LAPPEENRANTA
UNIVERSITY OF TECHNOLOGY

Faculty of Technology

Industrial Electronics

*Sultan Jumayev*

# Wind-power converter grid-side harmonics investigation

Examiners: Professor *Olli Pyrhönen*
Lappeenranta University of Technology
Finland

Professor *Pertti Silventoinen*
Lappeenranta University of Technology
Finland

Supervisor: Doctor of Science *Valentin Dzhankhotov*
The Switch
Finland

# ABSTRACT

Lappeenranta University of Technology
Faculty of Technology
Industrial Electronics

*Sultan Jumayev*

**Wind-power converter grid-side harmonics investigation**

Master's Thesis

2011

71 pages, 57 figures, 17 tables

Examiners: Professor *Olli Pyrhönen*
Professor *Pertti Silventoinen*

**Keywords**: wind-power drives, transformer model, grid side converter modeling, grid side filter modeling.

Frequency converters in wind-power applications allow more effective utilization of the wind energy. The PWM inverters with the filters are used in order to supply the power grid with the power of required quality.

The output low voltage produced by the wind power converter is converted into the medium voltage by the power transformers. Transformer, LC-filter and load together affect the quality produced by the power converter.

The proposed work considers how the leakage impedances affect the quality of the output power. Special attention is paid to the power transformer.

# Contents

# 1 Introduction

## 1.1. General observations on wind power

The wind energy is almost 3000 years used as an energy source. For a long time, it was needed in windmills and water pumping stations. In the end of the $19^{th}$ century, the wind energy was used to produce electricity for the first time. The pioneers in this field were USA and Denmark.

The production of the electricity using the wind turbines in the end of $20^{th}$ century in Europe increased more than 30% every 5 years (Burton et al. 2001 ). By growing the wind energy is the fastest renewable energy source in the world. At the end of 2009 the global wind energy power increased from 120 188 MW in 2008 (WWEA 2009) to 159 213 MW (WWEA 2010). It is reported in March 2011 that wind energy became the main electricity source in Spain (they provided 21% of the whole amount of electricity in this country).

A wind turbine is an apparatus that uses the kinetic energy of wind to produce electricity. Wind blows through the blades of the wind turbine and creates the running torque. The kinetic power of the wind can be determined by the next equation:

$$P_w = \frac{\rho}{2} A v^3, \tag{1.1}$$

Where $\rho$ is the specific air mass, which depends on the air pressure and air moisture (for practical calculations it may be assumed $\rho \approx 1.2 kg/m^3$), $A$ is an area of the wind turbine blades and $\upsilon$ is the velocity of the wind. It is important to notice that the kinetic power of the wind turbine changes by the cubic of the velocity of wind (Stiebler 2008).

In order to provide required quality of the output energy of the wind turbines, power electronic devices are usually used for electricity conversion between wind generator and grid. The concept of electrical part of wind generators depends on the rotating speed and can be classified as fixed speed, limited variable speed and variable speed.

The share of wind energy in electricity production is growing rapidly. That is why it is important to make grid-friendly interface between the grid and wind turbine to keep the required quality of the electricity for the grid (Svensson 1998).

*Fully Rated Converter (FRC) Wind Turbine*

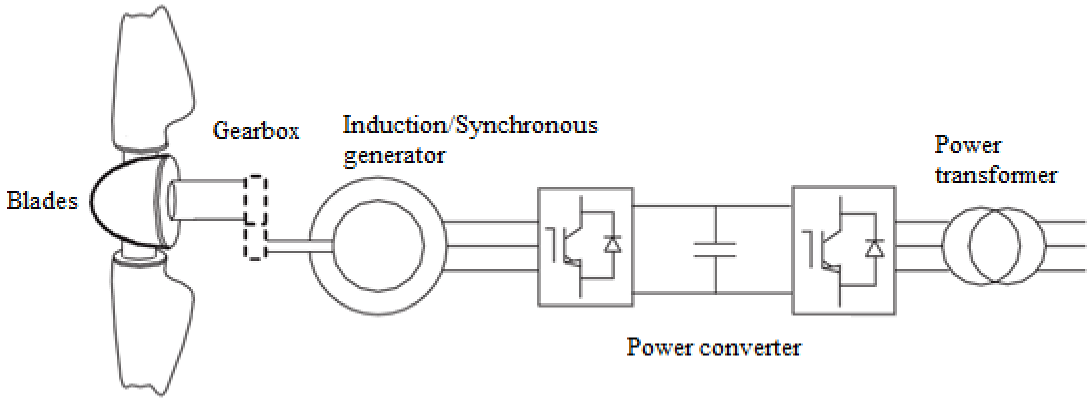


Figure 1.1. The scheme of variable-speed FRC wind turbine (Anaya-Lara et al. 2009)

In fully rated converter wind turbines, the induction or synchronous (mainly with permanent magnets on the rotor) generators are used. All electrical power of the wind turbine flows through the power converter. In this case, the electrical generator is fully isolated from the electrical grid. Using the power converter the speed of the generator can vary from zero to maximum possible speed. In case of induction generator a gearbox is needed, because of the low angular speed. The permanent magnet synchronous generators that are used in wind turbines have big number of pole pairs and necessity of the gearbox disappears.

Diode bridge or controllable IGBT rectifier can be used. In order to smooth DC voltage ripples at rectifier output (also referred as “DC-link”), a large capacitor is used. Smoothed DC voltage is applied to the inverter, which usually based on IGBT transistors, controlled with by means of pulse-width modulation method (PWM). Controlling the PWM inverter, we can control the reactive power of the output power (Anaya-Lara et al. 2009). Let us next consider the fully rated converters.

## 1.2. Wind power converter consideration

With increasing number of wind turbines, there are some problems related to the quality of the electrical energy supplied to the grid. Nowadays, almost all the wind turbines are equipped with the power electronics for electrical power conversion. The power electronic devices control the output reactive and active powers, output voltage and other parameters.

The power electronic equipment of the variable-speed FRC wind turbine plays a very important role, since all the electrical energy produced by generator passes through the power converter (Anaya-Lara et al. 2009).

The most world spread converter is the voltage source inverter (VSI). There are mainly two types of VSI: two level and three level power converters. The main difference between the two level and three level converters is the number of potentials in the output voltage. In two level inverters, the output voltage varies between the negative and positive half of the DC voltage value. In three level inverters, the third potential is zero value of the voltage. In wind turbine applications, two level converters are used. Converter consists of generator inverter, DC link (filter) and grid inverter.

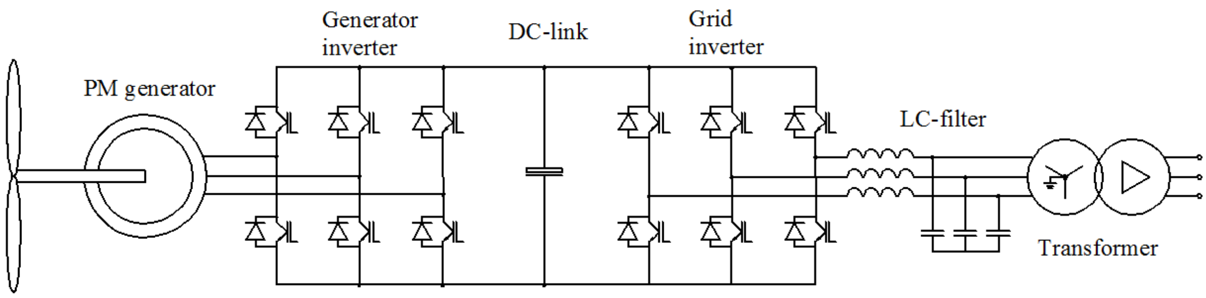


Figure 1.2 Electrical part of variable-speed wind turbine

Probable solution of electrical part of the variable-speed wind turbine is show in Figure 1.2. In this case, the permanent magnet synchronous generator (PMSG) is used (Svensson 1998). The converter consists of generator and grid inverters.

## 1.4. Problem formulation

Wind turbines include fast switching converters equipped with LC filters to transform the generated energy into the form suitable for the grid.

The PWM inverter output voltage contains high frequency components, which are multiples of the switching frequency of the inverter. Before reaching the power grid, these harmonics are filtered by a filter and a power transformer. Real filter and transformer models, however, contain the stray components, which worsen the filtering.

To make a model of the wind power converter, we need to investigate existent models of its components suitable for the frequency range up to 10 kHz (which is a minimum required to satisfy the standards).

The high frequency harmonics can also come from the electrical grid. This work is done cooperating with The Switch Drive Systems Oy, who is the globally known manufacturer of the high power drive trains for the wind-power turbines.

# 2 Model of wind power converter

## 2.1 Simulation environment consideration

The main simulation instrument, which is used in this work, was Matlab Simulink. Simulink, is commercial tool for modeling, simulating and analyzing dynamic systems developed by "MathWorks" Company. For modeling electrical tools in Simulink there is SimPowerSystems tool. With this tool, we can simulate the generation, transmission, distribution and consumption of electrical power. This tool provides to simulate almost all kind of electrical devices. There are models of many components, which can be needed in modeling the complex electrical systems. The results can be shown as a graphics of the measured signals. The analysis of the given result can be easily made by the simple graphic user interface. It is easy to make the harmonic analysis, e.g. calculate the Total Harmonic Distortion (THD) (Dugan et al. 2003).

All models of the SimPowerSystems library are based on the equations of the electrical apparatus proven in the textbooks, and their validity. The components in model are connected by physical connection that is ideal conduction path for electrical power. From the collected model, which looks like schematics, SimPowerSystems automatically constructs the differential algebraic equations that describe the behavior of the system (Dugan et al. 2003).

## 2.2 Structure and description of the model

The main task of the mathematical simulations is the simulation of the situations, which can happen in the real system during the operation. Sometimes to modulate a situation in real power equipment is impossible because of absence or complicacy of the power equipment. For which reason, the mathematical model helps to understand the behavior of the whole system.

In chapter 1.2, we described the structure of the electrical part of a wind turbine. To make a mathematical model of the whole system (wind turbine which is supplying the power grid) we need to consider the structure and models of each part of the wind turbine. First, we have to decide, what structure of the model, we choose and why. Second step is the consideration of the model parameters in the wind turbine structure.

The main aim of the work is defining harmonics in the grid side of the wind turbine. That is why, in our model we have to pay attention to the harmonics, which are coming from the PWM converter. That is why the modeling of the converter should not go beyond the modeling of the grid-side inverter supplied by DC voltage source; generator-side inverter can be neglected. LC-filter after the PWM grid-side inverter should be included in the model as well. Low voltage winding of the low-to-medium voltage transformer affects the converter performance as well; therefore transformer should also be included into the model. Finally, grid affects the converter performance via transformer. The low voltage winding of the transformer are usually connected is “star”; medium voltage winding is connected in “delta”. The model of the grid is a voltage source with an impedance. In further considerations we are neglecting the grid voltage distortions, assuming it is purely sinusoidal. Thus, investigated model structure suitable for PWM converter harmonics investigation is presented Figure 2.1.

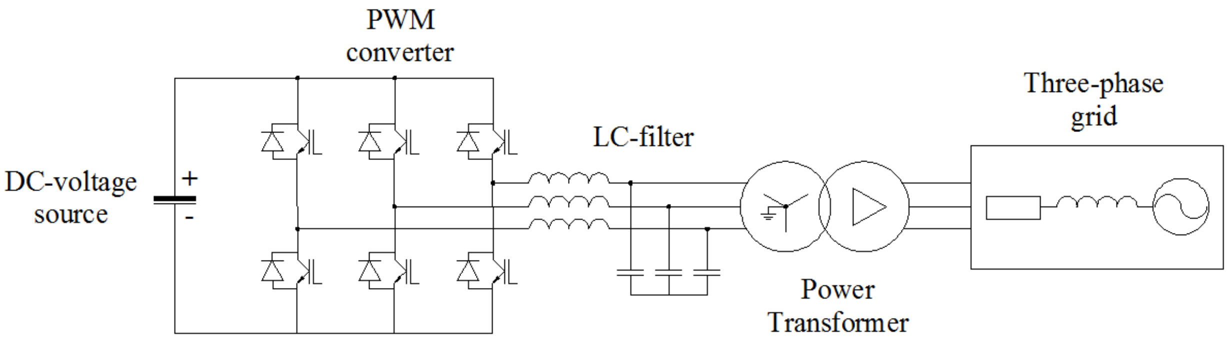


Figure 2.1 The structure of the wind power converter model

## 2.3 Model of the PWM inverter

The power part of PWM inverter has six IGB transistors with antiparallel diodes which provides a free-whiling path for the transient currents. These IGBTs are controlled by the low voltage pulse width modulator which controls the IGBTs by the pulses in accordance with the control algorithm. The IGBT is “on” when there is the positive voltage on the gate of the transistor and IGBT is “off” when there is zero or negative voltage. For simplification of the PWM computation, we use “sine-triangle comparison” PWM method, which is enough for harmonics considerations. In practice, however, the space vector PWM is used.

The PWM inverter model in MATLAB is presented in Figure 2.2.

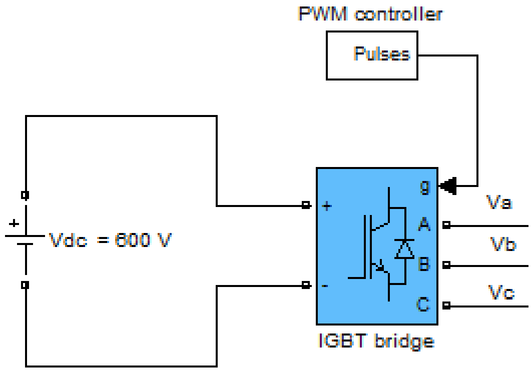


Figure 2.2 The model of PWM inverter in Matlab

The outputs of the PWM inverter are phase voltages that are shown in Figure 2.3.

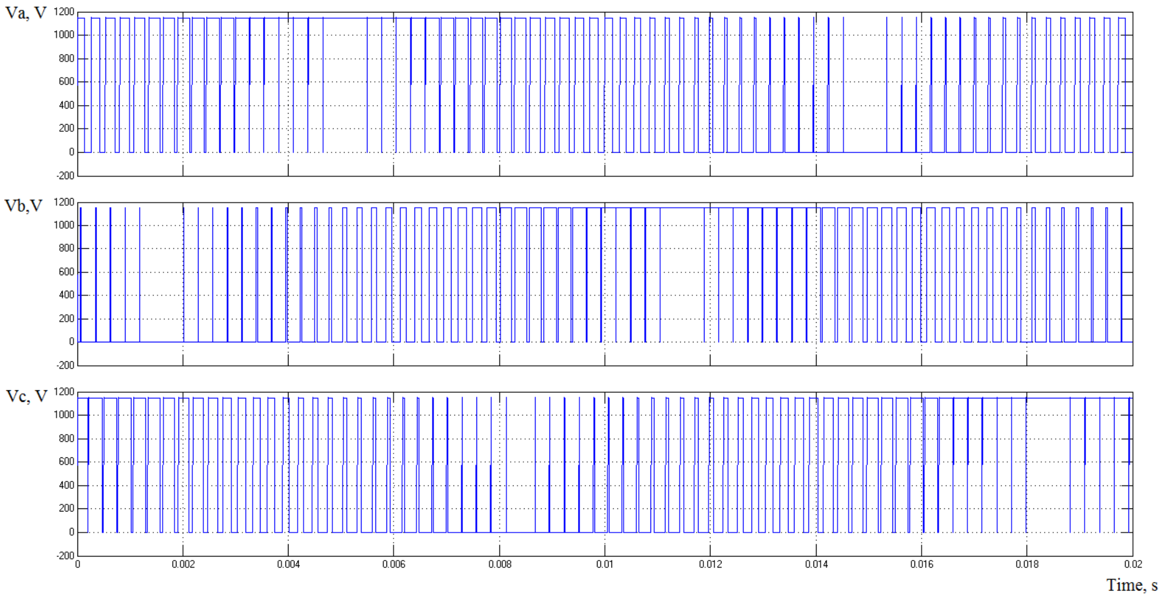


Figure 2.3 Output phase voltages of PWM inverter

The switching frequency is typically 3.5 kHz and the base frequency, (which is also called “the fundamental frequency”) is selected equal to 50Hz, assuming that investigated wind power converter is designed for usage in Europe. The sine wave voltages of PWM inverter are line-to-line voltages as shown in Figure 2.4.

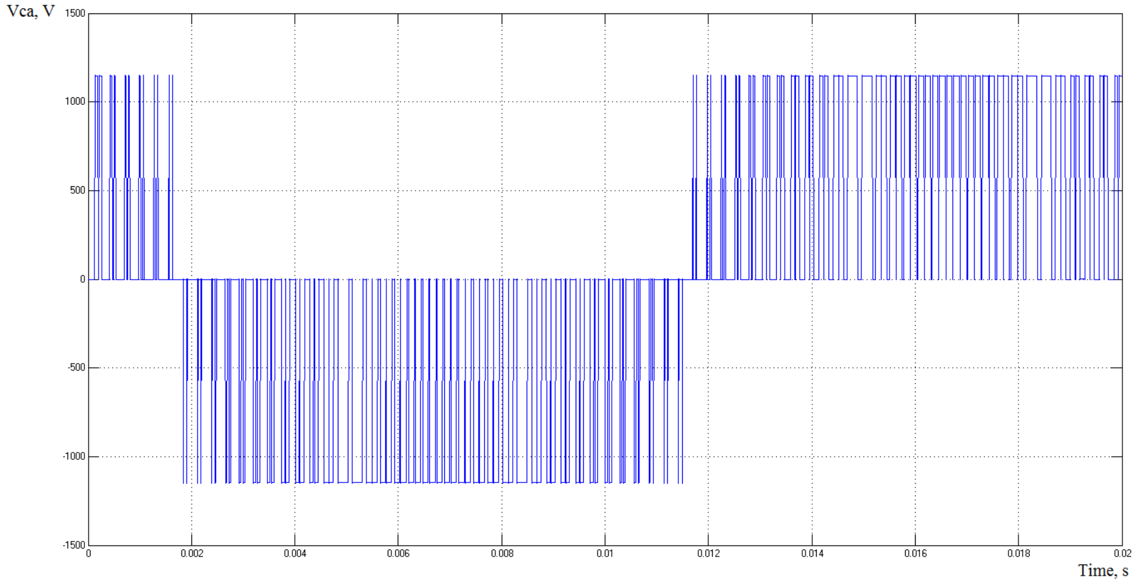


Figure 2.4 The line-to-line voltage in PWM inverter

The simulated fundamental frequency harmonic voltage of the line-to-line voltage shown in Figure 2.4 is 706 V (RMS). The harmonic content is shown in Figure 2.5.

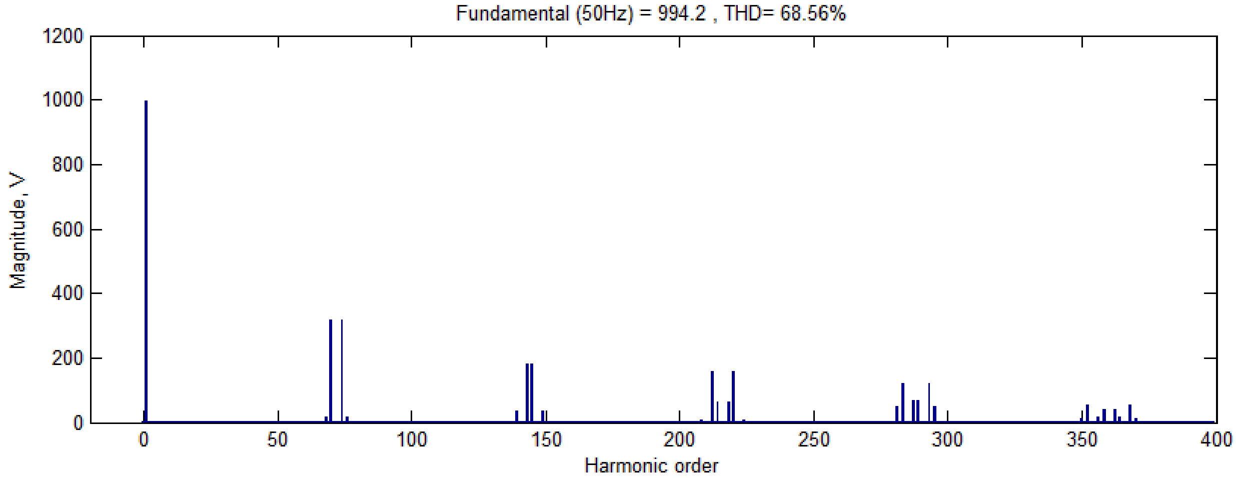


Figure 2.5 FFT analysis of line-to-line voltage of PWM inverter

Thus, the computer model of PWM inverter is in accordance with the power electronics theory.

## 2.4 LC-filter model

The model of ideal LC-filter in Simulink is shown in Figure 2.6. There are only inductive and capacitive elements in the model.

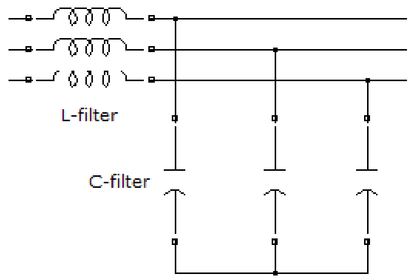


Figure 2.6. Model of LC-filter in Simulink

The model presented in Figure 2.6 is suitable for low-frequency investigations. It is shown in Figure 2.5 that actual PWM converter spectrum contains high-frequency components. Therefore LC-filter leakages should be taken into account. In accordance with passive components theory, inductor model contains a leakage resistance connected in series with the inductance and a leakage capacitor connected in parallel with the inductance (Fig. 2.7.a). Thus, the impedance of an ideal inductor tends to infinity while frequency increasing. However, high-frequency impedance of a real inductor dramatically falls down to the very small values because of the stray capacitance, i.e. stray capacitance neutralizes the damping properties of the real inductor at high frequencies. Therefore, the part of the high frequency noise created by PWM can easily penetrate via the real inductor to the grid.

The real capacitor can be modeled as a capacitance in series with an ideal inductance and in series with an ideal resistance (Fig. 2.7.b). The ideal capacitor impedance is infinite at DC and decreases as the applied voltage increases the frequency. The leakage inductance, however, prevent the noise penetration via the capacitance at high frequencies.

Thus, the leakage components presented in the LC filter worsen the high-frequency attenuation of the PWM harmonics.

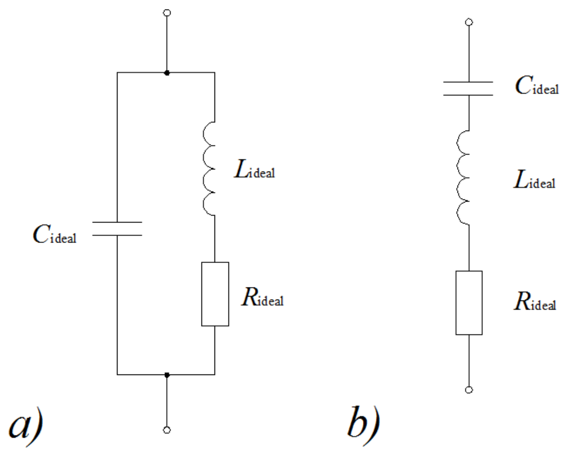


Figure 2.7. a) Model of a real inductor b) model of a real capacitor

On the other hand, modern grid standards require good attenuation in the frequency range up to 9 kHz. That is why our investigations are mainly done for frequencies up to 10 kHz. In this range a real LC filter can be considered as an ideal LC filter.

## 2.5 Model of the transformer

Let us first consider the ideal model of a transformer, which is shown in Fig. 2.8 (Wong 2004). The ideal transformer has no leakage losses. Hence, the efficiency of the transformer is equal to 1. The ideal transformer has only mutual inductances and the coupling coefficient of the transformer is equal to 1:

$$k = \frac{L_{12}}{\sqrt{L_{s1}L_{s2}}} = 1 \tag{2.1}$$

where, $L_{12}$ is mutual inductance between primary and secondary coils, $L_{s1}$ is primary coil inductance and $L_{s2}$ is secondary coil inductance.

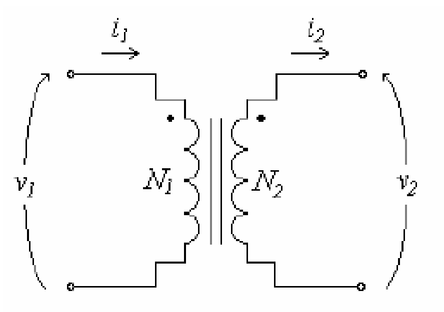


Figure 2.8 Electrical model of an ideal transformer (Wong 2004)

Although, the energy dissipation in real transformers is quite small, in practical models we need to take it into account leakage inductances and resistances, describing losses in windings and in a magnetic core (Wong 2004).

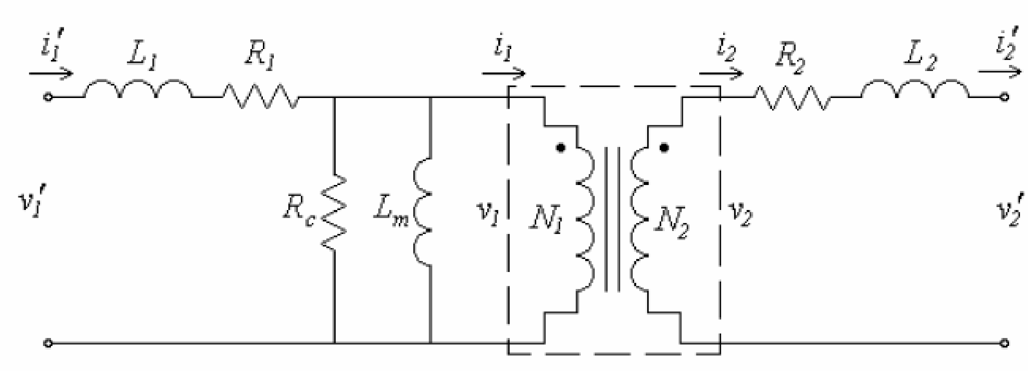


Figure 2.9. Electrical model of a real transformer (Wong 2004)

Fig. 2.9 shows the model of a the transformer with leakages. Model includes the leakage inductance of primary coil $L_1$, the leakage inductance of secondary coil $L_2$, equivalent resistance describing the core losses $R_c$, equivalent magnetizing inductance $L_m$, the resistance of the primary winding $R_1$ and the secondary winding resistance $R_2$. Taking these leakages into account, the input and output voltages can be rewritten as follows:

$$U'_1 = L_{s1}\frac{di'_1}{dt} - L_{12}\frac{di'_2}{dt} \quad (2.2)$$

$$U'_2 = L_{12}\frac{di'_1}{dt} - L_{s2}\frac{di'_2}{dt} \quad (2.3)$$

where, $L_{s1}$ and $L_{s2}$ are the self-inductances of the primary and secondary windings and $L_{12}$ is the mutual inductance between the windings. In that case, in accordance with equation (2.1), the coupling coefficient is less than 1, since there are leakage inductances lowering the mutual inductance (Wong 2004).

In wind turbine transformer is connected between the converter and grid and high-frequency harmonics pass via transformer. These high frequency harmonics can be up to MHz range or even higher. That is why low-frequency models of transformers, such as presented in Fig. 2.9, are not suitable for modern PWM applications, because high frequency harmonics will partly use stray components to leak. These components can contribute to EMC problems. Fig. 2.10 shows the model which takes into account stray capacitances inside the transformer.

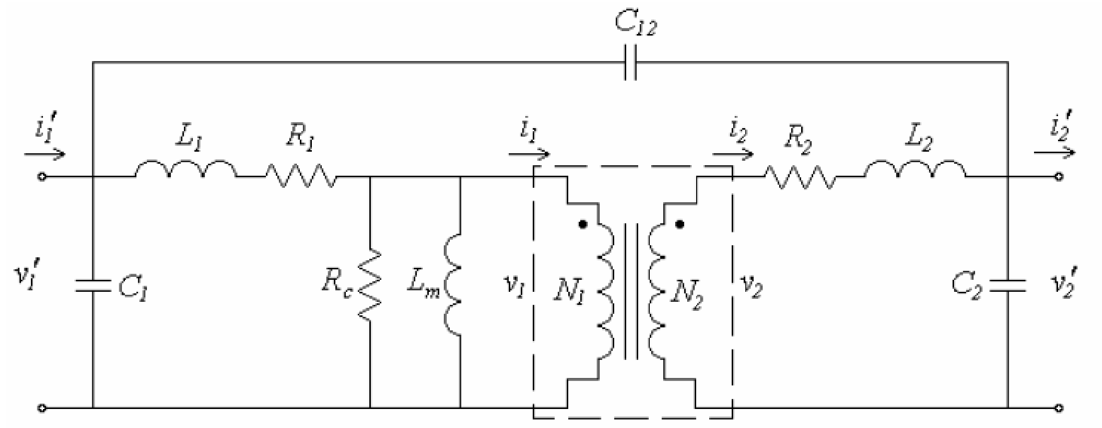


Figure 2.10 equivalent circuit of a broadband transformer (Wong 2004)

In Fig. 2.10, $C_1$ is the stray capacitance between the turns of the primary winding, $C_2$ is the stray capacitance between winding turns of the secondary winding and $C_{12}$ is the interwinding stray capacitance. This broadband model of the power transformer is suitable in the range of the frequency up to 20 000 Hz (Wong 2004).

# Conclusion

The converter is the source of the essential high-frequency harmonics, which are contained in the PWM signal. However, harmonic levels suitable for the grids are limited, for instance, in IEEE standard 519-1992. Therefore, filtering systems should be installed at the output of the frequency converter in order to decrease the PWM sequence harmonics.

An analysis presented in this work shows that filtering system and transformer cannot be represented by the conventional low frequency models. Stray impedances worsen the attenuation and resonate with the useful components of the system.

The transformer and filter components should be carefully selected and tested at filter design and prototyping. Special attention should be paid to harmonic measurements at converter prototyping.

# References

Anaya-Lara, O., Jenkins, N., Ekanayake, J., Cartwright, P., Hughes, M. 2009. Wind energy generation modelling and control. Chichester: John Wiley & Sons, Ltd.

Bose, B. K. 2002. Modern Power Electronics and AC Drives. Upper Saddle River: Prentice Hall PTR.

Burton, T., Sharpe, D., Jenkins, N., Bossaniy, E. 2001. Wind Energy Handbook. Chichester: John Wiley & Sons, Ltd.

Chimklai, S. 1995. High-Frequency Transformer Model for Switching Transient Studies. Doctoral dissertation. The University of British Columbia: Department of Electrical Engineering.

Dorf, R. C. 2003. The Circuits and Filters Handbook. Second Edition. Boca Raton: CRC Press LLC.

Dugan, R. C., McGranaghan, M. F., Santoso, S., Beaty, H. W. 2003. Electrical Power Systems Quality. Second Edition. The McGraw-Hill Companies.

Holmes, D. G. 1995. The Significance of Zero Space Vector Placement for Carrier Based PWM Schemes. Clayton: Monash University.

Li, H., Chen, Z. 2007. Overview of different wind generator systems and their comparisons. Denmark: Aalborg University. ISSN 1752-1416

Song, H., Nam, K. 1999. Dual Current Control Scheme for PWM Converter Under Unbalanced Input Voltage Conditions. Dept. of Electr. Eng., Pohang Inst. of Sci. & Technol.

Stiebler, M. 2008. Wind Energy Systems for Electric Power Generation. Berlin: Springer.

Storr, W. [webmaster@electronics-tutorials.ws] http://www.electronics-tutorials.ws/filter/filter_2.html. 1999

Svensson, J. 1998. Grid-Connected Voltage Source Converter – Controll Principels and Wind Energy Applications. Doctoral dissertation. Chalmers University of Technology: Department of Electric Power Engineering.

The Institute of Electrical and Electronics Engineers. 1998. IEEE Recommended Practice for Industrial and Commercial Power Systems Analysis. IEEE Std 399-1997. New-York. IEEE Industry Applications Society/Power Engineering Society

The Institute of Electrical and Electronics Engineers. IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems. IEEE Std. 519-1992. IEEE Industry Applications Society/Power Engineering Society

Trask, C. 2008. Wideband Transformer Models: Measurement and Calculation of Reactive Elements. Tempe, AZ 85285-5240

Voldek, A. I. 1974. Electrical machines. Leningrad: Energiya.

Wong, F. K. 2004. High Frequency Transformer for Switching Mode Power Supplies. Doctoral dissertation. Griffith University: Faculty of Engineering and Information Technology.

World Wind Energy Association. February 2009. World Wind Energy Report 2008. WWEA Head Office: Germany.

World Wind Energy Association. February 2009. World Wind Energy Report 2008. WWEA Head Office: Germany.

Zhao, L. 2004. Generalized Frequency Plane Model of Integrated Electromagnetic Power Passives. Doctoral dissertation. Faculty of the Virginia Polytechnic Institute and State University.