Design of Integrated Inductors through Selection from a Database Created Using Electromagnetic Simulation and Neural Networks

Romão Kowaltschuk, Wilson A. Artuzi, *Member IEEE*, and Oscar C. Gouveia Filho, *Member IEEE*

***Abstract*—The design of integrated inductors on silicon has become an important issue to decrease costs and to speed up the fabrication of telecommunication integrated circuits. Nevertheless, the formulae provided by the existing theory still do not show a good result in inductance prediction, specially if one figures that these inductances must fit the measured ones through a wide band of very high frequency values. Electromagnetic simulation is an alternative to cope with this problem, but if done in a non-ordered fashion, it will demand a lot of computer processing time and will also require a very skilled designer to select the inductors to be tested from a large set of possible devices, due to the large amount of variables involved in the device's specification. The purpose of this work is to propose a methodology to perform electromagnetic simulations in a systematic and automatic way. Once finished these electromagnetic simulations, the resulting electrical parameters are stored in a database that correlates these variables to the geometric specification of the inductors. In order to reduce the computation time demanded by the electromagnetic simulations, the possibility of generating the electrical parameters database using neural networks was also verified.**

***Index Terms*—CMOS inductors, passive integrated devices, device design methodology, electromagnetic inductor modeling using neural networks.**

I. Introduction

In an integrated circuit the electrical parameters necessary to model inductors are those related to the spiral inductor circuits and those related to the substrate parasite circuits where this spiral is laid down.

There are many references [1] on the evaluation of the self and mutual inductance, based on empirical specific purpose developed equations and also on analytical equations, derived from the electromagnetic theory [2].

This work was supported in part by COPEL - Companhia Paranaense de Energia and by the Federal University of Paraná.

Romão Kowaltschuk works for Companhia Paranaense de Energia, Curitiba, PR, Brazil, 80710-000, mailbox 318 (phone: 41-331-3188; fax: 41-331-2380; e-mail: romao.kowaltschuk@copel.com).

Wilson A. Artuzi Jr. works for the Department of Electrical Engineering, Federal University of Paraná, Curitiba, PR, Brazil, 81531-990, mailbox 19011 (e-mail: artuzi@eletrica.ufpr.br).

Oscar da Costa Gouveia Filho works for the Department of Electrical Engineering, Federal University of Paraná, Curitiba, PR, Brazil, 81531-990, mailbox 19011 (e-mail: ogouveia@eletrica.ufpr.br).

The evaluation of the spiral's resistance is done considering the physical (geometric) distribution of the tracks on the chip and also the consequences of the skin effect [1].

The capacitances to be considered are those derived from the superposition of metals on different layers. The capacitances between nearby tracks on the same metal layer are not important, due to the low potential differences existent between the tracks [1].

The values obtained through the use of the formulae created using such considerations [2] [3] are consistent to those found in practical measurements, at least for frequencies bellow 500 MHz and even higher, as long as the dimensions of the inductor's outer radius are smaller or equal to 150 μm. These formulae do not apply to productive design yet, since they demand a prior layout definition and an estimative of the conductor's lengths, spacings between tracks, track's widths and of distinct metal layers superposition areas. To do so it will require some additional effort, and it will have to be done manifolds, if there is no previous correlation evaluation between the electrical parameters desired and the geometric specifications.

The characteristics of the substrate circuit, inherent to the spiral circuit are very much more complex. They rely mainly on the manufacturing process and on the inductor geometry, affecting the circuit in such a complex way, which is quite complex to model by generic equations. The quality factor of the inductor is the most influenced variable by the substrate characteristics [1]. High quality factor values are determinant to the successful design of many circuits, such as filters and oscillators that require a very selective quality factor [4]. They are also important to assure a good circuitry performance regarding to the achievement of low noise levels.

The most effective and reliable existing technique to evaluate the behavior of both circuits (inductor spiral and parasite substrate) is the electromagnetic simulation. It models the spiral circuit and the inherent conductive substrate parasite circuits, considering technology characteristics and layout singularities.

II. The Electromagnetic Simulation

A. *A Systematic Methodology Proposal*

The main constraint of the electromagnetic simulation is that it demands excessive computer processing time and it still is not a practical design tool. This is a concept probably originated due to the fact that electromagnetic simulation applies the trial and error methodology to search the ideal device design. The objective of this research is to verify the possibility of doing the electromagnetic simulation in an automatic and ordered way, taking advantage of the powerful numerical methods that support it, which allows an accurate modeling of the spiral and substrate circuits simultaneous behavior. But to use this resource, certain auxiliary tools must be provided:

1) A fast electromagnetic simulator, created for passive device simulation purpose, able to process text files;

2) An inductor case editor program, able to generate input case simulation files, in simple text format, readable by the electromagnetic simulator;

3) A classifier and database generator program, able to read and classify the output text files created by the electromagnetic simulator. The database created by this program is the prime tool to be used in future selection and design of inductors;

4) A commercial database manager, or a specifically developed version for such application, enabling search and queries in the simulation database created.

B. Tool Selection and Development

The program ASITIC ("Analysis and Simulation of Inductors and Transformers for Integrated Circuits") [5] was chosen for the electromagnetic simulation purpose. This choice was based on the fact that this program has a consistent theoretical background [6], that it takes into consideration the effect of eddy currents in the substrate and also because it provides some specific powerful commands that ease the specification of special topology inductors. It allows the simulation of flat inductors in one metal layer, of parallel inductors in multiple layers and of serial inductors in multiple layers. This program is also interesting because it allows batch file processing, and accepts inputs and provides outputs in a simple text file format. It does not demand excessive computational resources. In fact, the program has versions designed to run in a personal computer, using the LINUX operational system, that was used in this project.

The electromagnetic simulator input file editor program and also the electromagnetic simulator output file reader and classifier program were developed in Microsoft Visual Basic 6.0 (a Microsoft registered product) programming language.

Since the data were picked up and classified from the text files created by the electromagnetic simulator by means of a program written in Visual Basic, it was a natural consequence that the database manager chosen was the commercial program ACCESS (a Microsoft registered product, also), which was amazingly fast in handling the huge amount of data generated.

C. Database specification and Device Selection

The database created is a simple relational database with only two tables [7]. One of them contains the independent variables, related to the physical specification of the inductor, called table of geometries (see table I and fig. 1).

TABLE I
GEOMETRY TABLE VARIABLES

Variable	Type	Unit
- Spiral identification	Integer	None
- Spiral construction technique (simple layer, multiple layer in series, multiple layer in parallel)	String	None
- Radius inscribing the spiral	Floating point number	μm
- Number of sides of the spiral	Integer	None
- Spacing between tracks of the spiral	Floating point number	μm
- Width of the spiral	Floating point number	μm
- Spiral number of turns	Floating point number	None

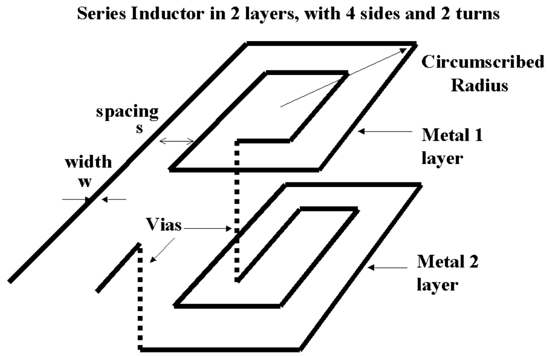

Fig. 1. Typical architecture of a multiple layer series inductor.

TABLE II
ELECTRICAL PARAMETER VARIABLES

Variable	Type	Unit
- Spiral identification number	Integer	None
- Simulated frequency	Integer	Hz
- Q factor of the input terminal	Floating point number	None
- Q factor of the output terminal	Floating point number	None
- Q factor between the input and output terminals	Floating point number	None
- Resistance between input and output terrninals	Floating point number	Ω
- Inductance between input and output terminals	Floating point number	nH
- Capacitance of the input terminal	Floating point number	pF
- Resistance of the input terminal	Floating point number	Ω
- Capacitance of the output terminal	Floating point number	pF
- Resistance of the output terminal	Floating point number	Ω
- Resonant frequency evaluated	Floating point number	Hz

The other table contains the electrical parameters calculated by the simulator and just one independent variable, the frequency, which determines specific values for the before mentioned electrical parameters (see table II).

Once completed the database with the electromagnetic simulation data, it is an easy task to select devices that accomplish the requirements of a specific design. A typical application is, for example:

"Select for a one layer square inductor all devices whose external diameter is smaller or equal than 200 μm, having inductance values ranging between 5.0 and 5.2 nH and resonant frequency higher than 3.5 GHz."

Table III shows the specification for the query and table IV shows part of the file generated, by listing the inductors whose parameters satisfy these query specifications.

A good result obtained from this query is that it also offers a good evaluation of the inductor performance for the range of frequencies simulated (see table IV). This evaluation is a very important decision tool, when choosing a device to be employed for a wide frequency band.

TABLE III
QUERY SPECIFICATION

Variable	Search Criteria
- Inductance between input and output terminals	L≤5.2 nH and L≥5.0 nH
- Radius inscribing the spiral	radius< 200 μm
- Resonant frequency	f > 3.5 GHz

TABLE IV
PARTIAL VIEW OF THE RESULT OF THE SPECIFIED QUERY

Spiral Id. Number	Radius (μm)	Freq. (MHz)	Induct. (nH)	Res. Freq. (GHz)
931	175	200	5.094	6.922
931	175	400	5.092	6.661
931	175	600	5.120	6.408
931	175	800	5.118	6.360
931	175	1000	5.114	6.580
931	175	1200	5.107	6.570
931	175	1400	5.100	6.567
931	175	1600	5.132	8.796
1048	150	200	5.090	7.088
1048	150	400	5.080	6.882
1048	150	600	5.121	6.696
1048	150	800	5.116	6.657
1048	150	1000	5.121	6.584
1048	150	1200	5.114	6.580
1048	150	1400	5.104	6.580

III. NEURAL NETWORK EVALUATION

Even considering these results as a very complete answer, the strong effort demanded by the electromagnetic simulations (which require many days of computer simulation) arouse the point that it would be desirable to create a database with an amount of data suitable for this design methodology, using computer techniques that do not demand so much processing time. The possibility of creating such a database whose values could be estimated by means of neural networks was investigated. The use of neural networks implies the need to follow the procedures listed bellow:

1) The topology of the neural network that best fits the problem must be chosen.

2) The error convergence algorithm that gives the smaller residual error must be chosen.

3) The data used to train the network must be normalized and selected in a way that allows for an accurate network response [8].

As an example, for solving the problem of evaluating the inductance, a feed-forward network with a five input entry was chosen (see fig. 2). Two hidden layers were specified, because the problem is not linear, with 20 neurons each. The output was specified with just one variable. The activation functions of the hidden layers were chosen as hyperbolic tangent, and as pure linear for the output layer. The chosen network is similar to networks used to solve Maxwell's propagation equations applied to wave guides [9].

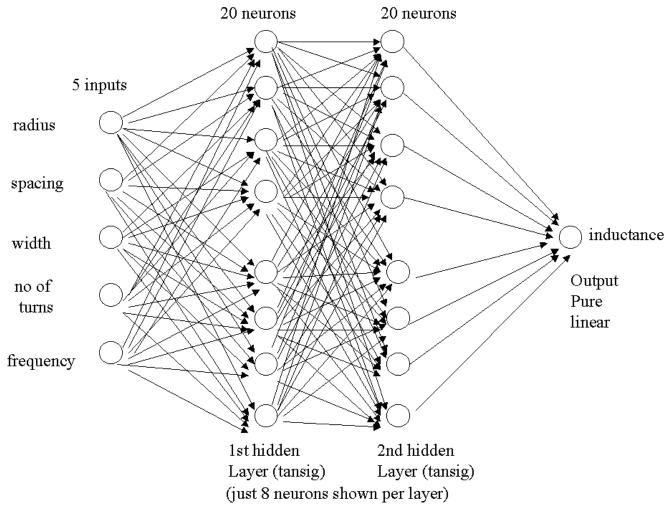

Fig. 2. Topology of the neural network.

Since the output of the network is limited to just one variable, distinct networks are necessary (at least 3) to create a searchable database (with data outputs of inductance, resonant frequency and quality factor).

To obtain the least mean squared error and also to have a minimum computer processing time, the resilient back-propagation method [10] was initially selected. Good numerical results were also obtained with the Levenberg-Marquardt algorithm, using a 5 input network, with two hidden layers of 14 and 12 neurons each, and a single neuron output layer, but simulation time and computer memory requirements were even higher [11].

Input and target training data were subject to linear normalization between 0.1 and 1.0 [8]. The data were also subject to modal normalization [8], because inductors of different construction architectures were not evaluated through the same neural network.

IV. RESULTS

Simulations were performed for a set of 1375 square inductors, through a frequency band from 0.2 to 3.0 GHz. A typical individual performance of a device in this frequency band, evaluated through the electromagnetic simulation and the neural network method is shown in fig. 3.

The simulations shown in fig. 4 to 8 show instances of approximately 33 inductors per figure, simulated from 0.2 to 3.0 GHz in steps of 200 MHz (each saw-tooth is the result for an inductor). Successive saw-teeth are the results of inductance evaluation for inductors whose design variables are changed following a previously established order: spiral's number of turns is varied first, spacing between tracks is varied next, followed by the track's width and, finally, the length of the radius that circumscribes the inductor. One can think that the horizontal axis (labeled as "number of the simulation") has effectively five variables: frequency, number of turns, spacing width, track width and circumscribed radius. The frequency assumes values as a periodic function, the number of turns assumes values in an order suitable to represent a spiral that becomes hollow, the spacing width and the track width assume progressively wider values, and the circumscribed radius assumes values to represent a shrinking spiral. The first inductors of figure 4 are inscribed in a 300 μm circumference and the last inductors of figure 8 in a 50 μm circumference. One of the curves (plotted using the thick line) contains the values of inductance obtained with the electromagnetic simulation for a set of 20625 input data vectors. The other curve (plotted using the thin line) has the inductances evaluated by the neural network for the same set. The weights and biases of the neural network were estimated using a reduced training set of 6875 vectors.

There is a fairly good approximation between the results generated through the neural network and those obtained using electromagnetic simulation, for inductances higher than 2 nH, inscribed in big radiuses. It can be clearly seen (fig. 4 to 6) that the frequency response for the neural network approximates the results for the electromagnetic simulation well, for big and medium inductors which may be of no practical use, due to the great variation of the inductance that can also be verified in the frequency range, specially for devices with a big number of turns.

For inductances of smaller values, inscribed in circumferences of smaller radiuses (fig. 7 and 8) the neural network approximation has higher relative errors. It was also verified that in this case results could be improved giving special attention to the training of the network. It is possible to reduce the relative deviation of inductance for small inductors inscribed in small radiuses, when random row permutation of the data and target matrix is performed simultaneously before running each epoch (an epoch is a single training session, using the whole training set), while training the network. It has also been noticed a slightly better frequency response performance. Fig. 7 to 8 display the results achieved in the simulations of small inductors with no special care given to the randomization of the training data input sequence. Fig. 9 to 10 show the improved results obtained with the randomization of this data input sequence, before each epoch. These last results were obtained using the Levenberg-Marquardt algorithm, that takes a lot of computer processing time and needs large computer memory. This fact has imposed limits to the trials with the Levenberg-Marquardt algorithm to networks of 5x14x12x1 neurons and training sets of 6875 vectors.

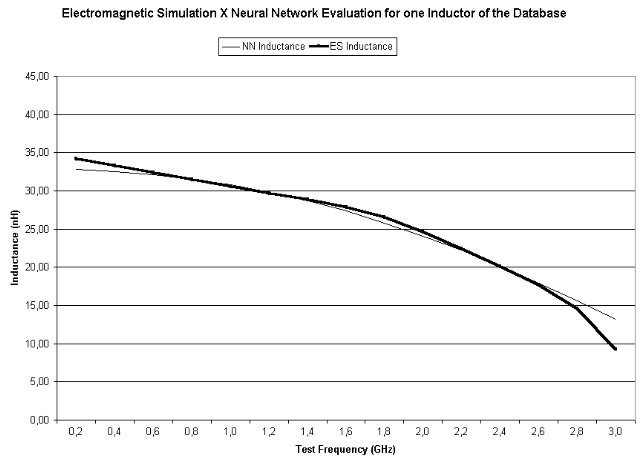

Fig. 3. Typical individual performance of an inductor for a frequency band from 0.2 to 3.0 GHz.

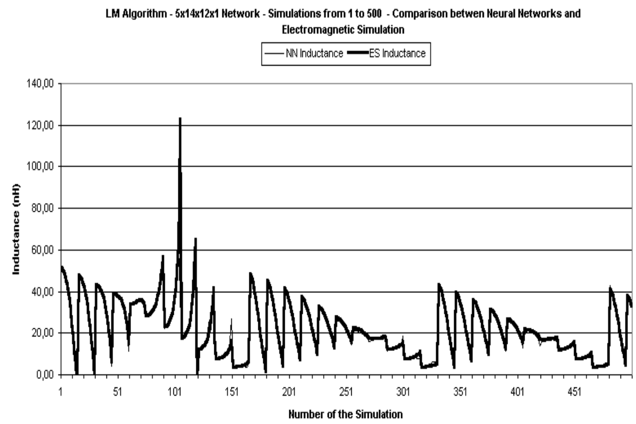

Fig. 4. There are no conflicts between the results of electromagnetic simulation and neural network evaluation for big inductors. Unfortunately such inductors may be of no practical use, due to the great range of variation of the inductance value in frequency.

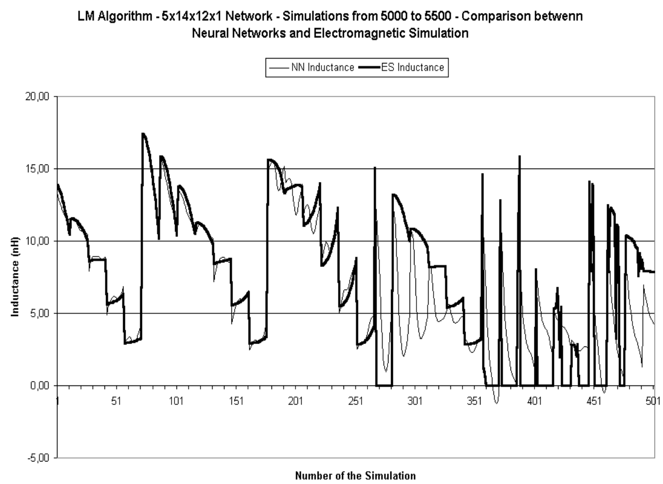

Fig. 5. The conflicts between the results of electromagnetic simulation and neural network simulation become visible. For some inductors it is possible to recognize that neural networks underestimate the performance of the devices at high frequencies. Resonant behavior is difficult to capture by the neural network too.

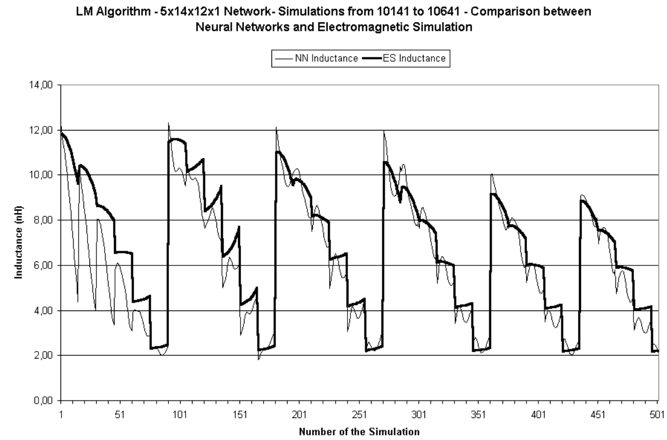

Fig. 6. Some conflicts between the results of electromagnetic simulation and neural network evaluation can be noticed. Absolute values of inductances at low frequencies are evaluated with good precision by the neural network.

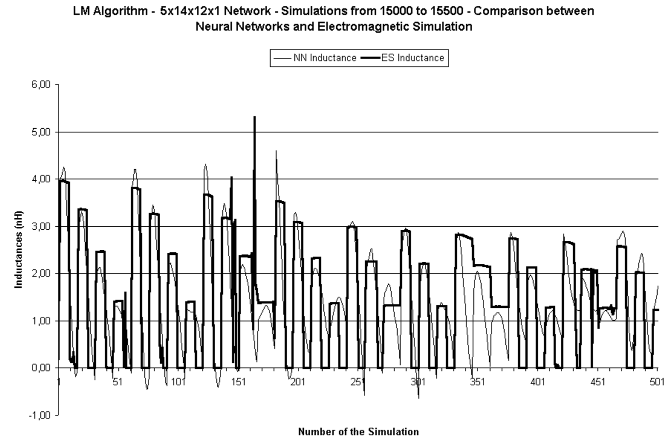

Fig. 7. More conflicts between the results of the electromagnetic simulation and the neural network approximation for the frequency response curve. Absolute values of inductances at low frequencies calculated by the neural network still offer a good precision.

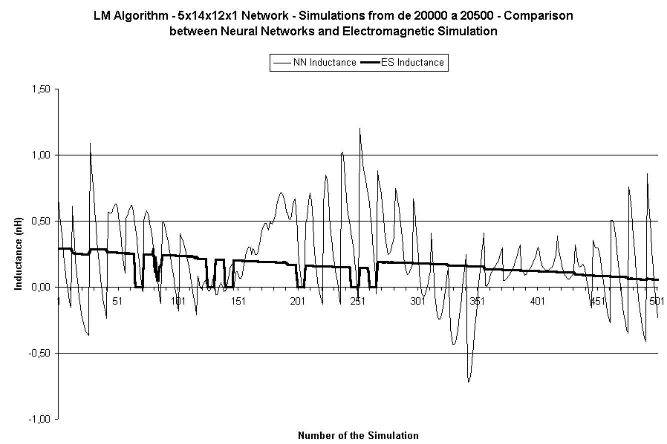

Fig. 8. There is almost no correlation between the results of the electromagnetic solution and the neural network for small inductors. Even inductances at low frequencies do not match electromagnetic simulation values any more.

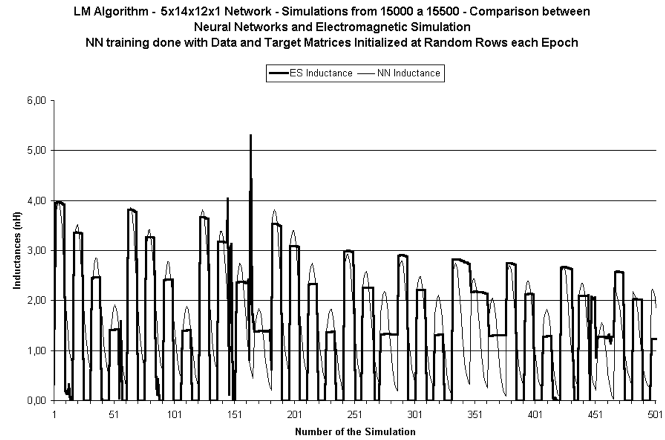

Fig. 9. Results from the neural network method considering a network trained with a special randomizing algorithm of the entry and target data. A careful comparison to fig. 7 shows a slightly better performance for inductance module prediction. It is difficult to judge on any improvement regarding the frequency performance, but a careful analysis also shows that the lower values of L, at high frequencies, are not so close to zero as they were in fig. 7.

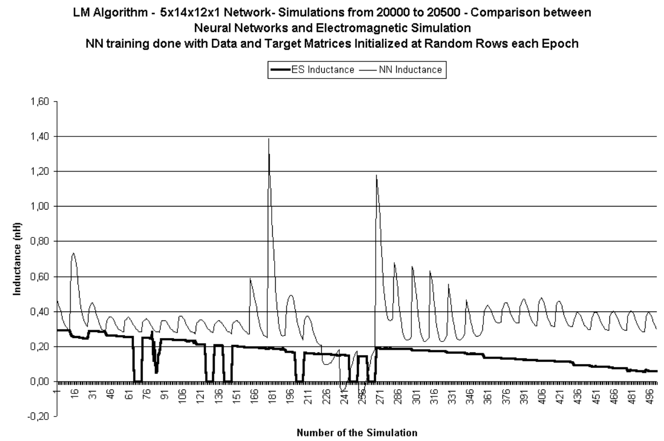

Fig. 10. This figure was also obtained for the neural network method considering a special randomizing algorithm of the entry and target data. A comparison to fig. 8 shows a much better performance for inductance prediction and frequency response.

Special care must be given to the analysis of frequency performance. Figure 11 illustrates that an inconsistent frequency response may jeopardize the choice of an inductor. Inductors numbers 808, 13, 698 and 703 satisfy a query condition that selects devices with inductance in the range between 4.0 nH and 4.4 nH, quality factor higher or equal to 2 and resonant frequency higher than 4.0 GHz. Nevertheless, inductor number 698 is the unique device that holds the condition of having the inductance values limited as specified, for the frequency range between 675 MHz and 3.0 GHz. Inductors 808 and 13 assume values higher than 4.4 for frequencies above 1.5 GHz, and inductor number 703 assumes values lower than 4.0 nH for frequencies above 2.0 GHz.

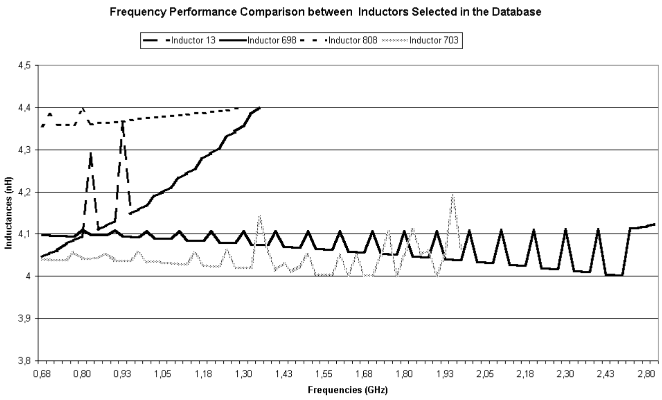

Fig. 11. A bad frequency response may jeopardize the result of a query. An inductor can be excluded in the selection process, if it does not fulfill the expected frequency response. Electromagnetic simulation still is the best evaluation tool for this analysis.

V. Conclusions

The design of integrated inductors using pre-selected inductors from a database is an effective and reliable technique that pays off the investment on human and computer resources, if there is the objective of using the database often.

Reliable databases can be obtained using data calculated by electromagnetic simulation. The drawback is the long computer simulation time demanded.

An alternative method that builds up a dataset calculated by means of neural networks, trained using smaller sets obtained from electromagnetic simulation was studied, but the imperfect accuracy obtained in inductance evaluation, specially its frequency response, still does not recommend the use of this technique. Nevertheless the results obtained for big, medium and even small size inductors show that it may be possible to obtain better results with this technique, if it is employed with an additional theoretical refinement (which implies using the Levenberg-Marquardt algorithm), with practical knowledge (which implies in careful data normalization, outlying values disposal and appropriate sequence of instances submitted to the neural network at training time) and with appropriate computer resources (which implies in larger computer memory resources and faster processors).

Acknowledgment

The corresponding author, Romão Kowaltschuk, wishes to thank Copel – Companhia Paranaense de Energia, for providing the fast Internet resources employed to obtain the bibliography used in this research.

References

[1] C. P. Yue, "On-chip spiral inductors for silicon-based radio-frequency integrated circuits", Ph. D. Thesis, University of Stanford, CA, USA, 1998.

[2] T. Yeung , "Analysis and design of on-chip spiral inductors and transformers for silicon RF integrated circuits" , M. Sc. Dissertation, The Hong Kong University of Science and Technology, Hong Kong, China, 1996.

[3] T. H. Bui " Design and optimization of a 10 nH square-spiral inductor for Si RF IC's", M. Sc. Dissertation, University of North Caroline, Charlotte, NC, 1999.

[4] E. Sacchi, "Building blocks for highly integrated CMOS-RF receiver", Ph. D. Thesis, Università degli Studi di Pavia, Pavia, Italy, 1999.

[5] A. M. Niknejad, "Analysis, design and optimization of spiral inductors and transformers for SI RF IC's, IEEE journal of solid state circuits, vol . 33, no. 10, October 1998.

[6] A. M. Niknejad, R. G. Meyer, "Analysis, simulation and applications of passive devices on conductive substrates", Ph. D. thesis, University of Berkeley, CA, USA, 2000.

[7] H. F. Korth, A. Silbershatz, "Database System Concepts", second edition, McGraw Hill Inc, 1994.

[8] G. W. Rumantir, "A hybrid statistical and feed-forward network model for forecasting with a limited amount of data: average monthly water demand time-series", M. Sc. Dissertation, Royal Meulborne Institute of Technology, Meulborne, Australia, 1995.

[9] E. Petriu, "Neural networks for modeling applications", Course material, School of Information Technology and Engineering, Otawa, Canada,2000.

[10] B. Draxler, K. Meisl, M. Theiner, "Empirical comparison of error convergence rate of standard and evolved artificial neural networks", research work, Computation Science Department, University of Salzburg, Germany, 2002.

[11] H. Demuth, M. Beale, "Neural Network Toolbox", The Mathworks Inc., Natik, Massachusetts, USA, 1997.