

# Prediction of Conducted EMI in Power Converters Using Numerical Methods

Junsheng Wei<sup>1</sup>, Dieter Gerling<sup>1</sup>, Sebastian P. Schmid<sup>2</sup>

<sup>1</sup>Institute of Electrical Drives and Actuators, Universitaet der Bundeswehr Muenchen, Neubiberg, Germany,  
Junsheng.Wei@unibw.de

<sup>2</sup>Siemens Corporate Technology, Munich, Germany

**Abstract** — This paper investigates the use of numerical methods for an accurate computer-aided prediction of conducted electro-magnetic interference (EMI), which attracts more and more attention from industry. The three parts of EMI mechanism, which are noise generation, noise propagation and noise receiver, are analyzed and modelled separately. Detailed modelling approaches are described. The prediction approach is then applied to a power converter example and correspondingly prototype of the example is built. With comparison between numerical simulation based prediction and measurement results, the potential to use such techniques in practical application is explored.

**Keywords** — EMI, three-phase power converters, quasi-peak, numerical methods, PEEC, FEM.

## I. INTRODUCTION

Computer-aided prediction of EMI in power converters makes it possible to consider the EMC performance in the design phase and thereby saves the efforts of engineers, the cost to build up prototypes and the time from laboratory to market. As the regulation on EMI stringer, the switching frequency higher, size of power electronics converters smaller, the demand from industry to have a solution to predict the EMI generated becomes higher. With today's powerful computer, such prediction approach has the potential to become a regular tool for the design engineers.

Due to the demand stated above, specialists in power electronics have proposed approaches to predict the EMI, by using physical based method or behavior based method. Recently, some authors have proposed to use behavior based method, such as the approach described in [1], [2] and [3], which regarded the power converters as "black box". This kind of approaches requires some measurement on the modeled objects and with the help of equivalent circuit/equivalent source, the EMI behavior of the object can be modeled. And afterwards the performance of EMI under other operation conditions or with external peripheral circuits can be predicted. This type of approaches has the advantage of simplicity and generality as they require only small computational effort and are not limited to certain type of converters. However, the requirement on some preliminary measurements means it is not suitable for a purely simulation based prediction.

Instead of behavior based simulation, physical based simulation can be used to predict the conducted EMI of

power converters. Time domain simulation and frequency domain simulation are the two types of simulation approaches for physical based simulation. Frequency domain simulation features by having both noise source and noise propagation modeled in frequency domain and due to the essence of EMI, this approach benefits from shorter simulation time. Some authors have already performed corresponding simulation of EMI using this method, such as [4], [5] and [6]. However, the generality of such approach is limited, because the description of noise source in frequency domain is not always straightforward for power converters.

Therefore, in this paper, time domain simulation is used to predict conducted EMI. The simulation in this paper tries to include the most important parts in power converters by using numerical simulation and delivers as accurate as possible results. The paper is constructed in such manner that the three parts of EMI mechanism are analyzed and modeled separately. Afterwards, validation of simulation approach by measurement results is given. The comparison then points out the potential of conducted EMI prediction using numerical methods.

## II. NUMERICAL MODELLING PROCEDURE OF CONDUCTED EMI

To model and predict the conducted EMI in power converters, analysis and segmentation of EMI mechanism is of great importance. A typical EMI measurement setup is shown in Fig. 1. Generally, the EMI mechanism can be analyzed in three parts separately: noise generation, noise propagation and noise receiver, as shown in Fig. 2. The possibility of using numerical methods to model these parts will be firstly analyzed.

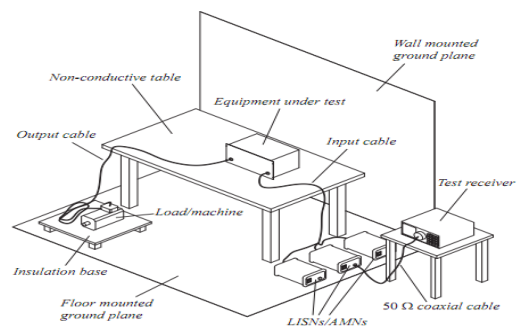


Fig. 1. EMI measurement setup according to standards [7]

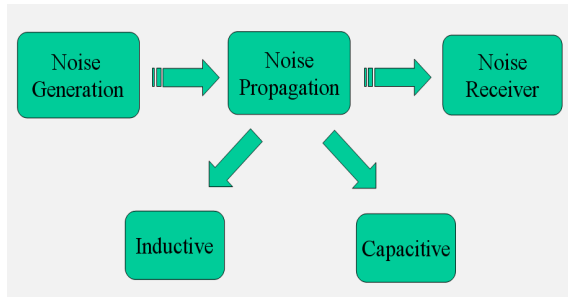


Fig. 2. EMI mechanism

For the noise generation, it is well known that the EMI noise in power converters are related to the high  $di/dt$  and high  $dv/dt$  rate resulting from the switching of semiconductor devices. There are some studies provided by other authors state that the modeling of noise source have great impact on EMI prediction and argue that some common models are not sufficient for EMI modeling, due to, for example, the simplification of nonlinear slope to one single slope rate [8]. However, in the Spice environment used in this paper, except for some self designed model, the Spice models provided by vendors are still the most trustful model to be used. And therefore, these Spice models will be used in the simulation in this paper to represent the noise generation.

Unlike the noise generation, in the part of noise propagation, numerical methods are applied. Depending on the specified model subject, different numerical methods will be adopted. The essential parts in noise propagation include power passive elements, parasitics on semiconductor and parasitics existing on the printed circuit board (PCB).

For the modeling of power passive elements, such as the capacitors and inductors, in the former papers, they will be either measured and an equivalent circuit is constructed with curve fitting or based on some simplified equivalent circuits which could not deliver impedance characteristic with sufficient accuracy up to 30 MHz. In order to achieve a purely simulation-based prediction, the frequency response of the power passive components will be predicted by numerical methods.

To predict the frequency response of inductors, finite element method is used [9]. Distributed parameter models for single-layer inductor as well as multi-layer inductor are constructed, as shown in Fig. 3.

For the frequency response of capacitors, due to the fact that they are normally purchased from manufacturer, rather than built by the power converter designer and also the inherent chemical process inside some types of capacitors is difficult to be modeled, they will be analyzed and modeled in an empirical way. Equivalent circuit is used with parameter in the circuit to be estimated by equations or simplified numerical simulation.

As already investigated by other authors, partial element equivalent circuit (PEEC) can be used for the modeling of parasitics of PCB strips, including parasitic inductance and capacitance. A part of the PCB and its corresponding PEEC model are shown in Fig. 4.

Besides the parasitics due to PCB strips, inside a power converter, because of the existence of inductor, the magnetic coupling between inductor leakage flux and other parts should be also considered. This modeling is also achieved by using PEEC method. The model with consideration of inductor effect is shown in Fig. 5.

One of the most important parasitics in the propagation path of noise is the parasitic capacitance between semiconductor and the heat sink, which is caused by the thermal conduction layer in between. This parasitic capacitance is responsible for the propagation of common mode noise. To model this parasitic effect or extract the capacitance value, numerical method is used. By opening the package of the semiconductor, the inner structure is well observed. The inner structure of an example diode is analyzed and it can be modeled with a structure which consists 3 layers. The inner structure is modeled in simulation program and the values of relevant capacitances are obtained.

Noise receiver has decisive impact on how the conducted EMI is displayed. From the measurement setup in Fig. 1 it can be seen that an equipment called LISN is used. LISN is defined by EMI standards, to provide constant grid impedance for different frequencies and avoid the disturbance of the noise from grid side. It guarantees the repeatability of the EMI measurement. In the considered range of the paper, which is conducted emission in the frequency range from 9 kHz to 30 MHz, an equivalent circuit [11] provided by CISPR standard is used.

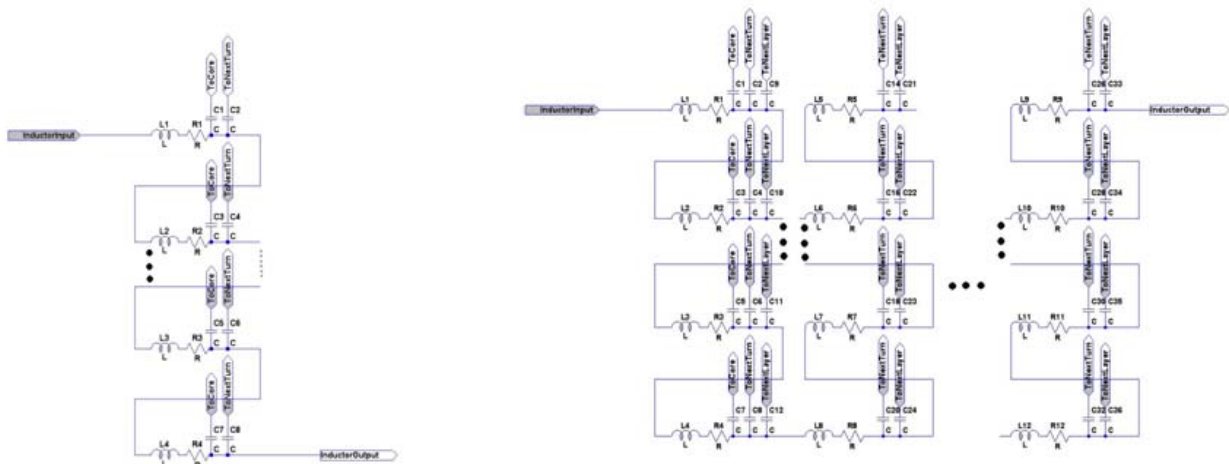


Fig.3. Model to predict the frequency response of single-layer inductor (left) and multi-layer inductor (right) [9]

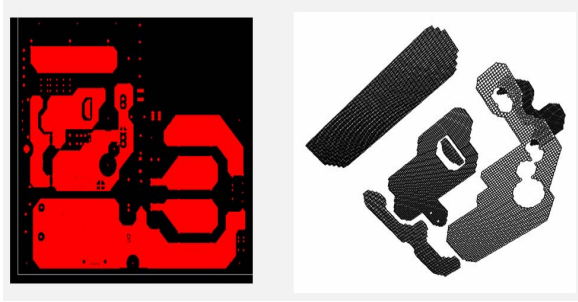


Fig.4 PCB (left) and part of its PEEC model (right)



Fig.5 Complete model with inductor's effect

After the noise is sensed at the LISN, it is processed through detector. Different kinds of detectors are available in EMI measurement, including average detector, peak detector and quasi-peak (QP) detector. As result of the history of EMI measurement, quasi-peak detector is of great importance and it will be considered in this paper together with the peak detector. With the signal process of a quasi-peak detector [12], by analyzing the detection procedure, its algorithm is implemented in Matlab to emulate the effect of detector. Since according the standards there are two frequency ranges, range 1 from 9 kHz to 150 kHz and range 2 from 150 kHz to 30 MHz. The IF filters has been defined for the ranges separately, which have bandwidth 200 Hz for range 1 and 9 kHz for range 2. Simplified presentation of peak detector has such form as (1) and can be used to evaluate the effect of detector. Here indices IF and BW stand for intermediate frequency and bandwidth.

$$Noise_{Peak} = \sum_{IF-BW}^{IF+BW} Noise(f) \quad (1)$$

### III. SIMULATION RESULTS AND MEASUREMENT VALIDATION

The circuit of simulated object is shown in Fig. 6 and its spice model is shown in Fig. 7.

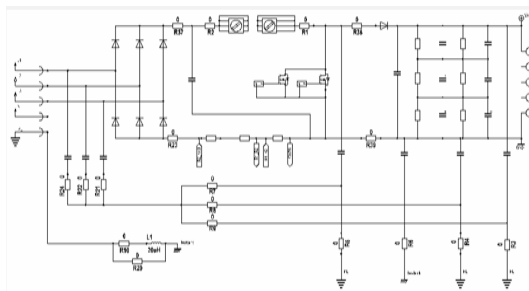


Fig. 6 Schematic of modeling object

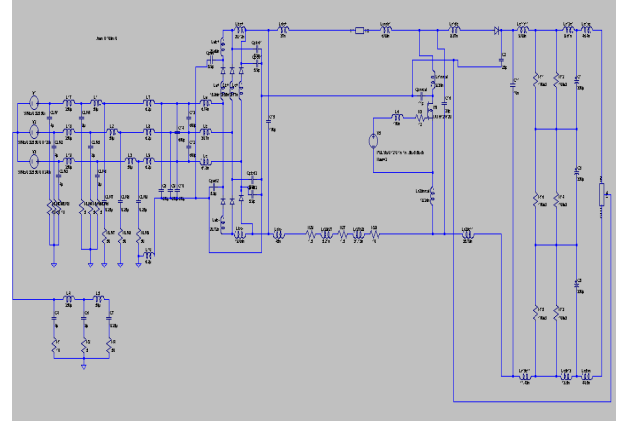


Fig.7 Simulation model of the whole circuit in SPICE

In order to verify the simulation approach, a prototype has been built, which is shown in Fig. 8. The prototype is built up according to the circuit shown in Fig.6 and fast recovery diodes are used. In order to be able to change the switching frequency, a wireless receiver is built onboard and can be controlled by laptop to drive the MOSFET at certain frequency. Besides, it is also built with the possibility to change the gate resistance which has important impact on the switching behavior of MOSFET. At the end, it should also be noted that the gate drive circuit is powered by a transformer connected to the same power supply of the power circuit. The transformer works to transform the line voltage to 12 V for the gate driver.

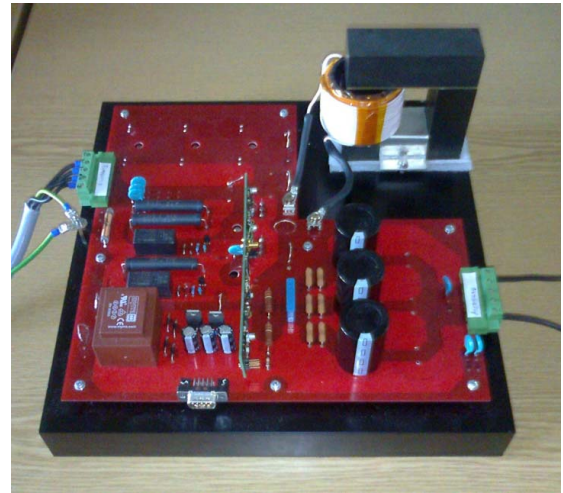


Fig. 8 Prototype for verification

With the model described above, the EMI performance of the power converter is simulated. Firstly, the three-phase rectifier part is simulated. The EMI in rectifier is mainly resulted from the reverse recovery effect of diodes. Due to time limit, instead of QP measurement, peak detector is selected in the test receiver to verify the modeling methods. The simulated peak EMI spectrum of 3-phase rectifier is shown in Fig. 9 in comparison with the measurement results. Note that the figure of simulated spectrum only shows noise higher than 0 dB.



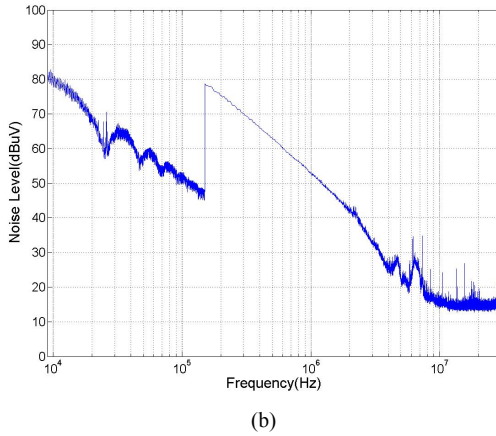
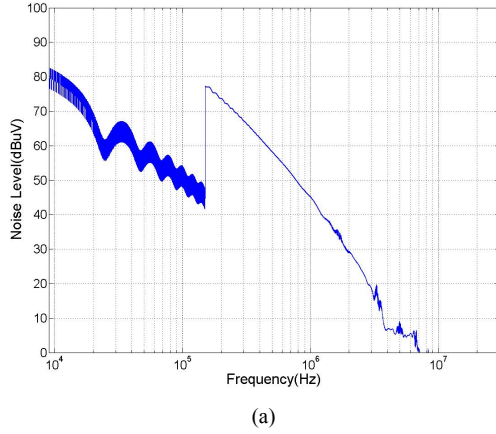


Fig. 9 Simulation (a) and measurement (b) results of 3-phase diode rectifier

As seen from the comparison for diode rectifier, in the low frequency range of 9 kHz to 150 MHz, the simulation result matches quit well the measurement result and it implicates a well-chosen simulation routine. In the middle frequency range, which is from 150 kHz to 5 MHz, the deviation between the simulation and measurement result is observable. The reason for that is the lack of ability of vendor-provided diode model to reproduce the reverse recovery effect. A reverse recovery test circuit has been built up in simulation. The test condition is 4 A forward current and current decrease slop rate of 50 A/ $\mu$ s. Compared with the peak reverse current of 5 A as indicated in datasheet, the simulated current has only peak reverse current of 1.2 A. Obviously, the insufficiency of the model can be understood. Thereby, a new diode model based on the analysis in [10] has been built. The diode model is shown in Fig. 10. With such diode model improved prediction result can be obtained as shown in Fig. 11 thanks to the better reproduced reverse recovery effect. In the high frequency range, which is from 5 MHz to 30 MHz, in measurement the noise is clamped at around 20 dB $\mu$ V but in simulation the noise level continues to decrease. Reason for that has been found out to be the test receiver. The test receiver has its eigen-noise and with the presence of cable, this noise is amplified. Measured spectrum with test receiver and cable, without energizing is shown in Fig.12 and compared that with the spectrum of noise from rectifier test, one can clearly see that they are almost the same in the concerned frequency range. This effect,

however, is difficult to be included in simulation.

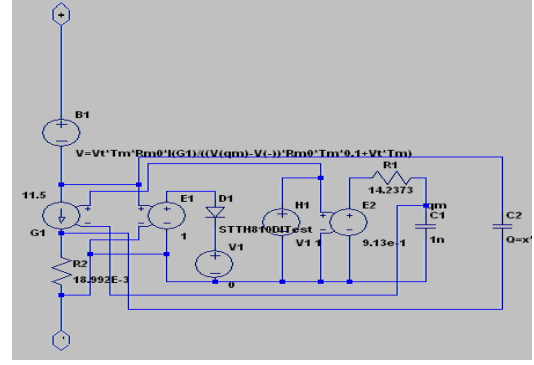


Fig. 10 New diode model with improved reverse recovery effect

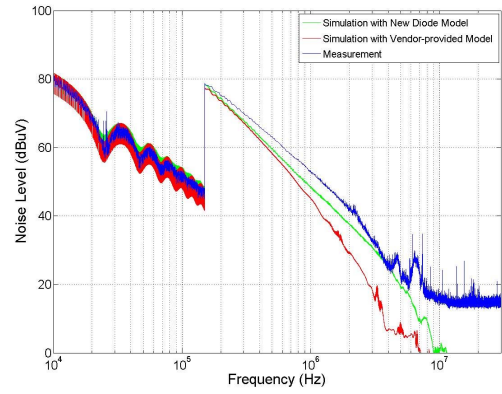


Fig. 11 Simulation and measurement results of 3-phase diode rectifier (green: with new diode model; red: with vendor-provided diode model; blue: measurement)

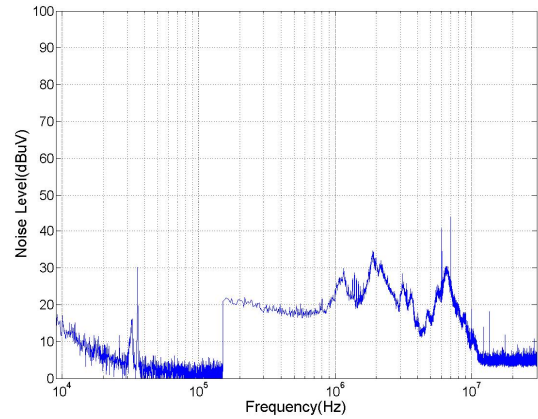
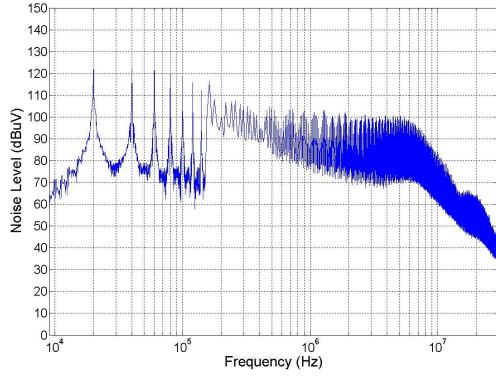
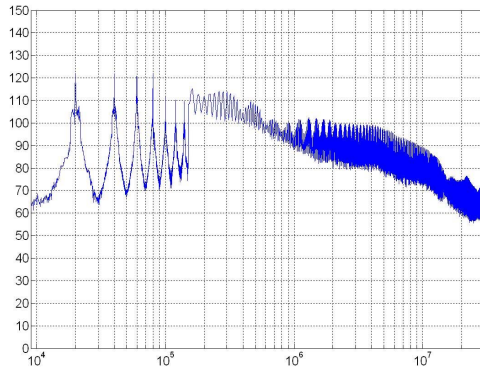


Fig. 12 Measured noise spectrum with only test receiver and cable

Afterwards, the more complex circuit is simulated, which is the whole circuit as shown in Fig. 6. The same as for the rectifier, the peak value of the noise is measured and compared with the simulation results as shown in Fig. 13.



(a)

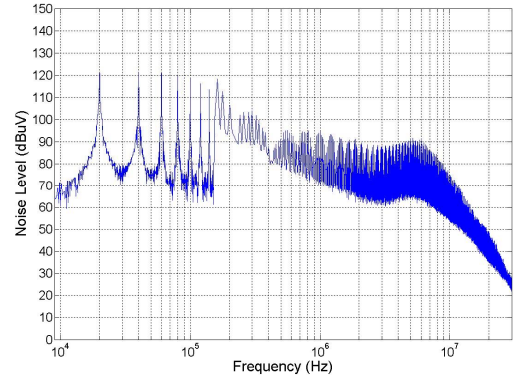


(b)

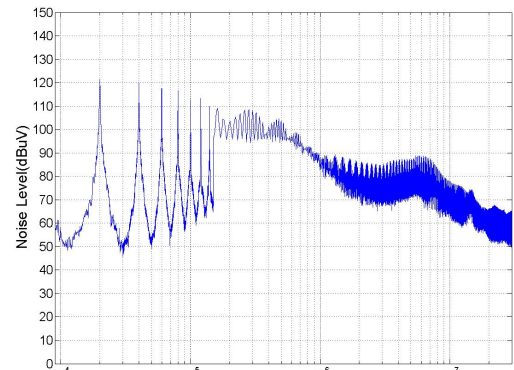
Fig. 13 Simulation (a) and measurement (b) total noise of 3-phase diode front-end boost converter

The measurement result of whole circuit has then also validated the modeling method and the results are in good agreement in frequency range from 9 kHz to 10 MHz. In this range, not only the tendency of change of the conducted EMI is well predicted, but also the noise levels are well predicted with a deviation of smaller than 5 dB $\mu$ V. In frequency range higher than 10 MHz, the deviation of predicted level from measured level increases. Reason for this increased error is that, in the simulation model, the effect of cable which locates between LISN and power converter, is not fully taken into account and as associated problem with SPICE MOSFET model, the transient state is modeled with constant slop rate which brings some errors [8]. Effort has been made to improve this deviation by implementing more accurate cable model. However, to include such accurate cable model in time domain simulation can easily lead to unacceptable long simulation time and the program out of memory.

In order to illustrate the accuracy of propagation path modeling, which is the main aspect of this paper, the DM noise generated by the researched object is also compared with simulation result. The DM noise is simply obtained by disconnected the earth line from test object. The comparison is shown in Fig. 14. Again, the measured DM noise shows similar envelope as the simulated one until 10 MHz, especially at the resonance point which validates the used modeling methods.



(a)



(b)

Fig. 14 Simulation (a) and measurement (b) DM noise of 3-phase diode front-end boost converter

## VI. CONCLUSION

In this paper, a complete modeling procedure based on numerical method is introduced for the prediction of conducted EMI in power converters. The modeling approaches for different parts according to the EMI mechanism are analyzed separately. With the information gathered from numerical methods, a spice-compatible model is built which enables the carry out of time domain simulation. Simulation results are then presented. To verify the prediction approach, prototype has been built and comparison between simulation and measurement is provided. Based on the comparison, the potential to use numerical method for EMI prediction is explored. It is shown that the numerical methods used in the paper is verified to be able to accurately model the propagation path of conducted EMI while due to the lack of accuracy of the device SPICE model, especially the diode model, the noise source is not well represented and thus the resulting noise level is influenced. Subsequently new model of the diode is built, which is proved to be able to deliver better prediction results. As mentioned above, an accurate model of the cable is also interesting for the study as long as the simulation time will not increase enormously with the presence of cable model. Another concern of the study is that the simulation time of a time domain simulation, which in this case is several hours, is still somehow too long for an optimization process. Because of this concern, approach of frequency domain

simulation with the information from numerical methods will be investigated. At the end, the numerical methods in this paper can also be applied for the design of optimal filter and test will also be carried out in the future.

#### ACKNOWLEDGEMENT

The authors would like to thank Siemens Corporate Technology for the financial and experimental support.

#### REFERENCES

- [1] Q.Liu, F.Wang, D.Boroyevich, "Conducted-EMI Prediction for AC Converter Systems Using an Equivalent Modular-Terminal-Behavioral (MTB) Source Model", *IEEE Trans. on Industry Applications*, vol.43, iss.5, 2007, pp. 1360-1370.
- [2] A.C. Baisden, D.Boroyevich, F.Wang, "Generalized Terminal Modeling of Electromagnetic Interference", *IEEE Trans. on Industry Applications*, vol.46, iss.5, 2010, pp. 2068-2079.
- [3] M.Foissac, J.-L.Schanen, C.Vollaire, "Black box" EMC Model for Power Electronics Converter", *IEEE Energy Conversion Congress and Exposition-ECCE 2009*, San Jose, CA, USA, 20-24th Sept. 2009, pp. 3069-3615.
- [4] L.Ran, S.Gokani, J.Clare, K.Bradley, C.Christopoulos, "Conducted Electromagnetic Emissions in Induction Motor Drive Systems Part II: Frequency Domain Models", *IEEE Trans. on Power Electronics*, vol.13, no.4, 1998, pp. 768-776.
- [5] J.Lai, X.Huang, E.Pepa, S.Chen, T.W. Nehl, "Inverter EMI Modeling and Simulation Methodologies", *IEEE Trans. on Industrial Electronics*, vol.53, no.3, 2006, pp. 736-744.
- [6] W.Teulings, J.L.Schanen, J.Roudet, "A New Technique for Spectral Analysis of Conducted Noise of a SMPS including Interconnects", *IEEE Power Electronics Specialist Conference-PESC'97*, St.Louis, Missouri, USA, 22-27th Jun. 1997, pp. 1516-1521.
- [7] M.L.Heldwein, "EMC Filtering of Three-Phase PWM Converters", *Ph.D Dissertation, ETH Zurich*, 2008.
- [8] J.Meng, W.Ma, "Power Converter EMI Analysis Including IGBT Nonlinear Switching Transient Model", *IEEE Transaction on Industrial Electronics*, vol.53, iss.5, 2006, pp. 1577-1583.
- [9] J.Wei, D.Gerling, "Simulation and Modeling of Power Passive Components for EMI Prediction", *IET Power Electronics, Machines and Drives Conf. PEMD 2012*, Bristol, UK, 27-29th Mar. 2012.
- [10] C.L.Ma, P.O.Lauritzen, "A simple power diode model with forward and reverse recovery", *IEEE Trans. on Power Electronics*, vol. 8, no. 4, 1993, 2007, pp. 342-346.
- [11] *International Standards, CISPR 16*, "Specification for radio disturbance and immunity measuring apparatus and methods", 2007.
- [12] *Application Note 150, Agilent Technologies*, "Spectrum Analysis Basics".