RF Inductor Development by Using the FEM

Z. Pólik, M. Kuczmann

“Széchenyi István” University Department of Telecommunication
H-9026 Győr, Egyetem tér 1. polikzoltan@gmail.com

Abstract: The design of inductors is not an easy and cheap task considering the dimensions, the nominal value of inductance, the quality factor and the impedance of the component. Before the beginning of manufacturing a new type of inductors, a lot of trial components have to produce, have to measure and have to try out. Finite element modelling is a well-tried process to examine engineering products before manufacturing them. To reduce the cost and the time of the design process, in the paper a finite element model has been built up to simulate inductors. By the implemented model the component designers can examine the behaviour of an arbitrary inductor and the effects of the modification on its geometry or on its winding.

Keywords: RF inductor, Finite element method, Quality factor, Absorbing boundary condition

1. Introduction

In the paper the model is presented, which is able to simulate the important attributes of the component, for example the inductance, the impedance and the quality factor. The comparison of the experimental and the simulated attributes of the inductor will also be shown. By using the built up model the development possibilities of the inductor have been examined through the modification of the winding.

An electronic component manufacturer develops, manufactures and markets electronic components, modules and systems, focusing on fast-growing leading-edge technology markets: in information technology (IT) and telecommunications, but also in automotive, industrial and consumer electronics. To satisfy the private demand of some customers, the company needs to design new components and modify the actual parameters of several types of inductors. The company has a developing team to find the best geometry, material, and manufacturing process of inductors. Many researches are improving the attributes of their components, i.e. the inductance, the quality factor, the maximum current, the sensitivity and so on, through applying new materials and new geometries, which are also developing there [1].

The first aim of this work is to build up a finite element model, with which the attributes of an optional inductor can be simulated. Since inductors are working in wide range of the frequency, the model has to provide correct results at low and very high frequencies, as well.
The second aim is to examine the development possibilities of the quality factor by modifying the coil of the component. In physics and engineering, the quality factor, or Q-factor is a dimensionless parameter that compares the time constant for decay of an oscillating physical system’s amplitude to its oscillation period. To increase the quality factor, the original winding of the inductor has been replaced by a newly designed one. In the new coil several wires and winding type – “closely-” and “widely spaced” coils – have been applied to found the best arrangement. The attributes of prepared components have been measured and by using the finite element model they have been simulated. The measured and the simulated results have been compared.

In the engineering point of view, the optimization of an attribute in the case of an optional component is a very huge problem, which cannot be solved by using the well-tried manufacture and measure method. Numerically, it can be solved by using a finite element model and an iterative modification of the parameters of the problem can be achieved. It is the main motivation of this research. Here, the model has been built up and checked by experimental results.

The inductor, which has been examined, is an SMT (Surface Mount Technology) one, which is usually working in the range of the radio frequency. The dimensions of the component are $1.24\pm0.04 \text{ mm} \times 1.22\pm0.04 \text{ mm} \times 2.03\pm0.04 \text{ mm}$ [1]. The component has a cubic coil on ferrite or ceramic core, depending on the application field of it. The diameter of the winding wire is 50 µm, is welded to the thick film coating on its terminations, is made of silver, palladium and platinum or, in another case it is made of wolfram, nickel and gold. It has a flat top made of epoxy for vacuum pickup. The major features of the inductor are the high resonant frequency, between 300 MHz and 9 GHz depending on the type of the component, and the close inductance tolerance. This type of inductor is used in resonant circuits, antenna amplifiers, mobile phones, Digital Enhanced Cordless Telecommunications (DECT) systems, car access systems, tire pressure monitoring systems (TPMS), wireless communication systems and global positioning systems (GPS) [1]. The microscopic photo of the component can be seen in Figure 1.

![Figure 1. The microscopic photo of the component](image)

It is important to note that different applications need different values of inductance, resistance, maximum current and quality factor. The most of the parameters can be changed easily by the modification of the winding wire or the material of the core, but the modification of one parameter causes variation in the other parameters, as well [2].
For example, if the inductance of the component is modified via the modification of the winding, i.e. the number of turns is increased or the distance between adjacent coils are decreased, the resistance of the inductor is increasing, the quality factor is decreasing and the SRF (self resonant frequency) is also decreasing both in the two cases. But the reason of the variation of the attributes is different in the mentioned two examples.

In the first case, the resistance is increasing in the effect of the more coils, because the longer wire means higher resistance, the quality factor is decreasing according to the expression of the quality factor, and the SRF is decreasing through the higher capacitance between the coils. In the second case, the resistance is increasing by the reason of the higher proximity effect between the coils, which get closer to each other, the Q-factor is decreasing because of the increasing of the resistance, and finally, the SRF is decreasing through the high capacitance between the closer coils. It seems that it is not an easy task to improve parameters without the deterioration of other ones [2].

Between 2.7 nH and 820 nH, inductors are manufactured with ceramic core and over 1 µH they are made with ferrite core. The reason of this is that the higher value of the inductance is only achievable with higher permeability of the core. However, ferrite core has disadvantages, i.e. the eddy current losses and the hysteresis losses, so the quality factor of a ceramic core inductor can be higher.

The quality factor is one of the most important attribute of inductors, the high value of the Q is necessary in several cases, for example in oscillators, and in tuned circuits. Because of the continuous development of electronic components manufacturers needs to produce inductors with higher and higher Q. Now, the reachable value of it is at least 60 between 85 MHz and 110 MHz. In the present, this value is about 30 as it can be seen in Figure 2. At first, only the effects of the modification of the winding wire have been examined. The core has standard dimensions and it is made of standard materials, so they should not be modified in the present study.

![Figure 2. The actual quality factor as a function of the frequency](image-url)
The finite element model of the problem has been built up by using the COMSOL Multiphysics software package and the trial components have been measured by an Agilent E4991A RF impedance and material analyzer, which can be seen in Figure 3 [3].

2. Governing equations

During the simulation of inductors, the base equations are the full form of the Maxwell’s equations, because at high frequency the effect of the eddy currents and the displacement currents cannot be neglected [2], [4]. Since only sinusoidal excitation have been used in the problem, the operator \(\frac{\partial}{\partial t}\) has been replaced by \(j\omega\).

The partial differential equations and the boundary conditions are the following in the investigated case [5]-[11]:

\[
\nabla \times (j \nabla \times A) - \omega^2 \varepsilon A = 0, \quad \text{in} \quad \Omega_s ,
\]

\[
\nabla \times (j \nabla \times A) + j \omega \sigma A = J_0, \quad \text{in} \quad \Omega_s ,
\]

\[
\nabla \times (j \nabla \times A) - \omega^2 \mu A = 0, \quad \text{in} \quad \Omega_D ,
\]

\[
\nabla \times A = 0, \quad \text{on} \quad \Gamma_{H_s} ,
\]

\[
\n \mathbf{n} \times A = 0, \quad \text{on} \quad \Gamma_B ,
\]

\[
\n \mathbf{n}_p \times A + \mathbf{n}_s \times A = 0, \quad \text{on} \quad \Gamma_{SD} ,
\]

\[
(\nabla \times A) \times \mathbf{n}_p + (\nabla \times A) \times \mathbf{n}_s = 0, \quad \text{on} \quad \Gamma_{SD} ,
\]

\[
\mathbf{n} \times A + \mathbf{n}_D \times A = 0, \quad \text{on} \quad \Gamma_{ED} ,
\]

\[
(\nabla \times A) \times \mathbf{n} + (\nabla \times A) \times \mathbf{n}_D = 0, \quad \text{on} \quad \Gamma_{ED} ,
\]
\[ n \times A = 0, \text{ on } \Gamma_E, \tag{10} \]
\[ \nu \nabla \times A = 0, \text{ on } \Gamma_{H_0}, \tag{11} \]
\[ (\nu \nabla \times A) \times n_0 + (\nu \nabla \times A) \times n_a = 0, \text{ on } \Gamma_{a0}, \tag{12} \]

where, \( A \) is the magnetic vector potential, \( \nu \) is \( 1/\mu \), where \( \mu \) is the permeability, \( \varepsilon \) is the permittivity, \( \sigma \) is the conductivity of the material, \( \omega \) is the angular frequency of the excitation, \( J_e \) is the current density of the excitation and \( n \) is the normal unit vector of the boundary. In this example (6) and (8) are satisfied automatically [5], [11]. In Figure 4, the structure of a wave propagation field problem can be seen, where a dielectric material is bounded by \( \Gamma_E, \Gamma_{H_0} \) and \( \Gamma_{a0} \); \( \Gamma_a \) is the artificial far boundary. The air is bounded by \( \Gamma_b \) and \( \Gamma_{H_0} \). \( \Gamma_{a0} \) is the boundary between the conducting material and the dielectric material.

2.1. Absorbing boundary condition

In some cases, particularly at high frequencies it is important that the electromagnetic waves should not reflect from the artificial far boundary. Here, the so-called absorbing boundary condition can be used, which can be formulated as [11]
\[ \frac{1}{\mu_{r1}} n \times (\nabla \times E) - \frac{j k_0}{\eta} n \times (n \times E) = 0, \tag{13} \]

or
\[ \frac{1}{\varepsilon_{r1}} n \times (\nabla \times H) - j k_0 \eta n \times (n \times H) = 0, \tag{14} \]

where \( \eta = \sqrt{\mu_{r1}/\varepsilon_{r1}} \) is the normalized intrinsic impedance of medium 1, which is equal to one in air, moreover \( k_0 = \omega \sqrt{\varepsilon_0 \mu_0} \) is the wave number, \( \varepsilon_{r2} = 1 \), and \( \mu_{r2} = 1 \).

Substituting \( \eta, k_0 \) and \( \mu_{r2} \) into (13) results in
\[ n \times (\nabla \times E) - j \omega \sqrt{\varepsilon_0 \mu_0} \cdot n \times (n \times E) = 0, \tag{15} \]

where \( \nabla \times E = -j \omega \mu_0 H \). After simplification, the absorbing boundary condition can be written as [2]
\[ \sqrt{\frac{\mu_0}{\varepsilon_0}} n \times H + n \times (n \times E) = 0. \tag{16} \]
The absorbing boundary condition has been used on the artificial far boundary $\Gamma_a$. Substituting $H = \nabla \times A$ and $E = -j\omega A$ into (16) results in the used boundary condition,

$$-v_{\epsilon}n \times \nabla \times A + j\omega \sqrt{\mu_0} n \times (n \times A) = 0, \quad \text{on} \quad \Gamma_a.$$  \hspace{1cm} (17)

It is important to note that the above partial differential equations and the absorbing boundary condition are valid only when the excitation is a sinusoidal current or a sinusoidal voltage.

The system of equation has been solved by using the weak form of the equations, which is the following:

$$\int_{\Omega} \left[ \nabla \times W_k \cdot \left( \nabla \times \tilde{A} \right) - j\omega \sqrt{\mu_0} \left( \nabla \times A \right) \right] d\Omega + \int_{\Gamma_a} j\omega \sqrt{\mu_0} W_k \tilde{A} d\Gamma = 0, \hspace{1cm} (18)$$

where $k = 1, \ldots, J$, and $\tilde{A}$ is the function approximated the magnetic vector potential $A$, moreover $W$ is a weighting function.

3. Finite element model

While building up the model, the first problem was the complexity of the component. The largest problem was the cubical coil of the inductor, because in the COMSOL Multiphysics [12] the current flowing in the coil can be described by a mathematical formula, which can be determined from the equation of the circle in the case of a helical coil [5].
That is the reason why the shape of the core and the cubic coil were neglected and a two dimensional axial symmetry model has been created. The COMSOL Multiphysics software package can handle a three dimensional axial symmetry model, as a two dimensional axial symmetry model, so the built up model is equivalent to a three dimensional one. The procedure of the simplification can be seen in Figure 5.

3.1. Simplification of the model

The solution of the above problem provides the results of the unknown quantities via the computed potentials and the calculated integrals and expressions. This is the first chance to check the results and to execute modifications about the model. After the early simulations serious problems were discovered. There are too many finite elements, 59952 in the mesh, which cause 120085 unknowns in the simulation, that yields the simulation to be very slow. The solution time of the problem is 406 seconds with a computer having an Intel Pentium D 3.4 GHz processor with two cores and 4 GB RAM.

To decrease the processing time, the number of the mesh elements has been decreased through the removal of the enamel insulation of the winding wire. The mesh of the insulation effects high mesh elements, because it is not in the same order of magnitude with the whole model. The results show that the insulation of the wire can be neglected, because the results of the simulation are almost the same with and without the insulation. After the simplification the solution time decreased to 230 seconds.

Another problem was that, by using the two dimensional model, some attributes could not be simulated, i.e. the resistance of the terminations and the capacitance between the terminations. The winding wire is welded to the terminations where higher resistance has been appeared. Furthermore, the terminations have large surface, which causes some additional capacitance.

In the simulation the less resistance and the less capacitance cause higher self-resonant frequency and higher maximum value of the quality factor than the measured ones. To compensate these effects, an electric network model was created, wherein a capacitor and a resistor are in parallel with the simulated inductor to consider the higher
capacitance and the higher resistance. In Figure 6 the applied electric network model can be seen [2].

The experiences show that the optimal value of the capacitance is 90 fF and the value of the resistance is 40 kΩ in the case of this type of inductor. The capacitance is marked by C and the resistance is symbolized by R. The network was built into the finite element model via the modification of the current passing through the component. The total current passing through the electric network can be determined by the following formula; henceforth it is used to calculate the impedance and other attributes [2],

\[
I_m = I_m + V_0 j \omega C + \frac{V_0}{R_0},
\]

(19)

Figure 6. The applied network to consider the resistance and the capacitance on the terminations

where \(I_m\) is the modified current, \(I_m\) is the total current of the finite element model and \(V_0\) is the voltage of the network.

It is important to note that the components of the network model are only parameters.

4. Results of the simulations

After building up the finite element model, the computed DC resistance and DC inductance have been compared with analytic calculations and measured data to check the correctness of the model at low frequencies. The calculated resistance results in 0.463088 Ω by using Nagaoka’s expression [2]. The DC resistance is 0.47 Ω, measured by the impedance analyzer. The computed DC resistance can be determined from the real part of the impedance, i.e. \(R_{DC} = \text{Re}(Z(\omega = 0))\), where \(Z(\omega = 0)\) is the value of the impedance in direct current case. The computed DC resistance results in 0.485 Ω.

The nominal value of the low frequency inductance is 180 nH of this type of inductor [1]. The \(L_{DC}\) DC inductance of the component is 178.9 nH, by using the following analytical formula:
where \( N \) is the number of turns, \( A \) is the cross section of the wire, \( l \) is the length of the coil and \( K \) is a constant, which is changing by the function of the length and the cross section of the coil \([2]\).

In the case of a specific inductor the measured inductance is 183 nH. The computed value of it in this case is 185 nH, which can be determined from the following equation \([4]\):

\[
L = \frac{\text{Im}(\mathcal{Z})}{2\pi f}.
\]

The obtained values are quite close to each other, so it is noticeable, that the created finite element model is working properly at low frequencies.

The comparison of the measured and the computed inductance between 10 MHz and 3 GHz can be seen in \(\text{Figure 7}\), and the measured and the computed quality factor can be seen in \(\text{Figure 8}\). It can be seen that the results are practically the same, so the finite element model is working properly at the whole range of the frequency. The difference between the measured and the computed quality factor, plotted in \(\text{Figure 8}\), is probably caused by the simplification of the core.

At this point, the investigation of the modification of the winding to find the best geometry of the coil can be started. The aim is to find the maximal value of the quality factor. Several inductor models, with larger and smaller diameter of the wire, with closely- and widely-spaced coil, and with one and two layered coil were drawn to COMSOL Multiphysics \([12]\). In \(\text{Figure 9}\) finite element meshes of inductors can be seen with three different windings. During the examination, the finite element models were created and simulated and trial components were manufactured and measured with the same windings to compare the results.

![Figure 7. The measured and the computed inductance](image-url)
The concrete experiments are the following about the increasing of the quality factor. It is trivial from the expression of the quality factor [4] that the value of it will increase if the imaginary part of the impedance increases or the real part of the impedance decreases. Because the nominal value of the inductance must be kept, the solution of the increasing of the $Q$-factor is the decreasing of the resistance.

The easiest way to decrease the resistance is using a wire with larger diameter in the coil. So a trial component was manufactured and a finite element model has been implemented with 60 µm diameter of the winding wire. The results in the simulation showed that the quality factor increase two or three percents in this case. Unfortunately, in the practice there are some problems. First of all, the measurements show that in the reality $Q$ is increased slightly than the simulation shows, and only at lower frequencies in the studied range. At higher frequencies $Q$ become smaller than in the case of the original wire, but it could not be a problem, because the quality factor has to increase at lower frequencies – between 85 MHz and 110 MHz. Furthermore, because of the manufacturing process the distance between the turns must be increased to eliminate the cross-windings, so using a wire with larger diameter and increasing the distance...
between the turns caused that the value of the inductance is fallen to 170 nH. Because of
the width of the winding cell, more turns to compensate the decreasing of the
inductance cannot be used. Consequently, it is impossible to increase the quality factor
by using thicker wire in the coil [2].

Then a wire with less diameter – it is 40 µm – has been tried out. By using thinner wire,
the value of the inductance is increasing, so it can be enough to wind less turns to the
core. Thus, there are more space to ‘play game’ with the wire. During the simulations
and the experiments, it is cleared that the inductance is not increasing significantly to
leave one or more turns. Therefore, 14 turns also must be used in this case. It is
executable to spread the coil on the core, i.e. to increase the distance between the turns,
to examine the effect of it. Our experiences show that the SRF is moved to higher
frequency, through the less stray capacitance between the turns, and via it the maximum
value of the $Q$-factor is also moved to higher frequency, moreover the maximum value
of it is increased slightly. The rise of the quality factor is faster in this case, but
unfortunately it starts in lower values than in the case of the original winding. Between
85 MHz and 110 MHz the $Q$ of this trial component is lower than the $Q$ of the present
manufactured one. Consequently, the using of thinner wire in the coil is not the solution
of the problem.

Another attempt was to manufacture the inductor with ferrite core. Because of the high
relative permeability, the nominal value of the inductance can be achieved with less
turns, effects the decreasing of the resistance of the coil. The examinations show that it
is true, but the quality factor is not increased, moreover it is decreased significantly. The
reason of this is the eddy currents and the hysteresis inside the ferrite core, which causes
eddy current loss and hysteresis loss. These losses result the lower quality factor of a
ferrite-cored component. Consequently, manufacturing inductors with ferrite core is not
the solution of the problem of the $Q$-factor.

Finally, it can be said that thank to the experiences of the engineers, the presently
manufactured component is nearly the best solution of the problem of the quality factor.
So, the answer to the first question is that by the modification of the winding the quality
factor cannot be increased significantly. But the question is hanging at poise: Is it
possible to increase the quality factor, or not? The answer is yes, by the modification of
the geometry and by using new materials.

5. Conclusions

The paper presents an actual problem of research engineers working with inductors and
electronic components.

To solve several problems beyond the examination of the quality factor, a finite element
model has been developed by using the COMSOL Multiphysics software package. The
weak form of the potential formulations to solve the presented problems has been
implemented from the Maxwell equations. The so-called absorbing boundary condition
has been determined and has been applied to eliminate the effect of the reflected
electromagnetic waves at the artificial far boundary.

The simulation of the simplified manufactured inductor has been done. To consider the
capacitance and the resistance of the terminals, an electric network has been
implemented and the values of the parameters have been set to fit the computed results to the measurements. The built up finite element model has been tested. The measurements of the trial components have been executed and the results have been described and analyzed. The measured and the analyzed data have been compared with the results of the simulations. It is observable that the implemented model is working properly, the simulated attributes and the measurements are practically the same.

Consequently it can be said that by using the present materials and the present manufacturing technology, the quality factor cannot be increased significantly, as our experiences have shown. The increasing of the quality factor can only be realized by applying new materials and new geometries in the manufacturing.

The future aim of the research is to try out new materials in the manufacturing and to examine the effects of these materials to the quality factor. To execute this examinations a three dimensional, more accurate finite element model must be built up.

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