Power handling analysis of microwave filters using circuit models and single resonator HFSS simulations

Morten Hagensen
Guided Wave Technology ApS, Hilleroed, Denmark

Anders Edquist
Field Application Engineer, ANSYS, Inc.
1. Introduction

The power handling capability for microwave filters has always been an important issue, and with introduction of new spectrum efficient wireless systems, with large crest factors and stringent filtering demands, the ability to accurately predict the power handling capacity of a filter is as relevant as ever.

When break-down occurs in a filter the surface is damaged and the interior gets contaminated with impurities, which often has the effect of decreasing the power handling capability of the filter as well as increasing the losses. Break-down is therefore most often a destructive event, which leads to replacement of the filter.

Some simple waveguide filters may be analyzed for power handling using simple mathematical expressions, but generally this is not the case and 3D EM simulators therefore often have to be taken in use for that purpose. In order to power analyze for example a coaxial cavity filter with a 3D simulator all couplings and tuning screw positions have to be optimized until the right filter characteristic is achieved. If the filter has more than just a few resonators, the task of obtaining a ‘nice’ filter characteristic will most often be an extremely time consuming matter – if possible at all.

In this article will be presented a detailed step by step approach for accurate power handling analysis of microwave filters – based on 3D EM analysis (HFSS) on a single cavity + knowledge about the filter obtained through circuit analysis (CMS).

This approach leads to accurate results even for complex filters using a fraction of the time needed for a full 3D simulation on the actual filter itself.

The analysis follows the methods outlined in [1] & [2].
2. **Procedure for the analysis**

   When a filter is designed and analyzed for power handling the procedure can be broken down in the following 8 steps:

   1. Synthesis of filter characteristic and coupling matrix based on simple lumped circuit models - or equivalent.
   2. Calculation of stored energies based on simple model.
   3. HFSS design of single cavity so that it fulfils frequency and unloaded Q requirements.
   4. HFSS eigen value simulation on designed cavity. Stored energy is calculated using the HFSS Fields Calculator.
   5. The calculated stored energy is used to find a scale factor, which when applied to the source gives a stored energy in the cavity equal to 1 nJ
   6. The scale factor is applied via the “Edit Sources” functionality in HFSS and a Field Plot is generated. The peak E-field value is noted.
   7. The relation between stored energy and E-field is now established for the cavity in question.
      This relation is used together with the stored energy - previously calculated for each resonator in the filter (step 2) - to get the maximum E-field strength, which can occur in the filter.
   8. This E-field value is compared to the break-down threshold for air in order to validate the power handling capability of the filter.

   All above points will be dealt with in details in the following.
3. **Power handling analysis**

To demonstrate the different steps outlined in section 2, a coaxial cavity filter, for which a design already exists [3], will be used. A HFSS model of the filter is shown in Figure 1.

3.1. **Example filter (step 1 & 2)**

The filter has been synthesized using the Filter and Coupling Matrix Synthesis tool (CMS) from Guided Wave Technology [4]. This tool uses coupling matrix synthesis techniques [5, 6] for deriving a suitable topology and corresponding coupling matrix. The transformation of the coupling matrix into a physical filter may follow different paths, some of which are described in [3, 7] but this subject will not be dealt with further here.

The main parameters of the example filter are.

- **Center frequency**: 1915 MHz
- **Ripple bandwidth**: 20 MHz
- **Return loss**: 18 dB
- **Transmission zero 1**: 1932 MHz (x-coupling between resonator 3 & 5)
- **Transmission zero 2**: 1942 MHz (x-coupling between resonator 1 & 3)

![Figure 1. HFSS model of filter to be analyzed for power handling capability](image)
The CMS synthesized filter characteristic and resulting coupling matrix are shown in Figure 2. The filter in Figure 1 has been designed using the technique outlined in [3]. All main- and x-coupling apertures therefore have dimensions, which implement the coupling matrix also shown in Figure 2.

The filter characteristics obtained through CMS is equivalent to the results one would get with a circuit simulator on lumped element models. The results are therefore most accurate for narrow band filters with relative bandwidths less than 10%.

Since the topic of this article is to investigate how accurate power handling can be predicted through simple analysis, the CMS model in Figure 2 has been adjusted slightly to fit with the HFSS model. It is seen from Figure 3 that it is possible to get an almost 100% match between the two models.
In order to calculate power handling of the final filter, we need to know the stored energy level of each individual resonator.

In CMS this information is available in the QL (Loaded Q) pane, whose content is shown in Figure 4.

It is here seen that the highest stored energy level (72 pJ/W) is found at resonator 2 just outside the pass-band (1926.2 MHz). At other frequencies the situation may be very different as seen from the figure. Across the pass-band, resonators 2, 3 and 4 have in turn the highest stored energy levels.

Loaded Q is an equivalent way of describing the same as stored energy.
The power handling capability of the filter will be analyzed at the center frequency (1915 MHz). The highest stored energy level at this frequency is found in resonator 3. From Figure 4, a stored energy level equal to 12.2 nJ/W is read.

It will be assumed for a start that a perfect match exists between the filter and the load (for example an antenna). This is obtained by entering a high dB value in the return loss field in the plot.

In reality perfect matching is not possible and a more realistic value would be 15 - 20 dB, but this will be dealt with later. In the following a perfect match is assumed.

Steps 1 & 2 in the procedure outlined in section 2 have now been completed.

3.2. **Single cavity HFSS simulation (step 3)**

In order to find the relationship between stored energy and peak E-field in the filter a simple HFSS model of a single resonator is made. The model should contain all relevant details of the resonator – especially near the top where the E-field is strongest. The model is shown in Figure 5.
The single resonator model has the same height and layout as the resonators in the example filter. The cavity is a simple square cavity with a base area tuned to give an overall resonance frequency close to \( f_c \) (1915 MHz - this is done fast in a few trials with the eigen mode solver). The height of the cavity is identical to the example filter cavity height.

### 3.2.1. Calculating stored energy (step 4)

A HFSS eigen mode simulation is now performed on this resonator. Since the highest field strength is restricted to a small area around the edge of the tuning screw it is important that the mesh is fine enough for accurate results. To ensure accuracy, the calculated stored energy can be used as convergence criteria in the adaptive mesh refinement.

When the simulation is done - post processing must be performed using the *Fields Calculator* in HFSS to find the stored energy. Ansoft has made a collection of recipes [8] in which one can find instructions about how to calculate the peak electrical energy in a volume.

In appendix A the script necessary for calculating the stored energy is listed. These few lines may be written and stored in a text file of type “.clc” and loaded into the field calculator. The “clc” file may also be downloaded from

[www.gwtsoft.com/Misc/StoredEnergy.zip](http://www.gwtsoft.com/Misc/StoredEnergy.zip)
When the fields calculator is started (in HFSS project ‘tree’: Right click on ‘Field Overlays’ and chose ‘Calculator’) the window in Figure 6 appears. Use the ‘Load From’ button to load the ‘StoredEnergy.clc’ script into the calculator – or write your own script using the built-in calculator functions.

**Important:** If you use the downloaded *StoredEnergy* script it is important to note that this script assumes that the model in Figure 5 consists of one single vacuum object with the name: *Cavity*. The resonator + tuning screw have been subtracted from the square cavity. The name of this vacuum object must match the name used in the script (i.e. ‘Cavity’).

![Figure 6 HFSS fields calculator](image-url)
When the StoredEnergy script is successfully loaded into the calculator it must be selected and made active by using the “Copy to stack” button. The stored energy can now be calculated by selecting the “Eval” button.

In the present case one gets: \( W_{HFSS} = 6.922 \times 10^{-21} \) J

### 3.2.2. Normalization (step 5 & 6)

The next step is to use the just found stored energy to adjust the source excitation so that the stored energy in the cavity becomes 1nJ. The reason for this is that the CMS generated stored energies use 1nJ as reference. See Figure 4.

The following normalization/scaling constant is defined:

\[
\text{norm} = \sqrt{1 \text{nJ}/W_{HFSS}} \quad \text{(Eq. 1)}
\]

\( W_{HFSS} \) is the stored energy just found by the fields calculator in HFSS.

One gets: \( \text{norm} = \sqrt{1 \times 10^{-9}/6.92 \times 10^{-21}} = 380080 \)

This voltage is inserted in the Magnitude field in the ‘Edit Sources’ menu (in HFSS project ‘tree’: Right click on ‘Field Overlays’ and chose ‘Edit Sources’) as shown in Figure 7.

---

**Figure 7** Insertion of normalized excitation in ‘Edit Sources’ menu
When the normalization is done it can verified that it has been done correctly by using the fields calculator again to find the stored energy, which should now give 1 nJ.

With the excitation voltage properly scaled it is now time to plot the E-fields in the cavity. This is shown in Figure 8.

The E-field strengths in the cavity can be read from the legend scale to the left in the figure.

**Hint:** Use the ‘ComplexMag_E’ function when plotting the E-field. This function displays the E-field at its maximum.

Figure 8  E-field plot in the cavity corresponding to a stored energy level of 1 nJ

A maximum E-field of 4.44E4 V/m is read. This value is obtained at the lower edge of the tuning screw. This E-field is what results from 1nJ stored energy in this cavity.

\[ E_{\text{norm,max}} = 4.44\text{E4} \, \text{V/m} / \sqrt{\text{nJ}} \]

All information necessary for calculating the power handling capability of the final filter is now available

**Hint:** In Figure 8 the E-field has been plotted in a plane through the center of the resonator. This is a better approach than plotting the E-field in the whole cavity volume. Numerical ‘fluctuations’ may locally (e.g. in a single mesh cell) give E-field strengths above the ‘true’ max level. By mapping E-field in planes instead of volumes, the probability of hitting such a cell is very low. To validate the result one
can rotate the plane 90 deg. to see that approximately the same max E-field is obtained.

3.3. **Power handling capability of example filter (step 7 & 8)**

With the maximum normalized E-field in a single cavity now determined, we make use of the simple equation below (Eq. 2) to find the actual maximum E-fields in resonator ‘i’ of the example filter [1]:

\[
E_{\text{max},i} = E_{\text{norm,max}} \times \sqrt{P \times W_{\text{CMS},i}}
\]  

(Eq. 2)

*E* \(_{\text{max},i}\) is the maximum E-field strength at the i’th resonator

*E* \(_{\text{norm,max}}\) is the maximum normalized E-field found by a single cavity HFSS simulation

*P* is the input power to the filter in Watt

*W* \(_{\text{CMS},i}\) is the stored energy of the i’th resonator found from the CMS model.

Please note that there is a typing error in the expression given in [1], which has been corrected in (Eq. 2).

From the CMS stored-energy simulation in Figure 4 it was found that the maximum stored energy at 1915 MHz was in resonator 3.

\[W_{\text{CMS},2} = 12.2 \text{ nJ/W}\]

It was also previously found that

\[E_{\text{norm,max}} = 4.44E4 \text{ V/m}\]

Assuming an input power \(P = 20\) W one then gets

\[E_{\text{max}} = 4.44E4 \times \sqrt{20 \times 12.2} = 0.69 \text{ MV/m}\]

which is the maximum E-field strength in the filter at 1915 MHz for 20 W input.

As a rule of thumb the break-down field-strength at 1 atmosphere for microwave signals is 2.3 MV/m [1].

For 20 W input to the filter a comfortable margin exists to the break down limit in resonator 3 at 1915 MHz.

Normally it is good practice to have a factor two safety margin to the break down limit.
Rewriting (Eq. 2) gives:

\[ P = \left( \frac{E_{\text{max},i}}{E_{\text{norm,max}}} \right)^2 / W_{\text{CMS},i} \quad (\text{Eq. 3}) \]

If \( E_{\text{max},i} \) is replaced in (Eq. 3) by the break-down field strength in normal pressure (2.3 MV/m) the following expression for the break-down input power appears:

\[ P_{\text{BD}} = \left( \frac{2.3 \times 10^6}{E_{\text{norm,max}}} \right)^2 / W_{\text{CMS},i} \quad (\text{Eq. 4}) \]

If the above used values for \( E_{\text{norm,max}} \) and \( W_{\text{CMS},i} \) are inserted one gets:

\[ P_{\text{BD}} = \left( \frac{2.3 \times 10^6}{4.44 \times 10^4} \right)^2 / 12.2 = 220 \text{ W} \]

which is the threshold input power for break-down in this filter at 1915 MHz.

At other frequencies the situation may be quite different. At little above the passband (1926.2 MHz) it is seen that resonator 2 is here the limiting resonator with a stored energy level equal to 72.1 nJ/W (\).

The break-down power is here:

\[ P_{\text{BD}} = \left( \frac{2.3 \times 10^6}{4.44 \times 10^4} \right)^2 / 72.1 = 37 \text{ W}, \text{ which is 6 times lower power-handling capacity compared to at the center frequency.} \]

3.4. **Comparison with a full HFSS filter simulation**

To validate the above results a breakdown analysis has been conducted on the complete filter whose filter characteristic has been optimized in HFSS to give the result shown in Figure 3.

From Figure 4 it is known that at the center frequency the highest stored energy for the complete filter is found in resonator 3. The field strengths are therefore plotted in a plane through the center of this resonator. The power at the input port has been set to 20W.
Figure 9  E field strengths in a plane through resonator 3 for 20 W input power.

It is seen that the field analysis of the complete filter gives a max E field equal to

0.69 MV/m.

From the simple analysis conducted in section 3.3 the max E field was previously found to be

0.69 MV/m.

**Identical results have therefore been obtained** - but with the simple method the time and computer resources used for the job have been at least an order of magnitude lower compared to HFSS treatment of the full problem.

### 3.5. Other factors with influence on the power handling.

#### 3.5.1. Load mismatch

It was mentioned in section 3.1 that load return loss has also an influence on the power handling capacity of a filter. If power is reflected at the load this leads to standing waves in the filter, which may severely decrease the power capacity of the filter.

If the reflection coefficient at the load is $\rho$, the worst case level of stored energy in the filter increases by a factor $(1+\rho)^2$.

In CMS it is possible to enter the actual load reflection coefficient when calculating stored energies in a filter (see Figure 4).
In the previous sections it was assumed that a perfect match existed between filter and load. If instead 15 dB return loss is assumed the break-down power will decrease from 220W to 149W at the center frequency.

Compared to a reflection free connection - the 15 dB load return loss will in worst case reduce the power handling capability of the filter by a third.

Whether or not a worst case situation appears is dependent on the actual phase condition of the connection between filter and load. Often this connection is difficult to control and one should therefore assure that the filter is capable of handling the worst case situation.

3.5.2. Pressure, temperature & moisture

Low pressure, high temperature & humidity will also decrease the power handling capacity of a filter. Of these especially pressure and temperature may give rise to problems under certain conditions.

These issues will not be dealt with here, but it shall only be mentioned that pressure must be considered for equipment intended for high altitudes, aeronautical applications or space: The power handling capability may well be reduced by a factor 100 when subjected to the low pressure environment at for example 10 km altitude.

An overview of these factors may be found in [9].
4. Conclusion

In this article a step-by-step approach has been described, which allows filter engineers to make accurate power handling analysis of microwave filters with minimum use of computer resources and time.

To demonstrate the method a circuit model has been combined with 3D electromagnetic simulations on a single resonator whereby the power handling capacity has been determined for a 5 pole coaxial cavity filter with two cross couplings. The method determines the peak electrical field strength in the filter - and the break down power.

To verify the results, full 3D simulations on the complete filter have also been carried out. It has here been demonstrated that the simple method gives near identical results to full 3D simulations - but with a time consumption which may well be an order of magnitude lower than 3D simulations on the complete filter.
Appendix A  Stored-energy script for HFSS fields calculator

```plaintext
$begin 'Named_Expression'
Name('StoredEnergy')
Expression('Integrate(Volume(Cavity),*(*(Real(Dot(Conj(<Ex,Ey,Ez>),<Ex,Ey,Ez>)),
8.854187817E-012), 0.5))')
Fundamental_Quantity('E')
Operation('Conj')
Fundamental_Quantity('E')
Operation('Dot')
Operation('Real')
Scalar_Constant(8.85419e-012)
Operation('*')
Scalar_Constant(0.5)
Operation('*')
EnterVolume('Cavity')
Operation('VolumeValue')
Operation('Integrate')
$end 'Named_Expression'
```


5. References


