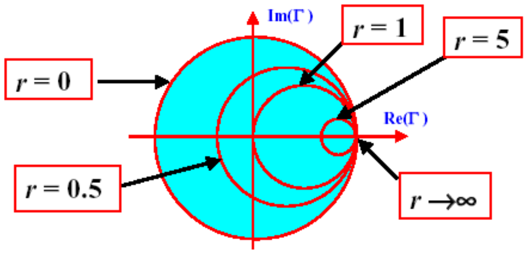
$$\Rightarrow \quad (\mathrm{Re}(\Gamma) - 1)^2 + \left[\mathrm{Im}(\Gamma) - \frac{1}{x}\right]^2 = \frac{1}{x^2}$$

Equation of a circle

The result for the real part indicates that on the complex plane with coordinates (Re(Γ), Im(Γ)) all the possible impedances with a given normalized resistance r are found on a circle with

$$\text{Center} = \left\{\frac{r}{1+r}, 0\right\} \qquad \text{Radius} = \frac{1}{1+r}$$

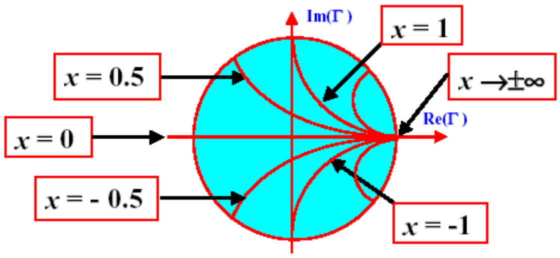
As the normalized resistance r varies from 0 to ∞ , we obtain a family of circles completely contained inside the domain of the reflection coefficient $|\Gamma| \leq 1$.



The result for the imaginary part indicates that on the complex plane with coordinates (Re(Γ), Im(Γ)) all the possible impedances with a given normalized reactance x are found on a circle with

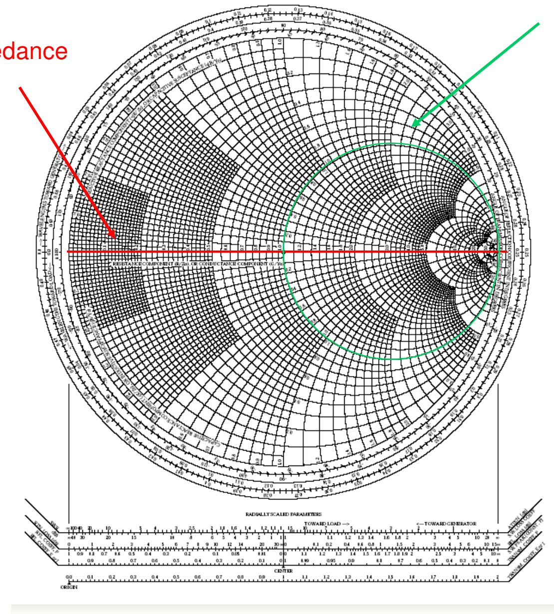
$$\text{Center} = \left\{1, \frac{1}{x}\right\} \qquad \text{Radius} = \frac{1}{x}$$

As the normalized reactance x varies from -∞ to ∞ , we obtain a family of arcs contained inside the domain of the reflection coefficient $|\Gamma| \leq 1$.

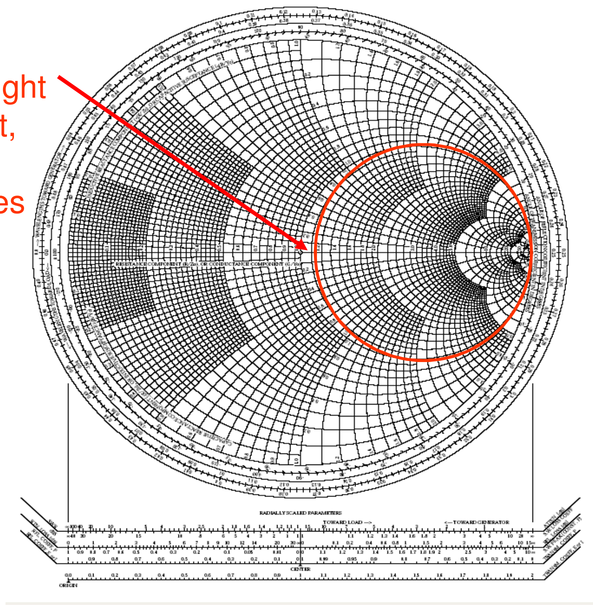


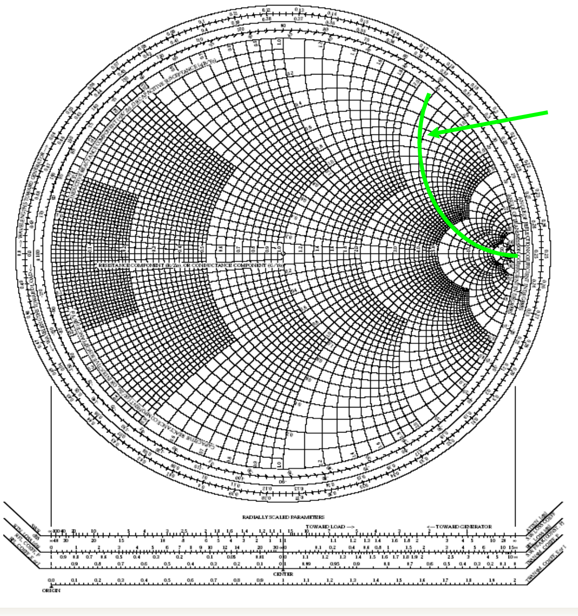
Real Impedance Axis

Imaginary Impedance Axis

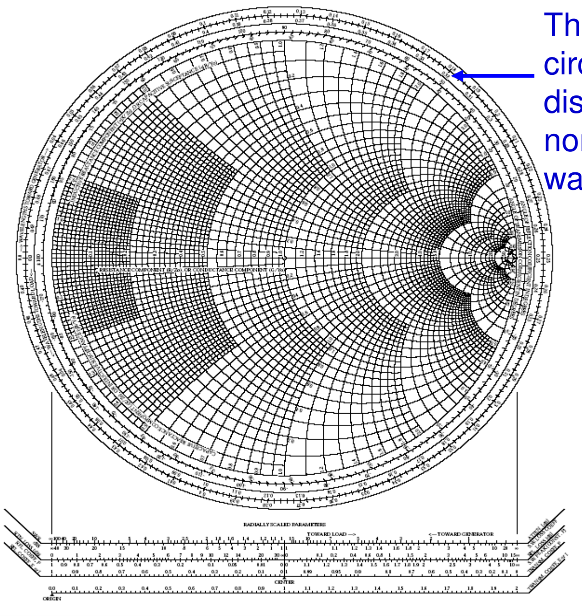


The circles, tangent to the right side of the chart, are constant resistance circles

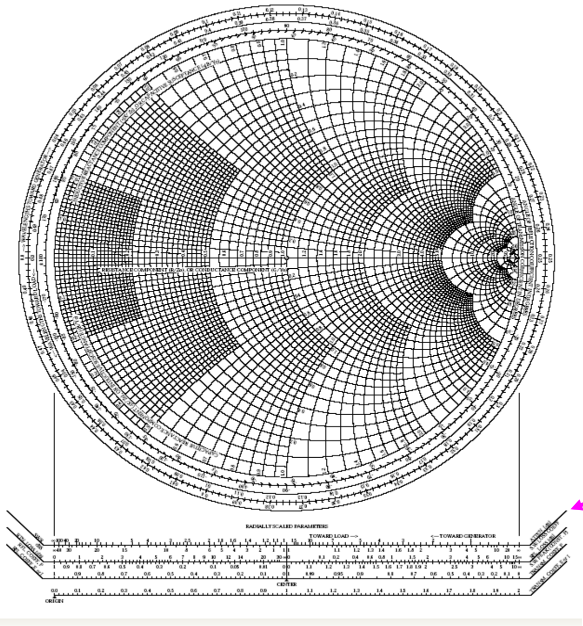




The curved lines from the outer circle terminating on the centerline at the right side of the chart are lines of reactance

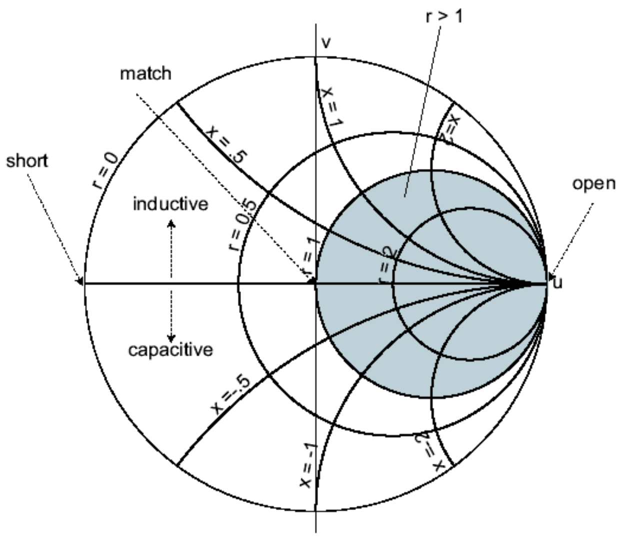


The outermost circle represents distance in normalized wavelength

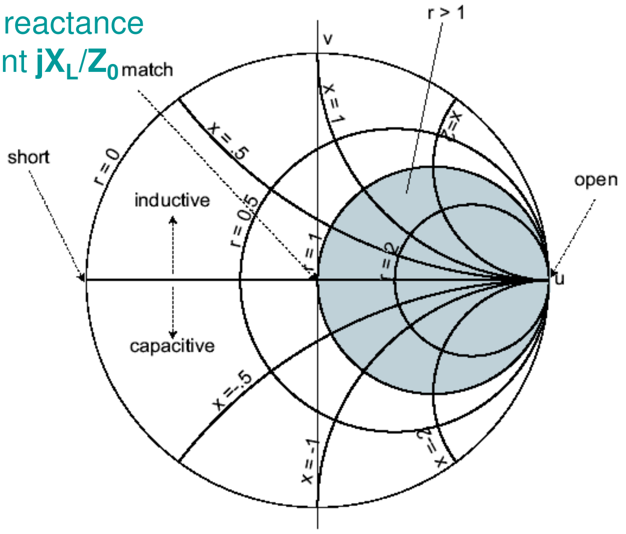


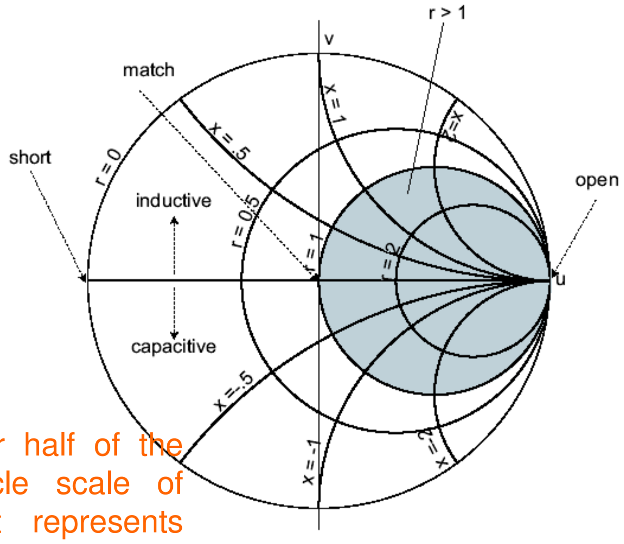
At the bottom the chart, there are radially scaled parameters that would be used to find the amplitude of the reflection coefficient, transmission coefficient, VSWR or return loss

Complete Smith Chart

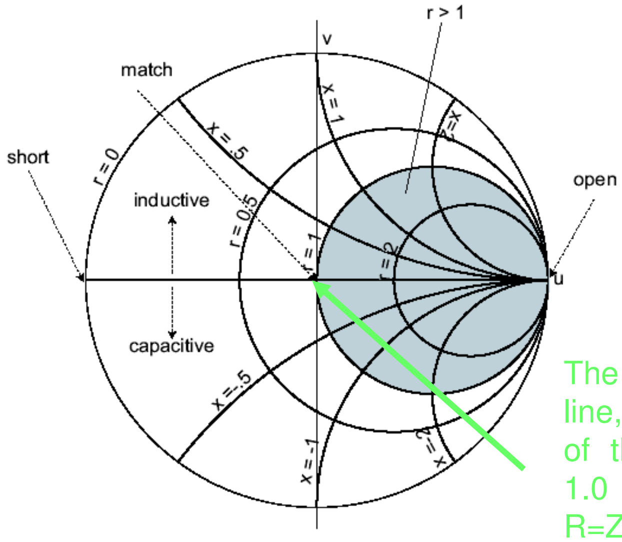


The upper half of the outer circle scale of the chart represents the inductive reactance component jX_L/Z_0





The lower half of the outer circle scale of the chart represents the capacitive reactance component $-jX_c/Z_0$



The center of the line, also the center of the chart, is the 1.0 point where $R=Z_0$.

At the point 1.0, the line termination is equal to the characteristic impedance of the line and no reflection occurs

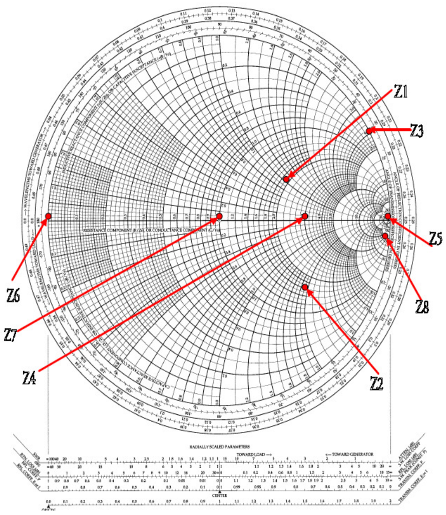
Smith Chart

- The outside of the chart shows location on the line in wavelengths.
- The combination of intersecting circles inside the chart allow us to locate the normalized impedance and then to find the impedance anywhere on the line.
- All impedance values are normalized with respect to the characteristic impedance of the transmission line.

- One revolution of the chart on the outermost circle is one-half wavelength.
- Impedances, voltages, currents, etc. all repeat every half wavelength
- The magnitude of the reflection coefficient, the standing wave ratio (SWR) do not change, so they characterize the voltage & current patterns on the line

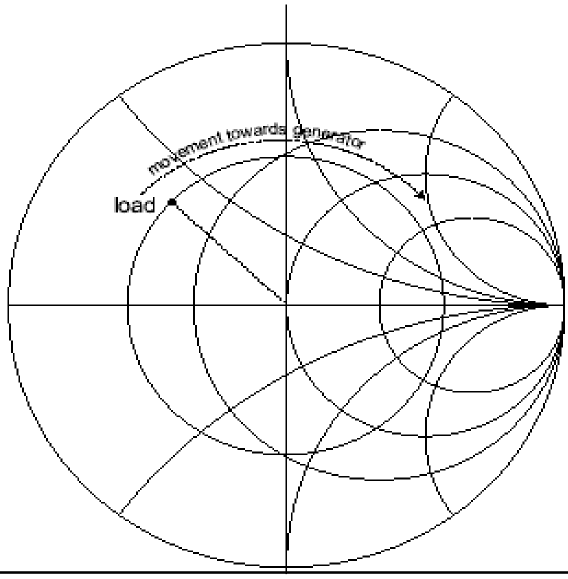
Smith Chart

- Impedance divided by line impedance (50 Ohms)
  - Z1 = 100 + j50
  - Z2 = 75 -j100
  - Z3 = j200
  - Z4 = 150
  - Z5 = infinity (an open circuit)
  - Z6 = 0 (a short circuit)
  - Z7 = 50
  - Z8 = 184 -j900
- Then, normalize and plot. The points are plotted as follows:
  - z1 = 2 + j
  - z2 = 1.5 -j2
  - z3 = j4
  - z4 = 3
  - z5 = infinity
  - z6 = 0
  - z7 = 1
  - z8 = 3.68 -j18



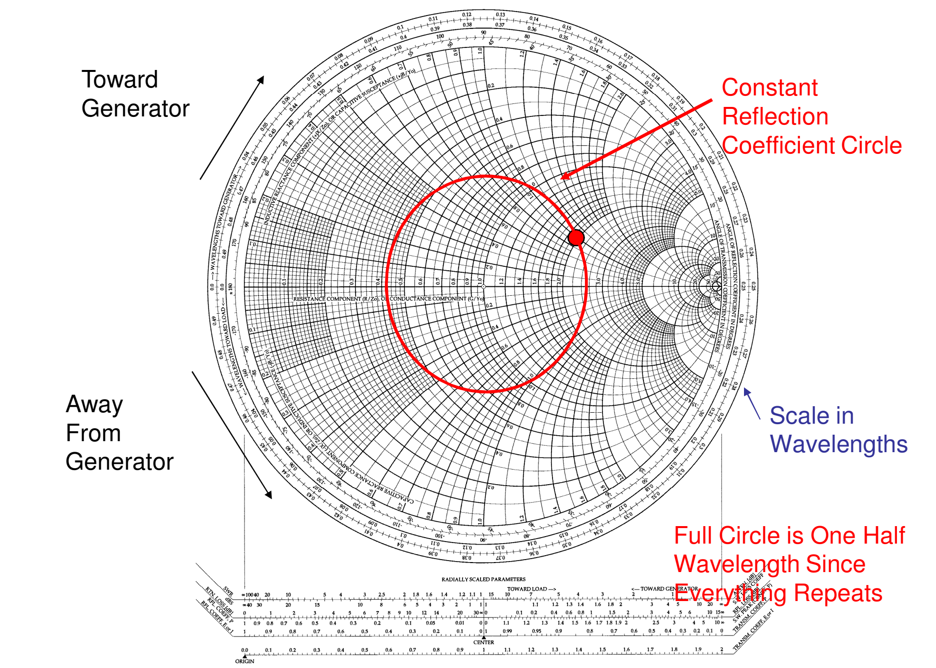
Motion Towards Generator

- Moving towards generator means $\Gamma(-l)=|\Gamma|e^{-j\beta l}$, or clockwise motion.
- We're back to where we started when $2\beta l=2\pi$, or $l=\lambda/2$.
- Thus the impedance is periodic.

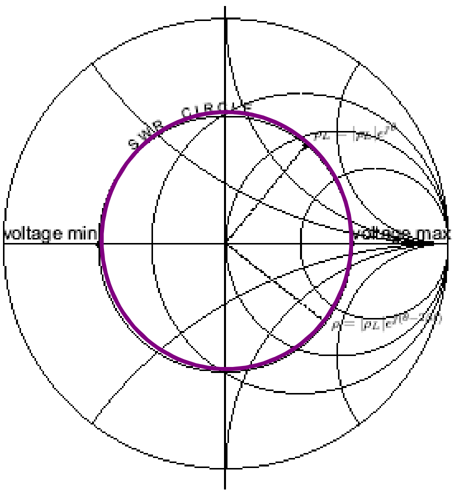


Smith Chart

- Thus, the first step in analyzing a transmission line is to locate the normalized load impedance on the chart
- Next, a circle is drawn that represents the reflection coefficient or SWR. The center of the circle is the center of the chart. The circle passes through the normalized load impedance
- Any point on the line is found on this circle. Rotate clockwise to move toward the generator (away from the load)
- The distance moved on the line is indicated on the outside of the chart in wavelengths



SWR Circle



- Since SWR is a function of $|\Gamma|$, a circle at origin in (r,x) plane is called an SWR circle
- Recall **the voltage max** occurs when the reflected wave is in phase with the forward wave, so

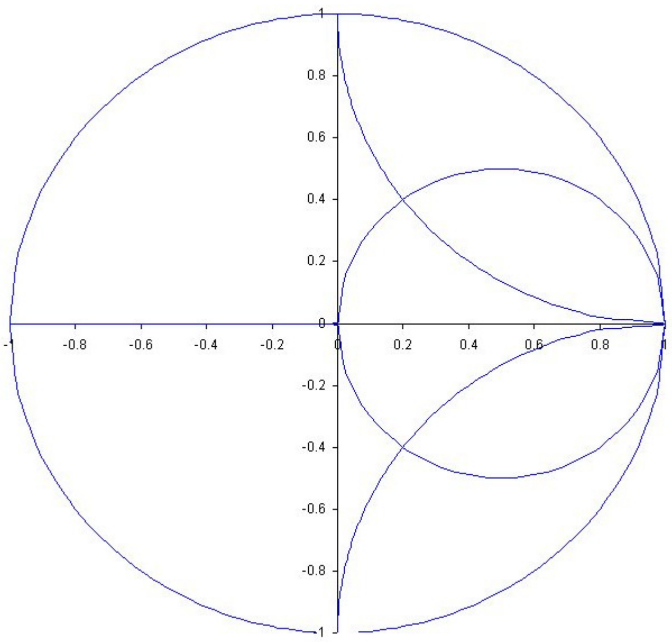
$\Gamma(z_{max}) = |\Gamma(l)|$

- This corresponds to the intersection of the SWR circle with the positive real axis
- Likewise, the intersection with the negative real axis is the location of **the voltage min**

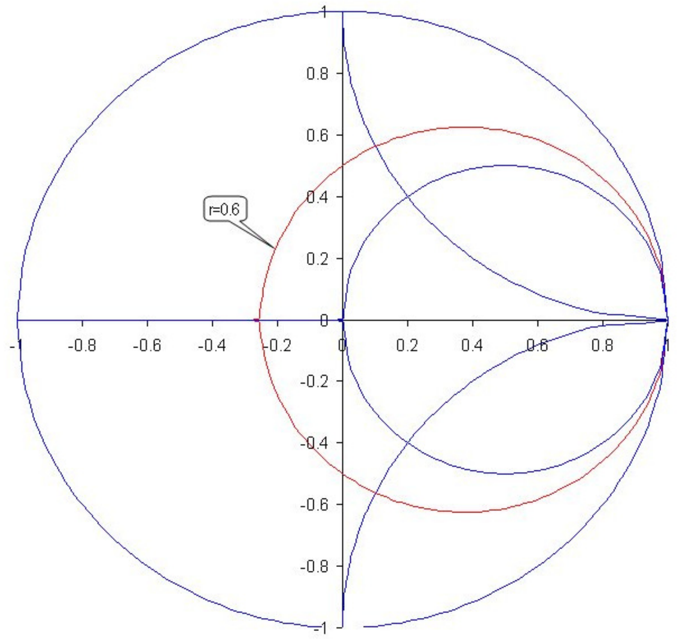
Smith Chart Example

- First, locate the normalized impedance on the chart for $Z_L = 30 + j70$ (Z_0=50 ohm)
- Then draw the circle through the point
- The circle gives us the reflection coefficient (the radius of the circle) which can be read from the scale at the bottom of most charts
- Also note that exactly opposite to the normalized load is its admittance. Thus, the chart can also be used to find the admittance. We use this fact in stub matching

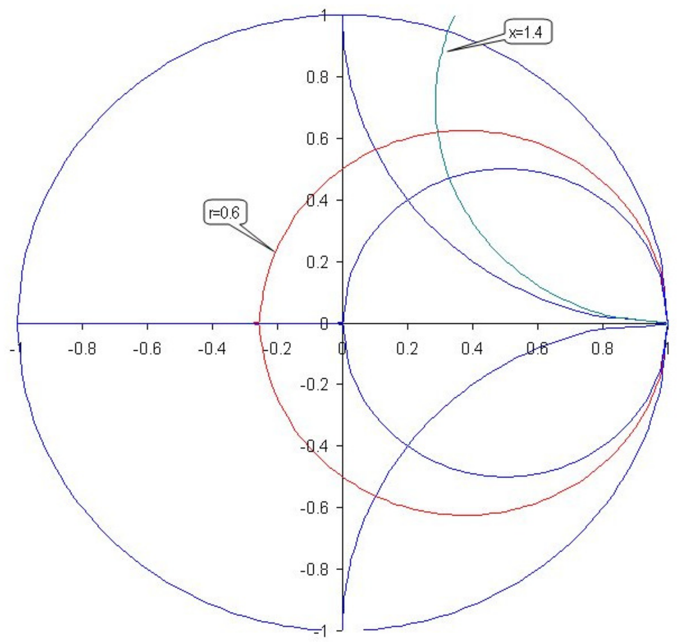
Start with the Smith Chart



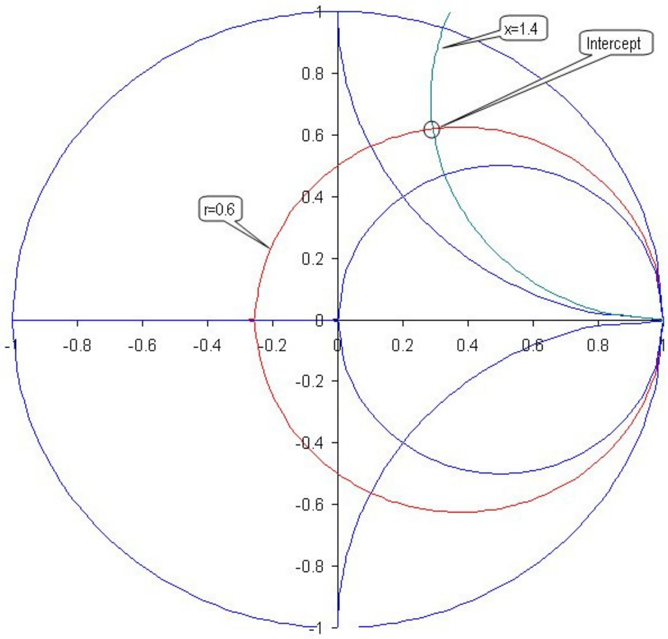
Locate r Circle of the normalized Load Impedance = Real part of (Z_L/Z_o)



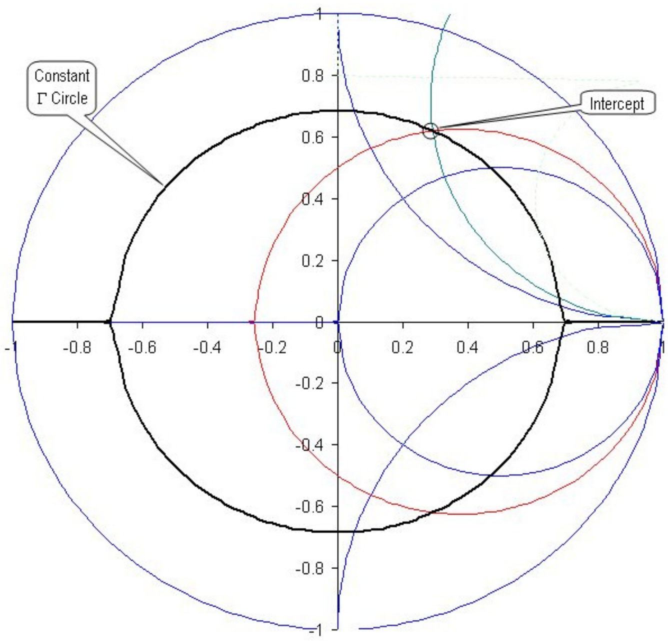
Locate the x Circle of the normalized Load Impedance = Imag part of (Z_L/Z_o)



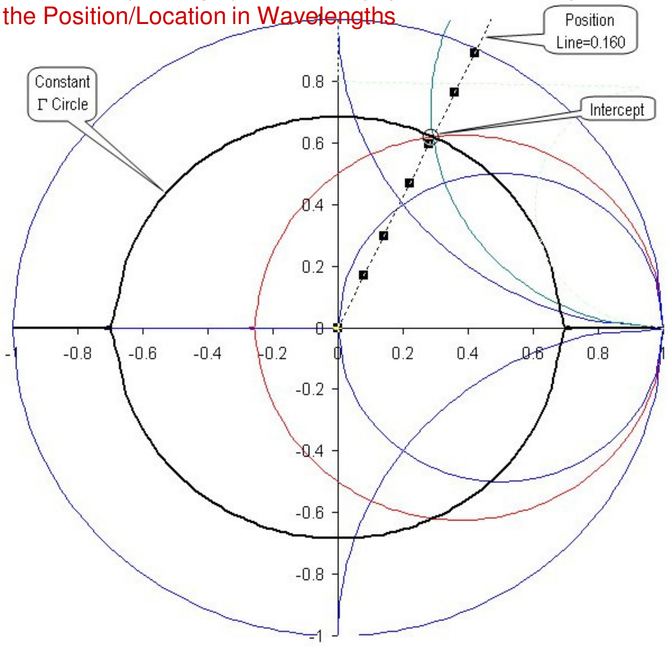
Locate the Intercept point of the r Circle and the x Circle for Load Impedance



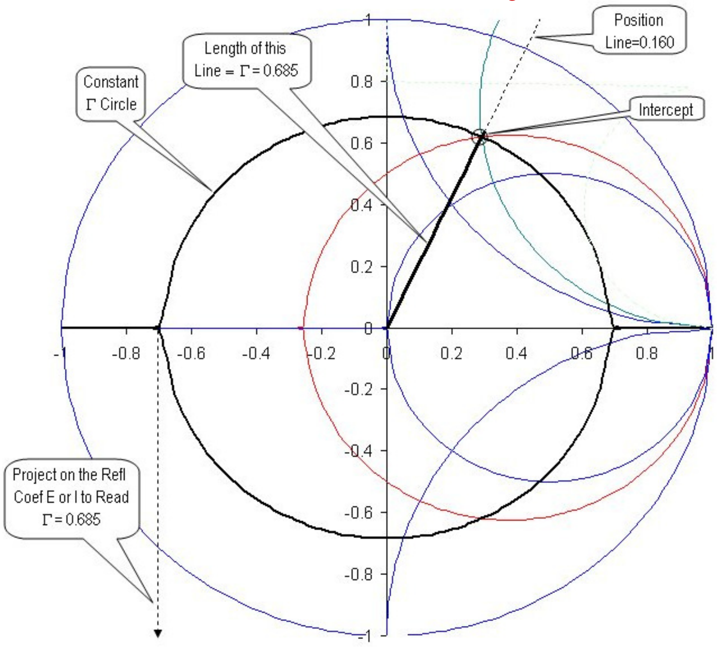
Draw a constant Γ Circle passing by the Intercept point for Load Impedance



Draw a Radial Line passing by the Intercept point for Load Impedance
Identify the Position/Location in Wavelengths



Measure the Radius of the Γ Circle. This is the Magnitude of Γ for the Load



Basic Smith Chart techniques for loss-less transmission lines

- Given $Z(\mathrm{d})$ $\Rightarrow$ Find $\Gamma(\mathrm{d})$
  Given $\Gamma(\mathrm{d})$ $\Rightarrow$ Find $Z(\mathrm{d})$
- Given Γ_R and Z_R $\Rightarrow$ Find $\Gamma(\mathrm{d})$ and $Z(\mathrm{d})$
  Given $\Gamma(\mathrm{d})$ and $Z(\mathrm{d})$ $\Rightarrow$ Find Γ_R and Z_R
- Find d_{max} and d_{min} (maximum and minimum locations for the voltage standing wave pattern)
- Find the Voltage Standing Wave Ratio (VSWR)
- Given $Z(\mathrm{d})$ $\Rightarrow$ Find $Y(\mathrm{d})$
  Given $Y(\mathrm{d})$ $\Rightarrow$ Find $Z(\mathrm{d})$

Given $Z(\mathrm{d})$ $\Rightarrow$ Find $\Gamma(\mathrm{d})$

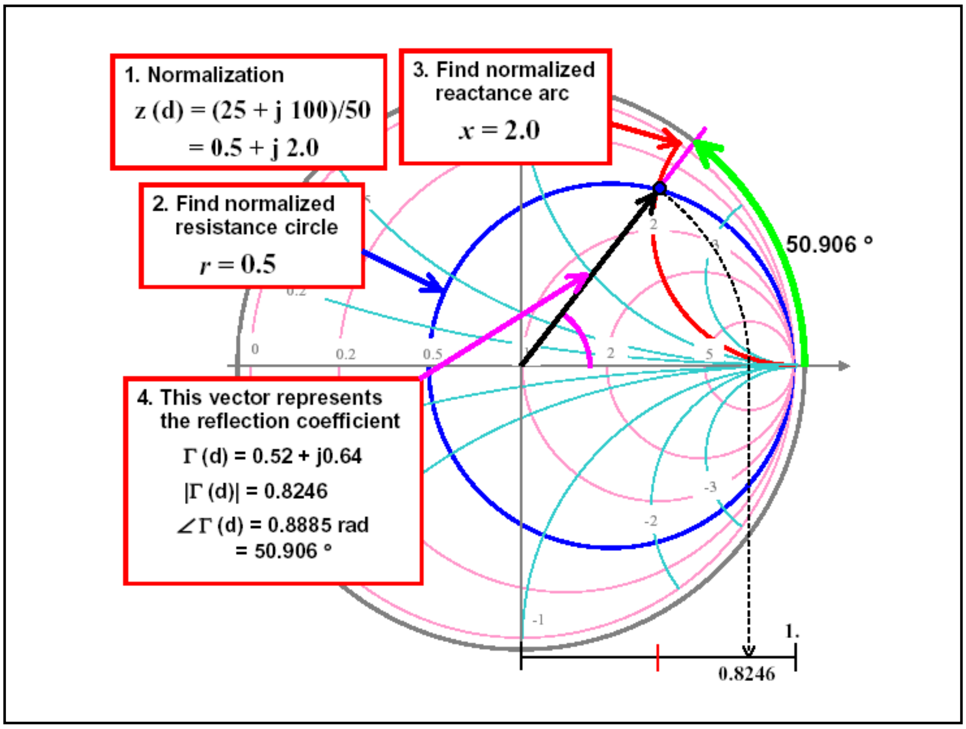
1. Normalize the impedance

$$z(\mathrm{d}) = \frac{Z(\mathrm{d})}{Z_0} = \frac{R}{Z_0} + j\,\frac{X}{Z_0} = r + j\,x$$

2. Find the circle of constant normalized resistance r
3. Find the arc of constant normalized reactance x
4. The intersection of the two curves indicates the reflection coefficient in the complex plane. The chart provides directly the magnitude and the phase angle of $\Gamma(\mathrm{d})$

Example: Find $\Gamma(\mathrm{d})$, given

$$Z(\mathrm{d}) = 25 + j\,100\ \Omega \qquad \text{with} \quad Z_0 = 50\ \Omega$$



Given $\Gamma(\mathrm{d})$ $\Rightarrow$ Find $Z(\mathrm{d})$

1. Determine the complex point representing the given reflection coefficient $\Gamma(\mathrm{d})$ on the chart.
2. Read the values of the normalized resistance r and of the normalized reactance x that correspond to the reflection coefficient point.
3. The normalized impedance is

$$z(\mathrm{d}) = r + j\,x$$

and the actual impedance is

$$Z(\mathrm{d}) = Z_0\; z(\mathrm{d}) = Z_0\,(r + j\,x) = Z_0\; r + j\,Z_0\; x$$

Given Γ_R and Z_R $\Longleftrightarrow$ Find $\Gamma(d)$ and $Z(d)$

NOTE: the magnitude of the reflection coefficient is constant along a loss-less transmission line terminated by a specified load, since

$$|\Gamma(d)| = |\Gamma_R \exp(-j2\beta d)| = |\Gamma_R|$$

Therefore, on the complex plane, a circle with center at the origin and radius $|\Gamma_R|$ represents all possible reflection coefficients found along the transmission line. When the circle of constant magnitude of the reflection coefficient is drawn on the Smith chart, one can determine the values of the line impedance at any location.

The graphical step-by-step procedure is:

1. Identify the load reflection coefficient Γ_R and the normalized load impedance Z_R on the Smith chart.

2. Draw the circle of constant reflection coefficient amplitude $|\Gamma(d)| = |\Gamma_R|$.
3. Starting from the point representing the load, travel on the circle in the clockwise direction, by an angle

$$\theta = 2\beta d = 2\frac{2\pi}{\lambda} d$$

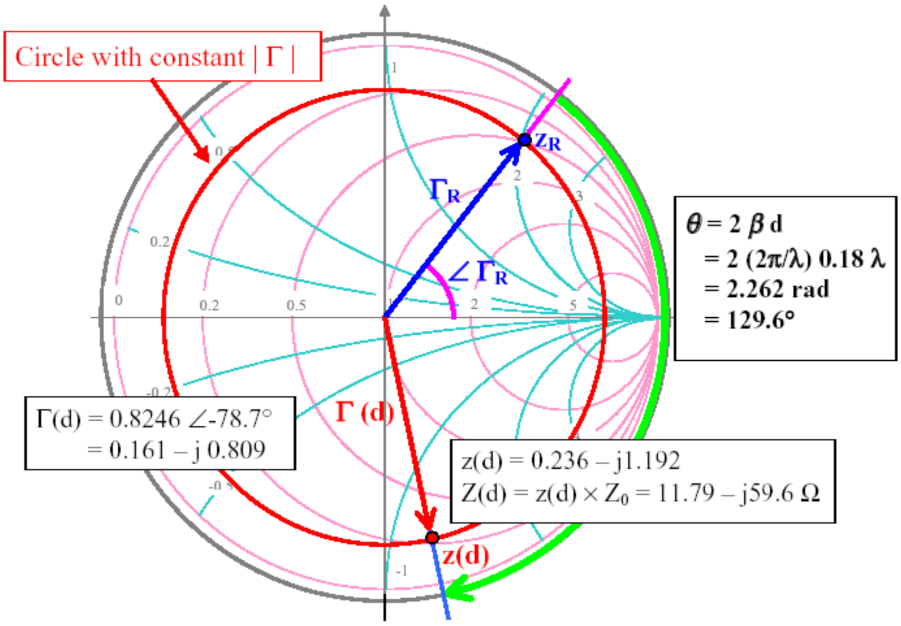
4. The new location on the chart corresponds to location d on the transmission line. Here, the values of $\Gamma(d)$ and $Z(d)$ can be read from the chart as before.

Example: Given

$$Z_R = 25 + j\,100\,\Omega \qquad \text{with} \qquad Z_0 = 50\,\Omega$$

find

$$Z(d) \quad \text{and} \quad \Gamma(d) \qquad \text{for} \qquad d = 0.18\lambda$$

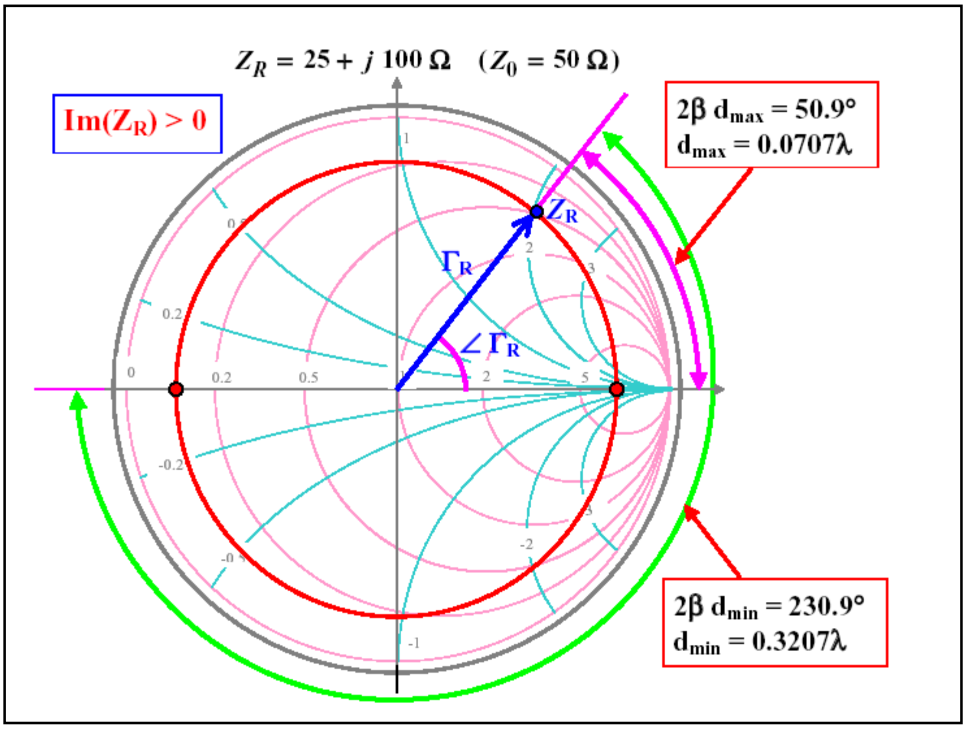


Given Γ_R and Z_R $\Rightarrow$ Find d_{max} and d_{min}

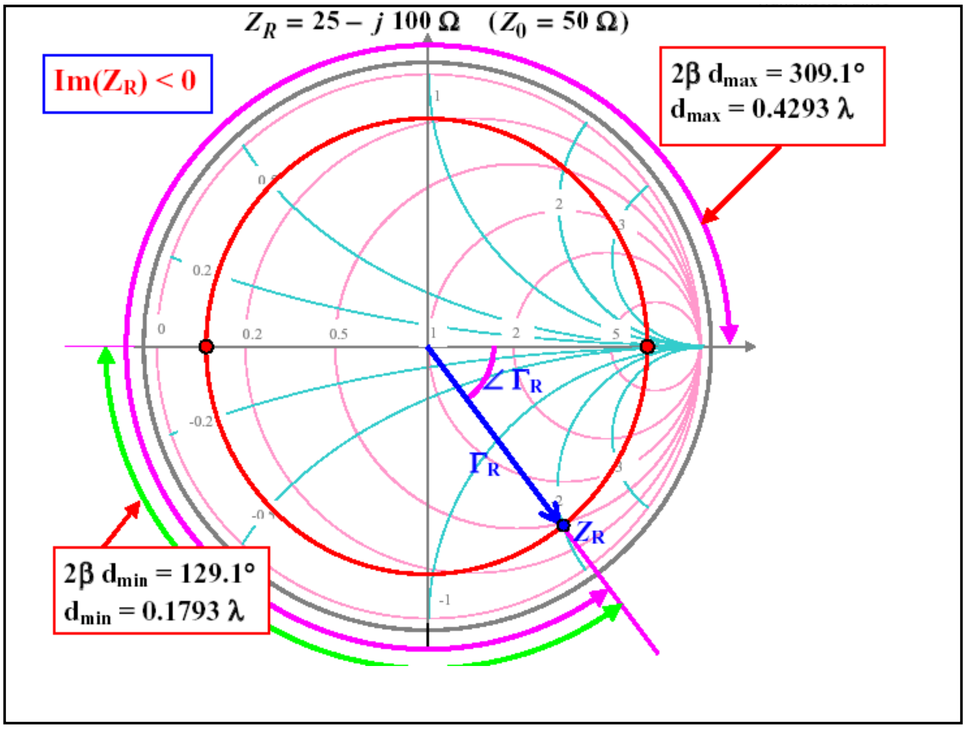
1. **Identify on the Smith chart the load reflection coefficient Γ_R or the normalized load impedance Z_R .**
2. **Draw the circle of constant reflection coefficient amplitude $|\Gamma(d)| = |\Gamma_R|$. The circle intersects the real axis of the reflection coefficient at two points which identify d_{max} (when $\Gamma(d)$ = Real positive) and d_{min} (when $\Gamma(d)$ = Real negative)**
3. **A commercial Smith chart provides an outer graduation where the distances normalized to the wavelength can be read directly. The angles, between the vector Γ_R and the real axis, also provide a way to compute d_{max} and d_{min} .**

Example: Find d_{max} and d_{min} for

$$Z_R = 25 + j\,100\,\Omega \quad ; \quad Z_R = 25 - j100\Omega \qquad (Z_0 = 50\ \Omega)$$



$Z_R = 25 + j\,100\ \Omega \quad (Z_0 = 50\ \Omega)$
Im(Z_R) > 0
$2\beta\, d_{max} = 50.9°$
$d_{max} = 0.0707\lambda$
Γ_R
Z_R
$\angle\Gamma_R$
$2\beta\, d_{min} = 230.9°$
$d_{min} = 0.3207\lambda$



$Z_R = 25 - j\,100\ \Omega \quad (Z_0 = 50\ \Omega)$
Im(Z_R) < 0
$2\beta\, d_{max} = 309.1°$
$d_{max} = 0.4293\ \lambda$
$\angle\Gamma_R$
Γ_R
Z_R
$2\beta\, d_{min} = 129.1°$
$d_{min} = 0.1793\ \lambda$

Given Γ_R and Z_R $\Rightarrow$ Find the Voltage Standing Wave Ratio (VSWR)

The Voltage standing Wave Ratio or VSWR is defined as

$$VSWR = \frac{V_{\max}}{V_{\min}} = \frac{1+|\Gamma_R|}{1-|\Gamma_R|}$$

The normalized impedance at a maximum location of the standing wave pattern is given by

$$z(d_{\max}) = \frac{1+\Gamma(d_{\max})}{1-\Gamma(d_{\max})} = \frac{1+|\Gamma_R|}{1-|\Gamma_R|} = VSWR!!!$$

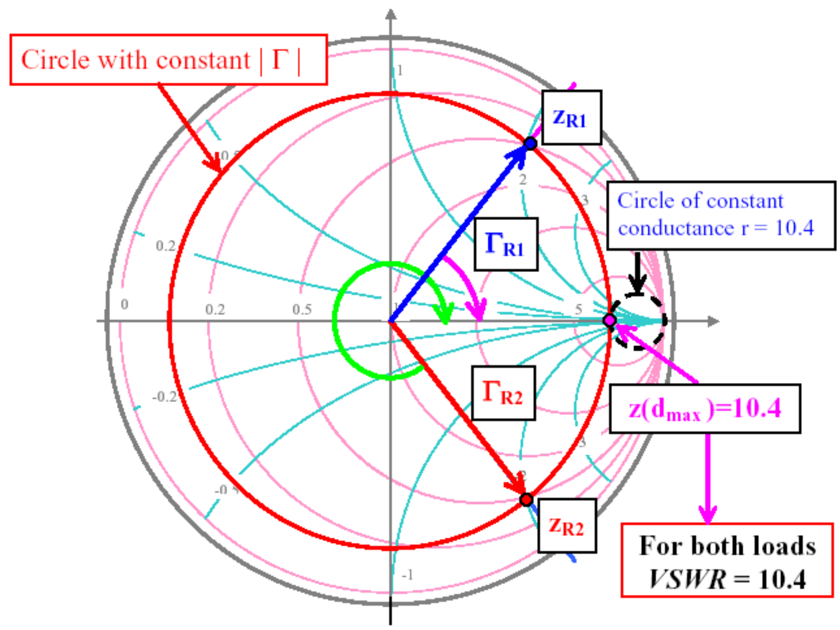
This quantity is always real and ≥ 1. The VSWR is simply obtained on the Smith chart, by reading the value of the (real) normalized impedance, at the location $d_{\max}$ where Γ is real and positive.

The graphical step-by-step procedure is:

1. Identify the load reflection coefficient Γ_R and the normalized load impedance Z_R on the Smith chart.
2. Draw the circle of constant reflection coefficient amplitude $|\Gamma(d)| = |\Gamma_R|$.
3. Find the intersection of this circle with the real positive axis for the reflection coefficient (corresponding to the transmission line location $d_{\max}$).
4. A circle of constant normalized resistance will also intersect this point. Read or interpolate the value of the normalized resistance to determine the $VSWR$.

Example: Find the $VSWR$ for

$$Z_{R1} = 25 + j\,100\ \Omega \ ; \ Z_{R2} = 25 - j100\Omega \quad (Z_0 = 50\ \Omega)$$



Given $Z(d)$ ⟺ Find $Y(d)$

Note: The normalized impedance and admittance are defined as

$$z(d) = \frac{1+\Gamma(d)}{1-\Gamma(d)} \qquad y(d) = \frac{1-\Gamma(d)}{1+\Gamma(d)}$$

Since

$$\Gamma\left(d+\frac{\lambda}{4}\right) = -\Gamma(d)$$

$$\Rightarrow \quad z\left(d+\frac{\lambda}{4}\right) = \frac{1+\Gamma\left(d+\frac{\lambda}{4}\right)}{1-\Gamma\left(d+\frac{\lambda}{4}\right)} = \frac{1-\Gamma(d)}{1+\Gamma(d)} = y(d)$$

Keep in mind that the equality

$$z\left(d+\frac{\lambda}{4}\right)=y(d)$$

is only valid for normalized impedance and admittance. The actual values are given by

$$Z\left(d+\frac{\lambda}{4}\right)=Z_0 \cdot z\left(d+\frac{\lambda}{4}\right)$$

$$Y(d)=Y_0 \cdot y(d)=\frac{y(d)}{Z_0}$$

where $Y_0=1/Z_0$ is the characteristic admittance of the transmission line.

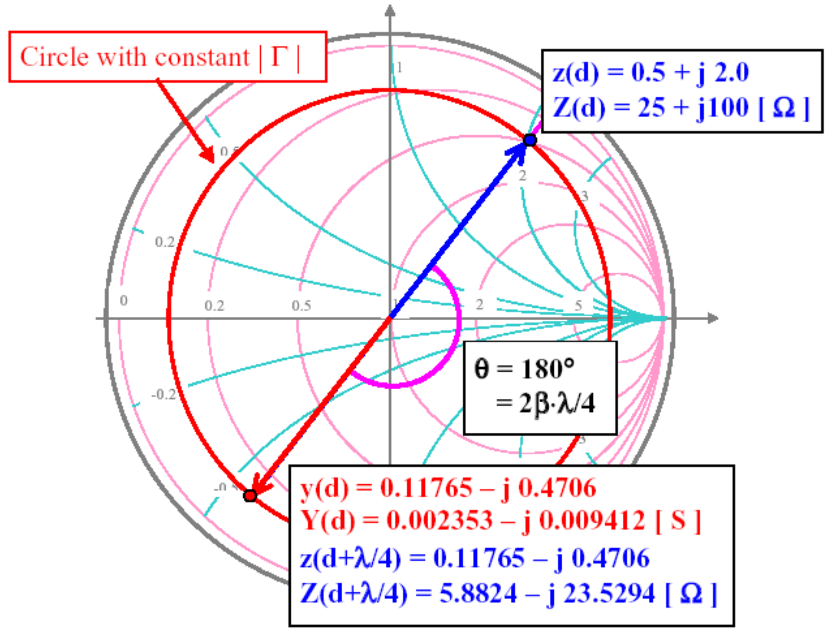
The graphical step-by-step procedure is:

1. Identify the load reflection coefficient Γ_R and the normalized load impedance Z_R on the Smith chart.
2. Draw the circle of constant reflection coefficient amplitude $|\Gamma(d)| = |\Gamma_R|$.
3. The normalized admittance is located at a point on the circle of constant $|\Gamma|$ which is diametrically opposite to the normalized impedance.

Example: Given

$$Z_R = 25 + j\,100\ \Omega \qquad \text{with} \qquad Z_0 = 50\ \Omega$$

find Y_R.



The Smith chart can be used for line admittances, by shifting the space reference to the admittance location. After that, one can move on the chart just reading the numerical values as representing admittances.

Let's review the impedance-admittance terminology:

Impedance = Resistance + j Reactance

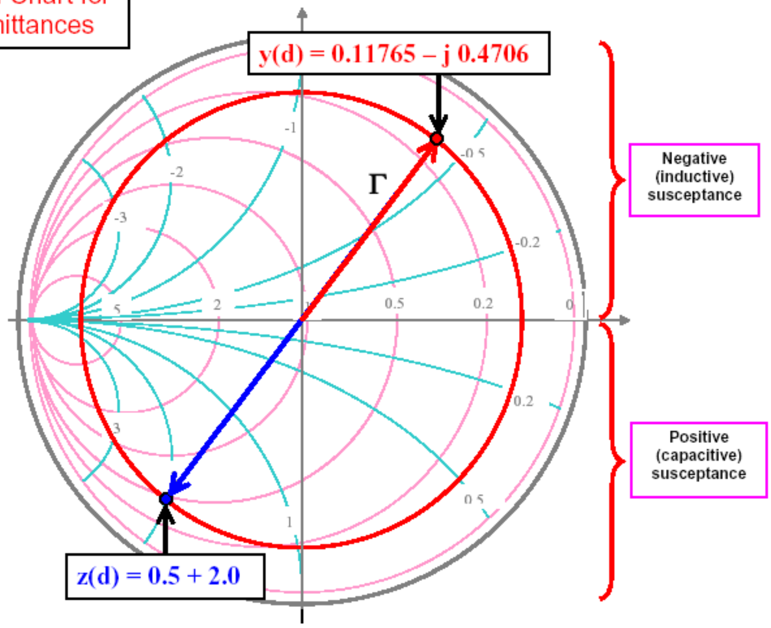
$$Z = R + jX$$

Admittance = Conductance + j Susceptance

$$Y = G + jB$$

On the impedance chart, the correct reflection coefficient is always represented by the vector corresponding to the normalized impedance. Charts specifically prepared for admittances are modified to give the correct reflection coefficient in correspondence of admittance.

Smith Chart for Admittances



Since related impedance and admittance are on opposite sides of the same Smith chart, the imaginary parts always have different sign.

Therefore, a positive (inductive) reactance corresponds to a negative (inductive) susceptance, while a negative (capacitive) reactance corresponds to a positive (capacitive) susceptance.

Numerically, we have

$$z = r + j\,x \qquad\qquad y = g + j\,b = \frac{1}{r + j\,x}$$

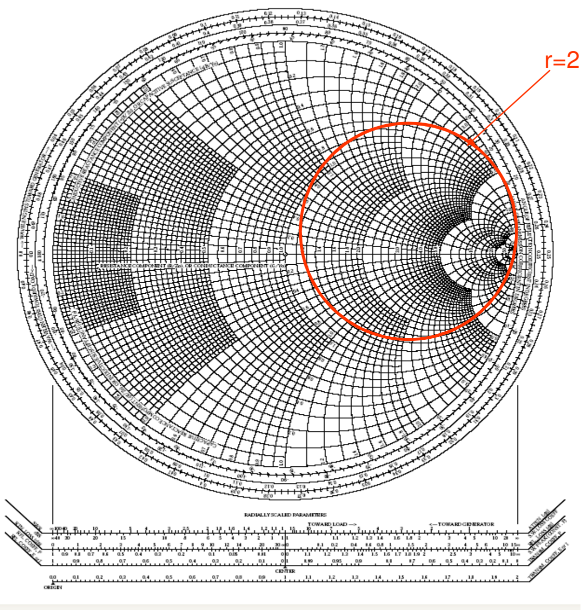
$$y = \frac{r - j\,x}{(r + j\,x)(r - j\,x)} = \frac{r - jx}{r^2 + x^2}$$

$$\Rightarrow \qquad g = \frac{r}{r^2 + x^2} \qquad\qquad b = -\frac{x}{r^2 + x^2}$$

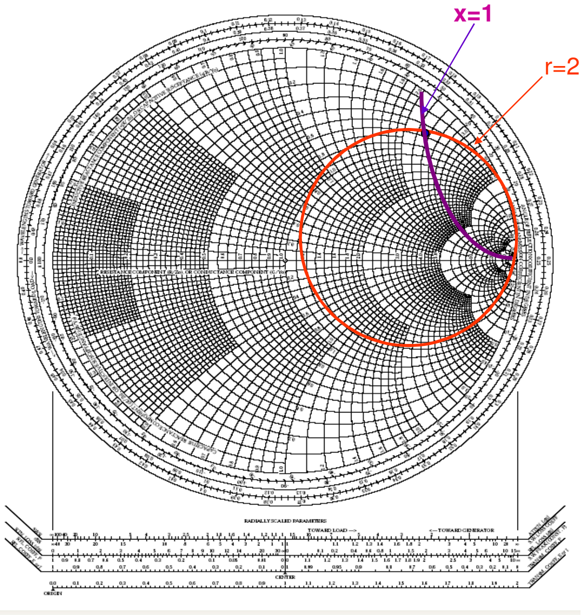
Example:Smith Chart operation using admitances

- A load of Z_L=100+j50Ω line. What are the load admittance and the input admittance if the line is 0.15λ long

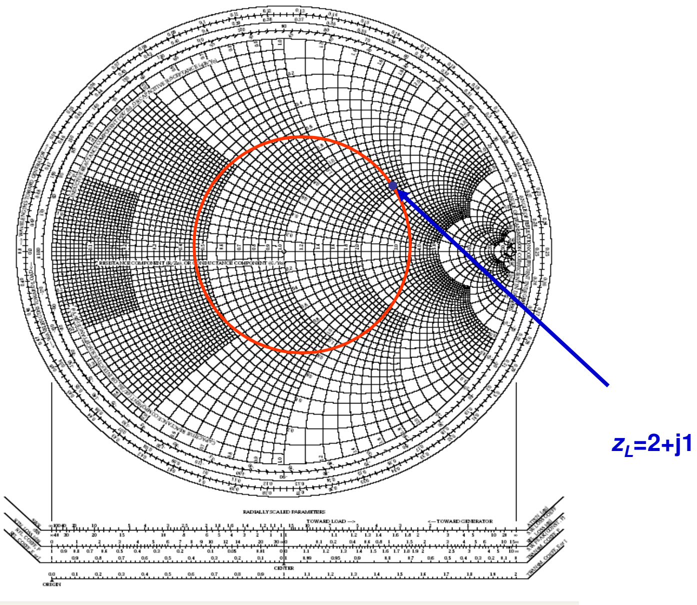
Locate r Circle of the normalized Load Impedance = Real part of (Z_L/Z_o)



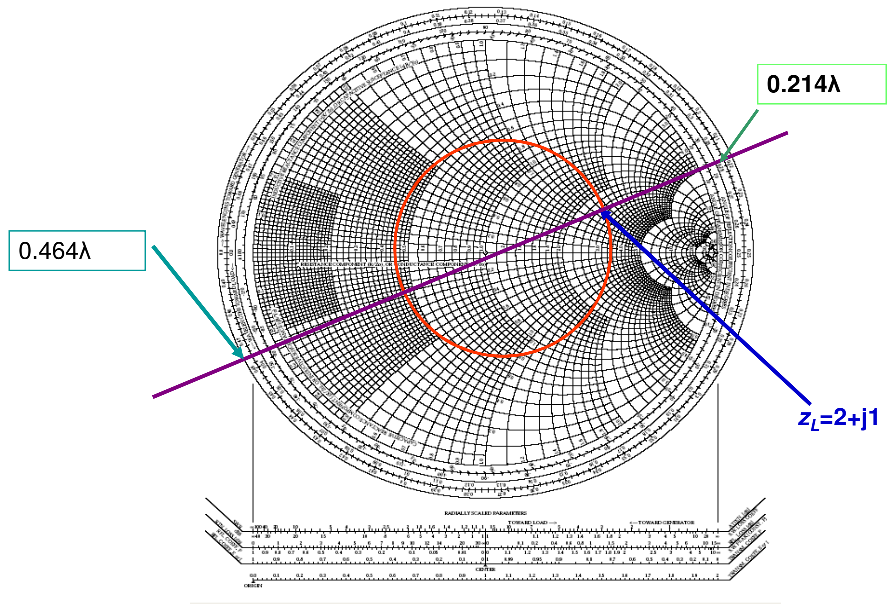
Locate the Intercept point of the r Circle and the x Circle for Load Impedance



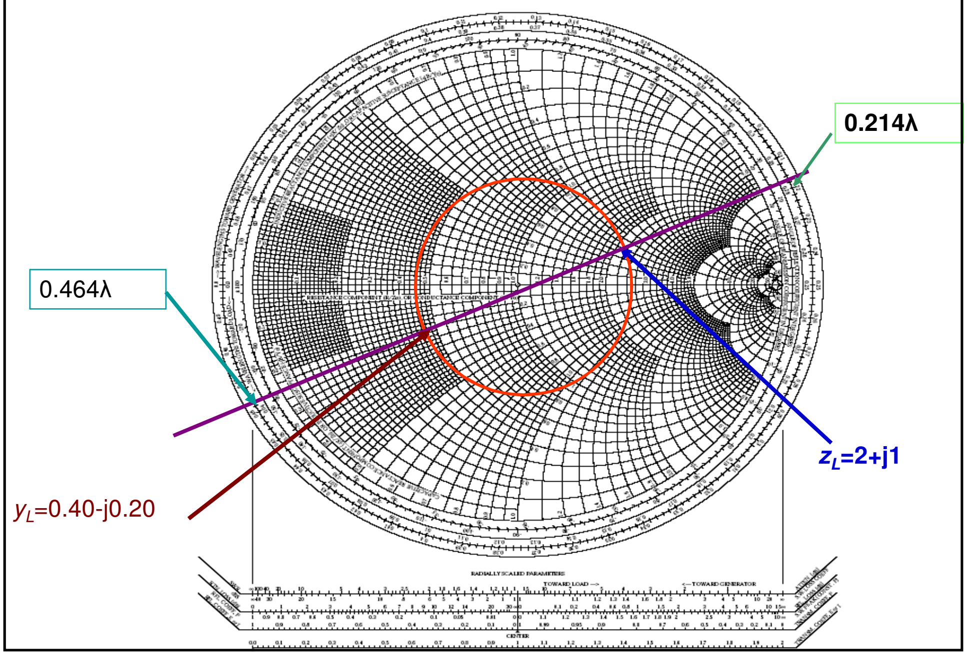
Draw the constant reflection coefficient (SWR) circle



Draw a Radial Line passing by the Intercept point for Load Impedance
Identify the Position/Location in Wavelengths



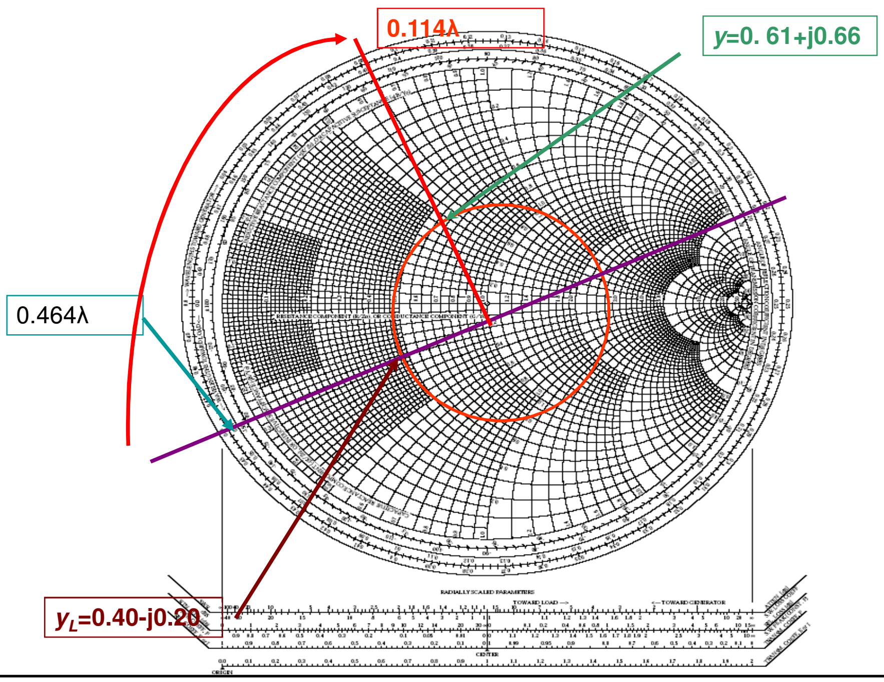
The normalized admittance is located at a point on the circle of SWR which is diametrically opposite to the normalized impedance



The actual load admittance

- $Y_L = y_L Y_0 = y_L / Z_0 = 0.0080 - j0.0040$ (S)

The normalized input admittance can be found by rotating 0.15λ from y_L



The actual input admittance

- $Y_L = yY_0 = y/Z_0 = 0.0122 - j0.00132$ (S)

Smith Chart References

- http://www.maxim-ic.com/appnotes.cfm/appnote_number/74/
- http://www.amanogawa.com/index.html
- hibp.**ecse**.rpi.edu/~connor/education/Fields/Smith_Chart.ppt
- http://tdl.ece.vt.edu/Riad/ECE4104/Handouts.htm