RIGA TECHNICAL UNIVERSITY

Faculty of Power and Electrical Engineering
Institute of Industrial Electronics and Electrical Engineering

Gundars ASMANIS
Doctoral Candidate Computerized Control of Electrical Technologies program

MEASUREMENT AND MODELING OF EMI FILTERS HIGH FREQUENCY PARASITIC PARAMETERS

Summary of PhD thesis

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DOCTORAL THESIS PRESENTED TO OBTAIN THE DOCTOR'S DEGREE IN ENGINEERING SCIENCES

Doctorate work for the doctor's degree in the engineering sciences was publicly presented on the 30. December 2014 at 11:00 o'clock in Riga Technical University, Azenes street 12-212.

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LLU TF

CONFIRMATION

Hereby, I confirm that I have worked out the present doctorate work, which is submitted for consideration to the Riga Technical university for the degree of Doctor of engineering sciences. Doctorate work has not been submitted in any other university for obtaining the Doctor's degree.

Gundars Asmanis………………..

Date: ………………………………

PhD thesis is divided in six chapters and includes 161 figures, 7 tables, 113 equations, 53 cross references in literature, annotation in English and Latvian, introduction, table of contents and is written on 162 pages.

Annotation

PHD thesis is devoted to field of Electromagnetic compatibility (EMC) - the branch of electrical sciences which studies the unintentional generation, propagation and reception of electromagnetic energy in conductive form and as radiation, leading to unwanted effects- electromagnetic interference (EMI). This thesis covers one of the EMC aspects- filters- more precisely- EMI power filters modeling, measurements and analysis.

First chapter is devoted to overview of EMC topical problems and recent research in the field of EMI power filters.

Second chapter covers mathematical background used in thesis- S-parameter application in filter characterization, S- parameter relationships, inductive component analysis using vector network analyzer, capacitive component analysis using vector network analyzer and errors related to measurement methodologies.

Third chapter analyzes effects of parasitic component parameters on Π type three phase EMI filters. Three phase filter parasitic components are extracted using S- parameter measurement techniques.

Forth chapter analyzes effects of parasitic component parameters on T type three phase EMI filters. Three phase filter parasitic components are extracted using S- parameter measurement techniques.

Fifth chapter introduces novel EMI power filter capacitor modeling using CST MWS. Three capacitor models are developed to increase modeling speed and decrease required PC resources. Mutual coupling between two capacitors and mutual coupling reduction techniques are modeled and modeling results compared to measurements.

Sixth chapter covers EMI power filter inductor modeling using CST MWS. Inductors are successfully analyzed. Mutual coupling between two inductors and mutual coupling reduction techniques are analyzed using CST MWS. Modeling results are compared to measurement results.

PHD thesis is divided in six chapters and includes 161 figures, 7 tables, 113 equations, 53 cross references in literature, annotation in English and Latvian, introduction, table of contents and is written on 162 pages.

Contents

Subject actuality

Nowadays electronics is integrated in a wide band of products available in market. Electronics clock speeds are still increasing, leading to low pulse rise-times and fall-times. Electronic components are shrinking in weight and volume, thus leading to compact and lightweight electronic devices. Compact placement of electronic components leads to interaction between them. The usage of EMI power line filter is one of possibilities to limit conductive and radiated noise propagation in the environment. Also, filters are shrinking in size and weight following the electronics evolution. It leads to closely spaced inductors and capacitors on PCB that interact to each other, reducing filter performance. Mutual inductance and parasitic capacitance between filter components and PCB becomes a very important aspect in high quality filter design.

PhD thesis discusses such aspects of EMC filters high frequency parasitic parameters as- three phase power filter parasitic parameter indirect measurement and extraction, 3D electromagnetic field modeling of filter components mutual couplings, filter inductive and capacitive component measurement techniques and measurement errors. PhD thesis describes novel three phase filter parasitic parameter extraction methodology. Three novel EMI power filter capacitor models for 3D electromagnetic field modeling are presented. EMI filter inductive component analysis is carried out using 3D electromagnetic field modeling. Mutual coupling reduction techniques in EMI power filters are developed and analyzed based on 3D electromagnetic field modeling. Upper mentioned research aspects are crucial to develop compact, high performance EMI filters.

The tasks of the thesis

The first task of the thesis is to develop methodology for three phase EMI filter component mutual coupling extraction.

Second task is to use CST MWS to develop methodology of EMI filter component mutual coupling modeling and to develop 3D electromagnetic models for EMI filter components.

The scientific novelty and main results

- There is developed methodology for three phase EMI filter component mutual coupling extraction;
- There is developed method for EMI filter component parasitic parameter measurement error calculation, using vector network analyzer;
- There are developed three novel EMI filter capacitor 3D electromagnetic models, to enable faster mutual coupling modeling in EMI filters;
- It is practically verified, that it is possible to use 3D electromagnetic field modeling software CST MWS in EMI filter component modeling, components mutual coupling extraction and components mutual coupling

reduction analysis between two capacitors and two inductors.

- There are developed inductor 3D electromagnetic model to enable fast mutual coupling modeling in EMI filters between two inductors.

Practical application

Caring out array of S-parameter measurements, based on developed methodology, three phase EMI filter component mutual couplings can be extracted. It gives possibility to diagnose the source of three phase filter poor performance. Mutual coupling reduction techniques and component optimal placement can be verified.

Developed EMI filter component models enable EMI filter mutual coupling modeling, extraction and reduction in design and prototyping phase, without carrying out set of measurements using expensive equipment. It is necessary to know filter component physical size and material properties, that usually can be successfully requested from manufacturer. Therefore, EMI filter can be designed with required parameters, such as input/output impedance, insertion loss and size.

The tools and methodology of the research

Research has been carried out using lumped element circuit modeling, 3D electromagnetic field modeling, measurements with vector network analyzer. All data has been processed to verify measurement and modeling results. Research, mainly, has been carried out using following software and hardware tools:

- Computer Simulation Technology Microwave Studio (CST MWS)- 3D electromagnetic field modeling,
- MATLAB- modeling and measurement data processing,
- Pspice- Circuit modeling,
- Orcad- PCB design,
- ZVRE- vector network analyzer.

Structure and volume of the thesis

PHD thesis is devoted to field of Electromagnetic compatibility (EMC) - the branch of electrical sciences which studies the unintentional generation, propagation and reception of electromagnetic energy in conductive form and as radiation, leading to unwanted effects- electromagnetic interference (EMI). This thesis covers one of the EMC aspects- filters- more precisely- EMI power filters modeling, measurements and analysis.

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The approbation of the results - list of relevant international conferences

1. Electric Power Quality and Supply Reliability Conference (PQ2010), Kuresare, Estonia.
2. International Symposium on Electromagnetic Compatibility 2012 (EMC EUROPE 2012), Rome, Italy.
3. Asia-Pacific Symposium on Electromagnetic Compatibility 2012 (APEMC 2012), Sentosa, Singapore.
4. International Symposium on Electromagnetic Compatibility 2014 (EMC Europe 2014), Gothenburg, Sweden.

List of the authors scientific publications on the topic of the thesis

1. L.Ribickis, G. Asmanis. Elektromagnētiskā savietojamība. - Riga, Latvia: RTU Izdevnieciba, 2010. 230 p.
2. L. Ribickis, V. Novikovs, A. Rusko, G. Asmanis, "Matrix frequency converter conducted and radiated emissions," in *Electric Power Quality and Supply Reliability Conference*, Kuressaare, Estonia, 2010, pp. 131 - 136.
3. G. Asmanis, A. Asmanis, D. Stepins, "Mutual couplings in three phase T-type EMI filters," in *2012 International Symposium on Electromagnetic Compatibility (EMC EUROPE)*, Rome, Italy, 2012, pp. 1-6.

4. D.Stepins, G. Asmanis, "Effects of Parasitic Parameters on Three Phase EMI Filters," *Topical Problems in the Field of Electrical and Power Engineering*, Tallin, Estonia, 2012, pp. 93-102.
5. G. Asmanis, A. Asmanis, L. Ribickis, "Analysis of high frequency effects in three phase EMI filters," in *2012 Asia-Pacific Symposium on Electromagnetic Compatibility (APEMC)*, Sentosa, Singapore, 2012, pp. 653 - 656.
6. G. Asmanis, A. Asmanis, D. Stepins, "Measuring capacitor parameters using vector network analyzers," *Electronics*, Palanga, Lithuania, vol. 18, no. 1, pp. 29-38, June 2014.
7. D. Stepins, A. Asmanis, L. Ribickis, G. Asmanis, "Capacitors mutual inductance modeling and reduction," in *International Symposium on Electromagnetic Compatibility (EMC Europe 2014)*, Gothenburg, Sweden, 2014, pp. 1176-1181.

1. EMC problem analysis

Electromagnetic compatibility is ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to other equipment, system or services in that environment. Equipment and system is electromagnetically compatible with its environment and other equipment and systems, if it satisfies the following three criteria:

1. It does not cause interference with other equipment and systems;

2. It is not susceptible to emissions from other equipment, systems and environment;

3. It does not cause interference with itself.

Designing electromagnetic compatibility is not only important for the desired functional performance. Equipment and systems must also meet legal requirements before they can be offered in the market. European Union has developed harmonized electromagnetic compatibility standards and issued Electromagnetic compatibility directive that should be adopted in all member states [1].

Basically, electromagnetic compatibility is concerned with the generation, transmission and reception of electromagnetic energy. These three aspects are illustrated in Fig. 1.1. Transfer of electromagnetic energy occurs via couple of paths. These paths are:

- Conductive coupling;

- Inductive coupling;
- Capacitive coupling;
- Electromagnetic coupling.

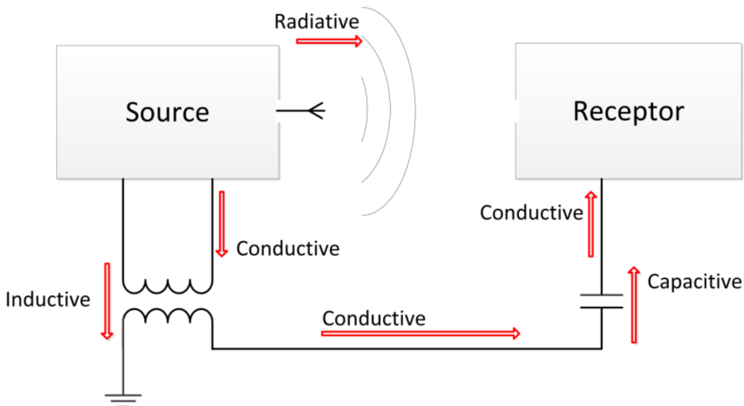


Fig. 1.1 Three aspects of electromagnetic compatibility- source, path, receptor

Various techniques exist to decrease path efficiency, but one technique is common for all paths reduction. It is a filter application. In Fig. 1.2. the application of filters is explained using coupling paths defined in Fig. 1.1.

Spectrum of electromagnetic disturbances is wide, starting from DC to couple tens of GHz. Thesis is devoted to filters, used for conducted emission mitigation in frequency range 150kHz-30MHz. These filters are used in all electronic devices that are directly connected to mains network. As nowadays, electronics volume and weight are shrinking, also EMI filters size shrinks. Therefore EMI filter components are positioned as close to each other as possible. If components are positioned in close proximity, mutual couplings between components starts to play important role [2], [3], especially in MHz range. Filter insertion loss is also affected by filter component self parasitics [4], [5], [6], [7], [8], [9].

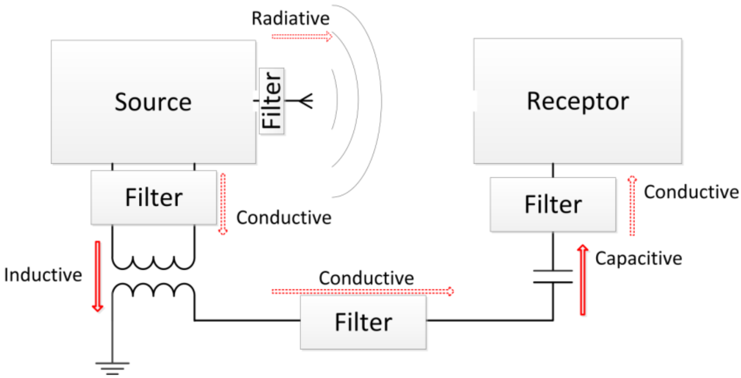


Fig. 1.2 Filter application to reduce coupling paths between source and receptor

2. Characterization of filter parameters using S-parameters

EMI filters are characterized by several parameters- input impedance, output impedance, insertion loss. Insertion loss depends on frequency, source, load impedance and current, that drives inductor cores in to saturation. Almost all EMI filter manufacturers using CISPR17 standard [10], provides technical documentation at fixed source and load impedance- 0.1Ω, 50Ω, 100Ω. It gives incomplete EMI filter description as source and load impedances are frequency dependent. S-parameter measurements provides enough data to calculate filter insertion loss ar any source and load impedance. Using S-parameters, filter is treated as two port network and described in terms of transmission and reflection coefficients. It gives possibility to propose array of equivalent circuits and indirectly measure mutual couplings between filter components.

S-parameters are measured using vector network analyzer. Vector network analyzer can be used also used in filter component measurements, replacing more expensive impedance analyzers that are quite expensive and rear in the market. There exists couple of component measurement techniques Fig. 2.1. Each of the methods is usable in filter component measurements, but measurement error depends on used method, component impedance and frequency range.

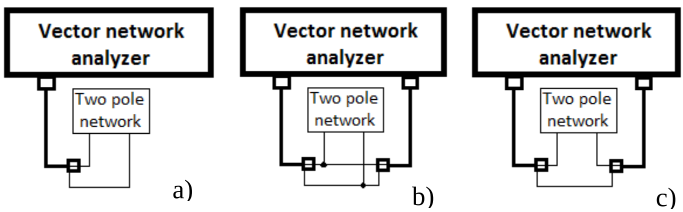


Fig. 2.1. Three impedance measurement techniques using vector network analyzer: a) first method, b) second method, c) third method

Current PhD chapter includes and analyzes all mathematical basis that is used in research, development of methods and measurement, modeling result analysis. Filter capacitive and inductive component equivalent schematics are developed, based on S-parameter measurements, covering parasitic parameters that are essential for research.

3. Effects of parasitic component parameters on three phase Π type EMI filter

This chapter is devoted to three phase Π type EMI filter component mutual coupling analysis. For analysis, mutual coupling measurement method development and verification typical three phase filter is used. These filters are nearly in all industrial electronic equipment. Filter schematic is represented in Fig. 3.1. EMI filter can be assembled in several forms, using different components and PCB layout. For research purpose single PCB layout is chosen, with two different common mode chokes. One of the common mode chokes has vertical alignment, the second horizontal alignment as in Fig. 3.2.

There are analyzed following Π type EMI filter mutual couplings:

- Mutual inductance between capacitors;
- Mutual inductance between capacitor an common mode choke;
- Mutual inductance between common mode choke and PCB ground layer;
- Mutual inductance between filter input and output;

- Mutual between filter input/output and common mode choke;
- Parasitic capacitance between filter input and output.

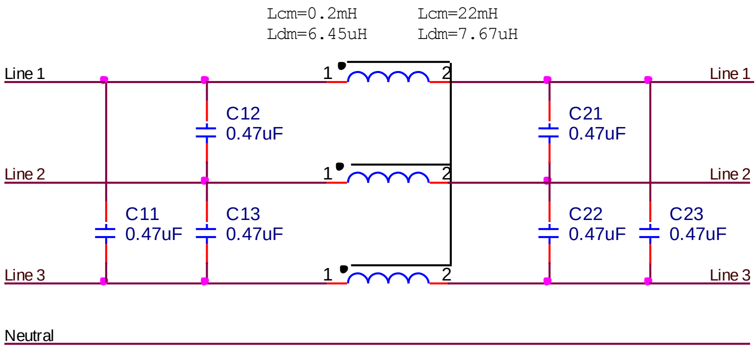


Fig. 3.1. Three phase filter prototype schematic

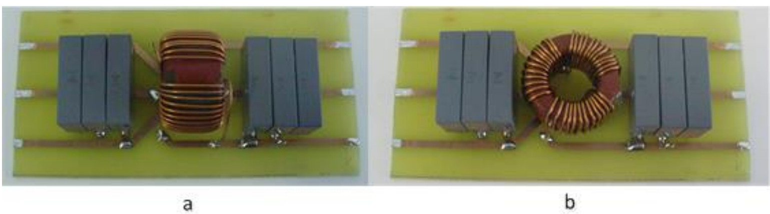


Fig. 3.2. a) Filter prototype with vertical CM choke b) Filter prototype with horizontal CM choke

Developed three phase filter equivalent circuit, that includes component self parasitics and mutual couplings between components are modeled in PSpice. Modeling results are compared with measurement results.

EMI filter component mutual couplings and insertion loss are analyzed using PSpice. The most important mutual couplings, that degrades filter insertion loss, creating “short-cut” for high frequency noise, are defined.

4. Effects of parasitic component parameters on three phase T type EMI filter

This chapter is devoted to three phase T type EMI filter component mutual coupling analysis. For analysis, mutual coupling measurement method development and verification typical three phase filter is used. These filters are nearly in all industrial electronic equipment. Filter schematic is represented in Fig. 4.1. EMI filter can be assembled in several forms, using different components and PCB layout. For research purpose single PCB layout is chosen, with two different common mode chokes. One of the common mode chokes has vertical alignment, the second horizontal alignment as in Fig. 4.2.

There are analyzed following T type EMI filter component mutual couplings:

- Mutual inductance between common mode chokes;
- Mutual inductance between capacitor and common mode choke;
- Mutual inductance between common mode choke and PCB ground layer;
- Parasitic capacitance between filter input and output.

Such mutual coupling are not analyzed:

- Mutual inductance between filter input and output;
- Mutual inductance between filter input/output and common mode choke;

due to the fact that they have negligible effect on filter performance.

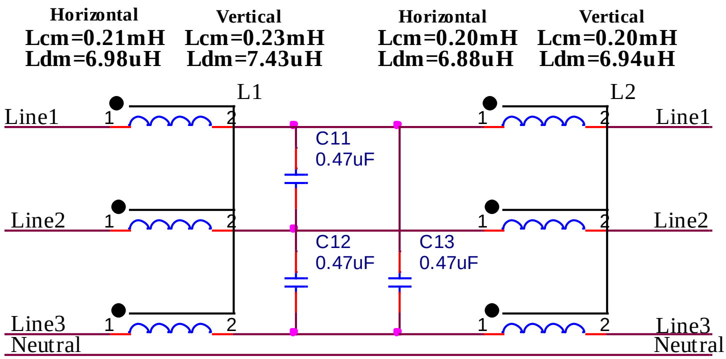
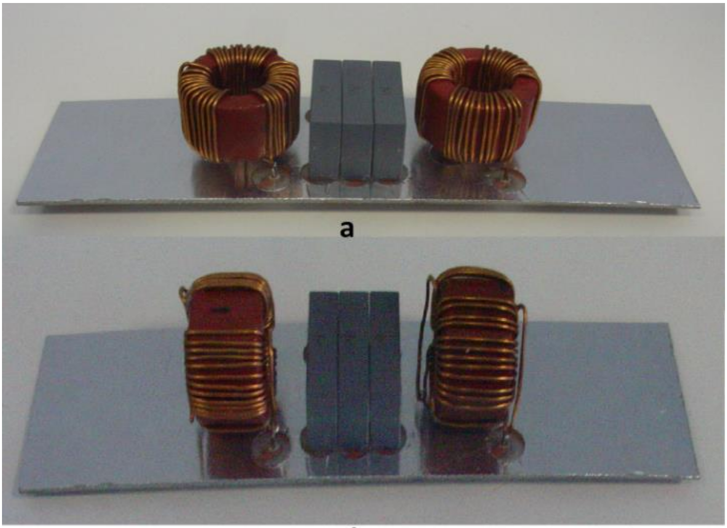


Fig. 4.1. Three phase T type filter prototype schematic

Developed three phase filter equivalent circuit, that includes component self parasitics and mutual couplings between components are modeled in PSpice. Modeling results are compared with measurement results.



b

Fig. 4.2. (a Filter prototype with horizontal CM chokes, b) Filter prototype with vertical CM chokes

EMI filter component mutual couplings and insertion loss are analyzed using PSpice. The most important mutual couplings, that degrades filter insertion loss, creating “short-cut” for high frequency noise, are defined.

5. Capacitors mutual inductance modeling

In EMI filter components are mounted next to each other as close as possible, leading to mutual couplings [11] degrading filter performance. There have been presented various measurement techniques for mutual coupling measurement [12], [11] extraction

[13], mutual coupling reduction [14] and optimization [15], [16], [17]. Therefore there is lack of information on techniques and possibilities, using in market available, the most popular 3D electromagnetic modeling tools that could help in more effective manner to solve these problems. However, there are some articles that have described 3D electromagnetic modeling tools in EMI filter modeling [18], [19], [20], but these are not the industry driven 3D electromagnetic modeling tools.

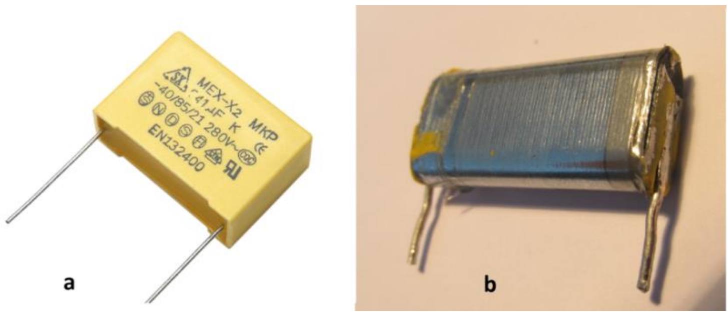


Fig. 5.1. Capacitor used for measurements: (a) intact capacitor; (b) inner structure of capacitor

Usually capacitor is made of several thousands of metalized film layers Fig. 5.1. Apparently, description of the exact internal geometry with all the layers is not appropriate, as it takes huge amount of memory and huge amount of computational power to solve the task.

In this chapter three EMI filter capacitor models are developed for modeling in CST MWS. Capacitor models are presented in Fig. 5.2.

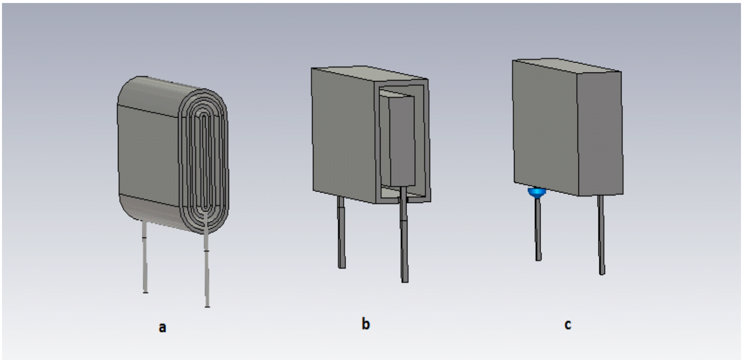


Fig. 5.2. Capacitor models proposed in the paper: (a) the most complex capacitor model proposed - Cap1; (b) medium complex capacitor model proposed - Cap2; (c) the simplest capacitor model proposed - Cap3

Developed capacitor models are verified, carrying out prototype measurements and 3D model modeling. Measurement and modeling results agrees very well.

Using CST MWS 3D electromagnetic field modeling and mathematical basis, defined in chapter 2, it is possible to predict mutual coupling characteristic, without measurements, carried out by vector network analyzer.

There have been evaluated mutual coupling reduction techniques, using CST MWS software. Capacitors mutual coupling can be visualized using surface current modeling, searching for high surface current density. In Fig. 5.3. mutual coupling reduction technique have been modeled, if shielding between capacitors is connected in two points to PCB ground layer.

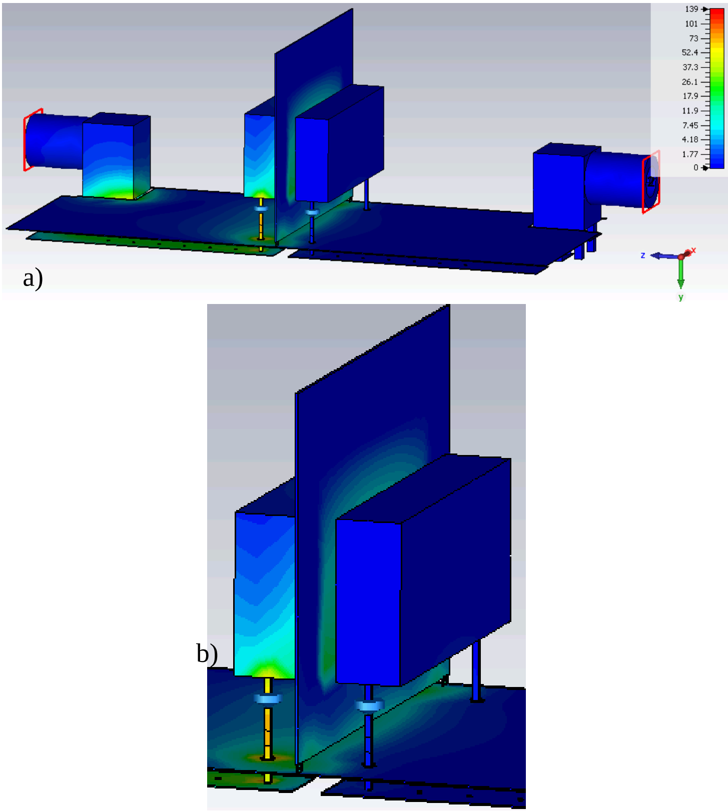


Fig. 5.3. Surface current modeling results, if copper shield is not connected in whole length: a) whole PCB, b) zoomed capacitors and shielding

6. Modeling of inductors mutual inductance

Nowadays all modern equipment is equipped with electromagnetic interference filters for conducted EMI reduction. In order to reduce the size of EMI filters, components such as inductors, are often placed very close to each other. This leads to noticeable mutual couplings which can degrade EMI filter performance [11]. Various measurement techniques for the mutual coupling measurements have been proposed in [13], [12]. Extraction of mutual couplings has been discussed in [21], but in [15], [17], [14] mutual couplings reduction and optimization have been presented. However, there is still insufficient information in the literature about the techniques and possibilities, using in market available, the most popular 3D electromagnetic modeling tools that could help in more effective manner to solve problems related to inductor-inductor mutual couplings. Despite the fact that there are some articles that have described 3D electromagnetic modeling tools in EMI filter modeling [19], [20], [18], these are not the industry driven 3D electromagnetic modeling tools.

Conventional inductor is made from couple of windings on core, made from magnetic material or nonmagnetic material. Characterization of inductor with toroid core is complex and time consuming task. Inductor parasitic parameters depends on physical dimensions of inductor components- core material, core size, core insulation thickness, winding wire diameter, winding wire material and insulation thickness, winding turn spacing and winding turn count.

There is developed inductor 3D model. The model and prototype are shown in Fig. 6.1. Model is verified carrying out prototype measurements and 3D model modeling in CST MSW. Modeling results predicts measurement results, but precision strongly depends on right material property definition, 3D model optimization in specific frequency range.

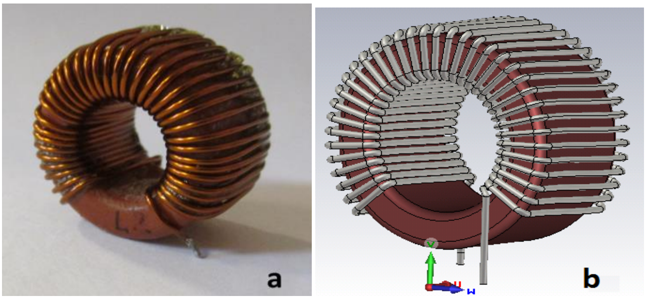


Fig. 6.1. a) Measurement prototype inductor, b) CST MSW 3D model of inductor

Using CST MWS 3D electromagnetic field modeling and mathematical basis, defined in chapter 2, it is possible to predict mutual coupling characteristic, without measurements, carried out by vector network analyzer.

There have been evaluated mutual coupling reduction techniques, using CST MWS software. Inductor mutual couplings can be visualized using surface current modeling, searching for high surface current density. Surface current modeling example is shown in Fig. 6.2.

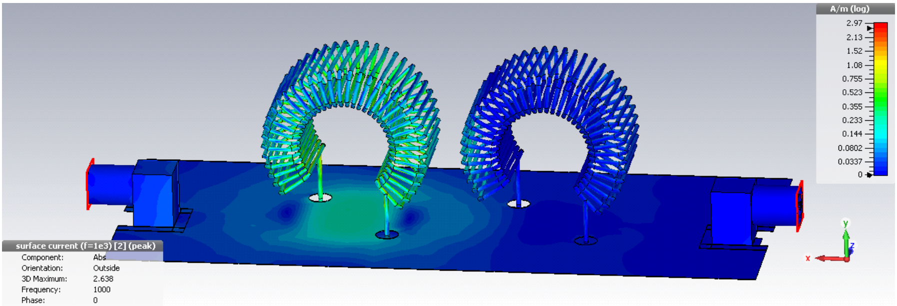


Fig. 6.2. Surface current modeling in CST MWS

7. Conclusions

Thesis is devoted to mutual coupling analysis between EMI filter components. Research can be divided in two parts. The first one is devoted to three phase EMI filter components mutual coupling indirect measurement methodology development and analysis. The second is devoted to mutual coupling modeling between two capacitors and two inductors in EMI filter using CST MWS 3D electromagnetic field modeling.

Indirect measurement of component mutual couplings in EMI filter is time consuming process. Based on measurements carried out with vector network analyzer, it is possible to calculate mutual couplings for each phase separately. Therefore, it is possible to analyze mutual couplings only phase by phase, even if the filter is symmetric. Analysis is very important, to troubleshoot EMI filter performance and to find the source of poor insertion loss:

- Mutual coupling between capacitors in Π type filters and mutual coupling between inductors in T type filter creates effective transmission path for high frequency disturbances;
- Parasitic capacitance between filter input and output is the second most important parasitic in EMI filters, especially in high frequency range;
- Mutual coupling between filter input and output plays an important role in cases if EMI filter input and output are in close proximity.

Other mutual couplings- mutual coupling between capacitor and inductor, mutual coupling between inductor and PCB has negligible effect on three phase EMI filter insertion loss.

Mutual coupling extraction in three phase filters is complex. Also, there must be filter prototype, to modify and carry out measurements using vector network analyzer. Vector network analyzers are not the most universal tool for industrial electronic developers. It is possible to use 3D electromagnetic field modeling software tool- CST MSW, to enable fast and efficient EMI filter design.

There are developed three capacitor models- Cap1, Cap2, Cap3. All models are verified. These models enable efficient mutual coupling modeling between two capacitors and helps in mutual coupling reduction method development. Capacitor model Cap1 is the most complex model, due to the fact that it contains arc surfaces, with high length to width ratio. The lowest complexity offers Cap3 model that is created out of rectangular shapes. All three capacitor models offer considerable accuracy in mutual coupling prediction between capacitors.

In EMI filters, between inductors exist mutual coupling that is directly proportional to distance between inductors. There are developed 3D inductor model that predicts mutual coupling between inductors in EMI filter. Positioning of inductors leave negligible impact on mutual coupling, but this conclusion cannot be referred to all situations, as coupling depends on inductors impedance.

CST MSW can be successively used in inductors and capacitors self parasitics modeling, mutual coupling modeling between two capacitors and mutual coupling modeling between two inductors.

8. Future research

Thesis covers only part of necessary research, development and validation, to carry out complete and successful EMI filter modeling. Currently, such modeling is not carried out using leading in market available 3D electromagnetic modeling tools. In future it is intended to continue research covering following aspects:

- Mutual coupling modeling between inductor and capacitor;
- Mutual coupling modeling between filter components and PCB;
- Common mode choke modeling;
- Complete one phase filter modeling;
- Complete three phase filter modeling.

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