Journal of Automation, Electronics and Electrical Engineering

Characterization and Selection of Electromagnetic Interference (EMI) Line Filter for Variable-Frequency Drive (VFD) Application

Juha KALLUNKI

Helsinki University of Applied Sciences, PL 4000, Helsinki, Finland, juha.kallunki@metropolia.fi

DOI: https://doi.org/10.24136/jaeee.2025.007

Abstract – This study investigates conductive interference in a low-power variable-frequency drive (VFD). The VFD generates high-frequency voltage harmonics at 16kHz and 24kHz. A suitable commercial electromagnetic interference (EMI) line filter is identified, which effectively reduces the amplitudes of these harmonic voltages. A simulation model of the EMI line filter is developed to analyse its common-mode and differential-mode noise attenuation properties in greater detail. The simulation results confirm the filter's suitability for this specific VFD application. The filter's performance is further validated through experimental measurements. In conclusion, a simple step-by-step guideline for EMI filter selection is proposed. The findings of this study may also serve as a foundation for educational material for undergraduate students, with several potential practical exercises developed based on this work.

Key words – variable-frequency drive, electromagnetic interference, electromagnetic compatibility, EMI filter, education

Introduction

Non-linear loads, such as variable-frequency drives (VFDs), are significant sources of electromagnetic interference (EMI), including both low- and high-frequency interference. They can generate both radiative and conductive EMI. Ensuring that VFD installations comply with electromagnetic compatibility (EMC) regulations is crucial. In most cases, adhering strictly to the manufacturer's installation instructions ensures compliance with EMC regulations. However, improper installation from an EMC perspective can lead to severe malfunctions or, in the worst case, device failures [1,2,3,4].

Various standards define acceptable emission limits for specific products and devices. For example, IEC/EN 61800-3 ("Adjustable Speed Electrical Power Drive Systems – Part 3: EMC Requirements and Specific Test Methods") specifies emission limits for VFDs. One critical aspect of EMC in VFD applications is the motor cable. If the cable is unshielded, it can act as an antenna, radiating interference into the surrounding environment. Additionally, VFDs introduce harmonic voltages and currents into the supply network. The characteristics of these harmonics depend on the drive unit's design, including the type of power semiconductor components and the number of rectifier pulses. Specifically, pulse-width modulated (PWM) inverters are major contributors to voltage and current harmonics.

Frequency harmonics are integer multiples of the supply network frequency. The IEC/EN 50160 standard ("Voltage Characteristics of Public Distribution Systems") defines permissible voltage harmonic limits up to the 25th order. Assuming a supply frequency of 50Hz, the 25th-order harmonic corresponds to 1250Hz. Harmonics can be filtered out using either passive or active filters. In addition to these harmonics, VFDs can also generate conductive voltage interference at higher frequencies, reaching several hundred megahertz. The IEC/EN 61800-3 standard sets limits for conductive emissions in the frequency range of 0.15MHz to 30MHz. These high-frequency interferences can be controlled using radio frequency interference (RFI) filters, typically passive filters.

This study focuses on conductive interference produced by VFDs in the frequency range of 5kHz to 30kHz. Two primary noise coupling mechanisms are considered: differential-mode noise, which occurs between power supply lines, and common-mode noise, which occurs between the supply and ground [5]. The performance of EMI filters must be evaluated for both types of noise. It is often difficult to predict which noise mechanism will dominate; common- or differential mode. Conducted EMI primarily results from rapid voltage changes (du/dt) and fast switching of converters or inverters [3,6]. Line EMI filters are predominantly passive low-pass filters designed to mitigate this interference [7]. Chapter 2 presents the harmonic voltage measurements. Chapter 3 discusses the theory of EMI line filters, the simulation model used, and the corresponding results. The filter performance is analysed in Chapter 4. Finally, Chapter 5 summarizes the conclusions and outlines potential directions for future research.

1. MEASUREMENTS

In this study, we selected a mini-scale variable-frequency drive (VFD) with a nominal operating power of 750W. This VFD drives a small three-phase induction motor with a nominal power rating of 40W. A small-scale VFD was chosen due to its ease of modification, allowing for efficient and rapid adjustments during testing. The VFD operates with a single-phase input voltage and a three-phase output. The primary objective was to assess the extent of the voltage harmonics generated by the VFD.

Harmonic measurements were conducted using a Fluke 1775 Power Quality Analyzer, which allows, for instance, for the measurement of voltage and current harmonics in the frequency range of 2kHz to 30kHz for both single- and three-phase systems. In this study, we focused solely on voltage harmonics, partly due to the relatively low operating power of the VFD. Due to low current consumption, also current harmonic distortion is preferably low.

Figure 1 presents the harmonic voltage measurements, displayed in root-mean-square (RMS) values. The lower trend plot illustrates the variation in total harmonic distortion (THD) over a 10-minute period. In the upper panel of Figure 1, the measured voltage harmonics and their corresponding frequencies are shown. Two dominant harmonic voltages were identified: 1.6V (RMS) at 16kHz and 1.7V (RMS) at 24kHz. The amplitudes of other voltage harmonics were significantly lower (< 0.5V). The lower panel of Figure 1 shows the total voltage harmonic distortion over the 10-minute period. Similar conductive EMI interference frequencies in VFDs have also been observed previously [8].

The objective of this study is to identify a suitable EMI line filter capable of attenuating the two strongest harmonic components. In practice, the measured harmonic values are relatively small (< 1%) and are unlikely to cause significant issues, except in highly sensitive environments. However, this study provides a valuable approach for selecting an appropriate EMI filter.

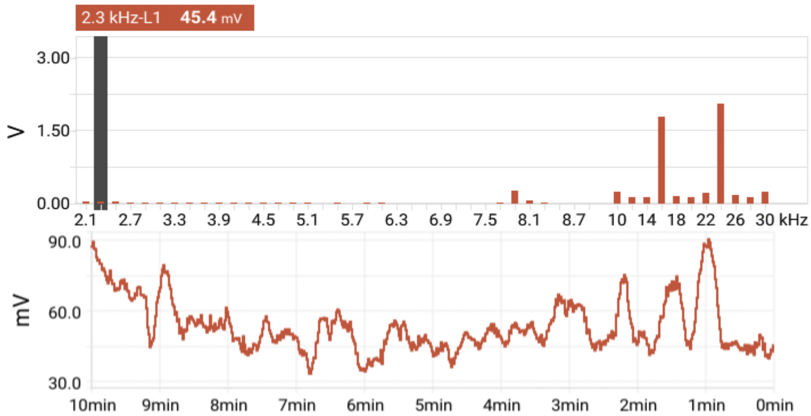

Fig 1. Voltage harmonic measurements were taken before the installation of the EMI filter. The upper panel shows two harmonic components at frequencies of 16kHz and 24kHz. The lower panel presents the voltage total harmonic distortion over a 10-minute period.

2. Filter Analysis

Selecting a suitable filter for any application requires detailed information about the source and load impedances [9]. However, accurately determining these values is often challenging. The CISPR 17 standard ("Methods of Measurement of the Suppression Characteristics of Passive EMC Filtering Devices") recommends using the so-called "Approximate Worst-Case Method" when estimating filter performance. In practice, this method involves evaluating the filter's performance under two conditions: first, with a source impedance of 0.1Ω and a load impedance of 100Ω, and second, with the values reversed (source impedance of 100Ω and load impedance of 0.1Ω). Additionally, a standard 50Ω / 50Ω (source/load) test is regularly conducted.

Figure 2 illustrates a typical topology (so called π-topology) of an EMI line filter, which is also applicable to the filter selected in this study. The filter's design effectively reduces both common-mode and differential-mode interference. The primary objective of this work is to identify a suitable commercial EMI line filter and evaluate its performance and usability for the device under test (DUT).

The primary requirement for the selected EMI filter is its ability to attenuate or significantly reduce the two detected harmonic voltage signals at frequencies of 16kHz and 24kHz. Many low-cost single-phase EMI filters have cut-off frequencies starting at 150kHz, making careful selection essential in this case. A promising filter was identified: the Schaffner FN2030-12-06 passive EMI filter. The filter's cut-off frequency is low enough to meet our requirements based on the filter's data sheet.

Although the attenuation characteristics for both common-mode and differential-mode noise are provided in the component datasheet, we extended our study by developing a simulation model for this specific EMI filter. Parasitic values of individual components were not included in the simulation, as they are unknown—this limitation is a known drawback of passive EMI filters. However, the simulation allows us to evaluate, for instance, filter performance under different source and load impedance conditions, as well as the system's common- and differential-mode noise properties [5,7,10].

Figure 2 presents the simulation model used for analysing differential-mode noise, while Figure 3 illustrates the corresponding model for common-mode noise analysis. The simulations were conducted using the NI Multisim circuit simulator. An AC (alternating current) sweep analysis was performed on the circuit. The AC sweep varies through different frequencies while maintaining a constant amplitude.

The operating principle of an EMI line filter is relatively straightforward. The capacitors C_x primarily attenuate differential-mode noise signals and suppress voltage spikes that occur between the line and neutral wires. C_y are connected between the line (and neutral) and ground wires, with their main function being the attenuation of common-mode noise. The inductor in the EMI line filter serves to block high-frequency noise in general.

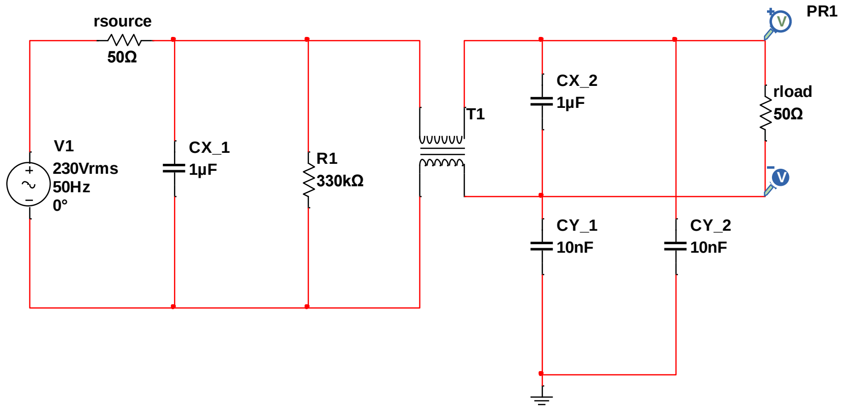

Fig. 2. EMI filter (FN-2030-16-06) topology, with both source and load impedances set to 50Ω. The parasitic components are not included in the investigation. This model is used for differential-mode noise analysis, with the voltage across the load resistor being examined.

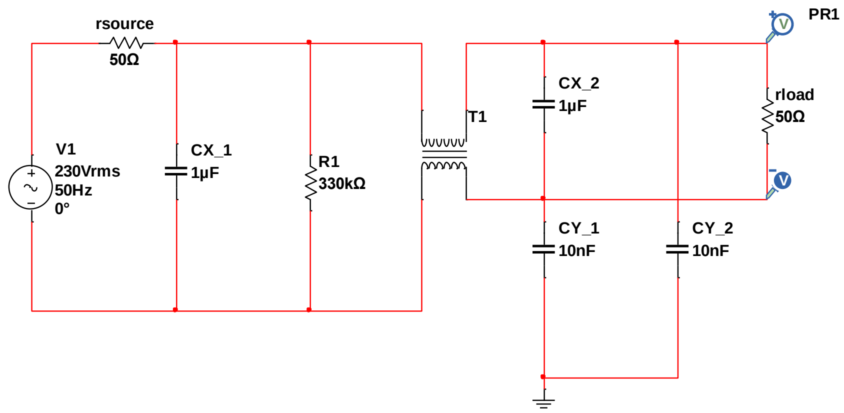

Fig. 3. EMI filter (FN-2030-16-06) topology, with both source and load impedances set to 50Ω. The parasitic components are not included in the investigation. This model is used for common-mode noise analysis, with the voltage across the load resistor being examined.

Figure 4 presents the attenuation profile (50Ω / 50Ω) of the EMI filter for both differential-mode and common-mode noise. The plot demonstrates that the attenuation is sufficient for our application. Additionally, the filter's attenuation slope remains stable across the analysed frequency range (1kHz - 100MHz). In table 1, the attenuation values at frequencies of 16kHz and 24kHz are given.

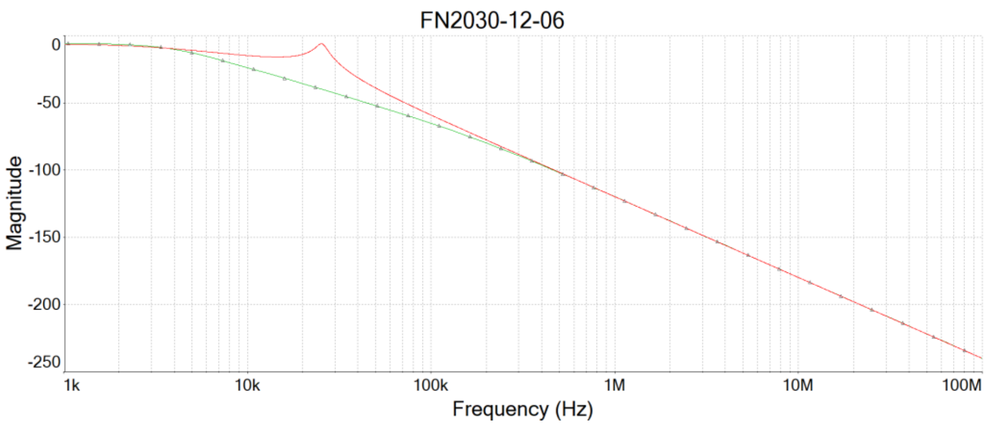

Fig. 4. The attenuation profile of the filter (FN2030-12-06) is shown at the frequency range between 1kHz and 100MHz. The red curve represents the differential-mode noise attenuation (magnitude), while the green curve represents the common-mode noise attenuation.

Table 1. The attenuation values at selected frequencies: 16kHz and 24kHz.

	Attenuation (dB), DM	Attenuation (dB), CM
16kHz	15.8	32.2
24kHz	7.1	39.2

As mentioned earlier, the source and load impedances are unknown. Therefore, the simulation was conducted using 50Ω / 50Ω (source/load) values. In addition to this standard simulation, other source and load impedance values were also tested. These simulations confirmed that the filter's performance is suitable for this application.

The results further emphasize that source and load impedance values have a significant impact on overall filter performance. While the simulations in this case are indicative rather than definitive, they provide valuable insights, such as reasonable estimates of the filter's cut-off frequencies. This, in turn, allows us to approximate the filter's attenuation with a reasonable degree of accuracy.

In the common-mode (CM) noise case, the filter cut-off frequency ($\boldsymbol{f_{c,CM}}$) can be estimated with reasonable accuracy using the following equation [11]:

$$\boldsymbol{f_{c,CM}} = \frac{\mathbf{1}}{\mathbf{2}\boldsymbol{\pi}\sqrt{\mathbf{2} \times \boldsymbol{LC_y}}} \tag{1}$$

where $\boldsymbol{L}$ is a common-mode choke value and $\boldsymbol{C_y}$ is capacitor (line-to-ground) value. In the differential-mode (DM) noise case, the filter cut-off frequency ($\boldsymbol{f_{c,DM}}$) can be with reasonable accuracy using the following equation [11]:

$$\boldsymbol{f_{c,DM}} = \frac{\mathbf{1}}{\mathbf{2}\boldsymbol{\pi}} \times \sqrt{\frac{\mathbf{2}}{\boldsymbol{LC_x}}} \tag{2}$$

where $\boldsymbol{C_x}$ is capacitor (line-to-neutral) value. The cut-off frequency is the frequency at which the filter begins to significantly attenuate unwanted noise.

For the selected filter, the cut-off frequencies are 3.6kHz (differential-mode) and 17.8kHz (common-mode). While the common-mode cutoff frequency is slightly higher than desired, the other frequencies are suitable. We can reasonably assume that the filter has some effect, at least a minor one, at the 16kHz frequency. The calculated cutoff frequencies are also consistent with the simulation results.

3. RESULTS

The EMI filter was installed in front of the VFD unit's power supply, with the cable length between the filter and the VFD kept as short as possible (< 20cm). Figure 5 presents the schematic of the complete VFD unit. Passive EMI filters have also been successfully used and studied in other VFD applications [3].

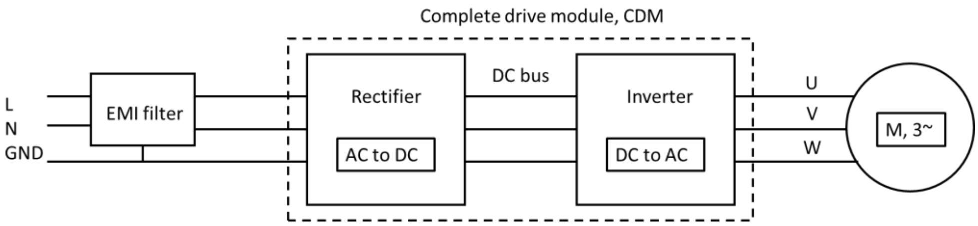

Fig. 5. The schematic of the complete DUT (Device Under Test) after the EMI line filter has been installed.

The harmonic measurements were repeated after the EMI filter was installed. Figure 6 shows the measurement results. The same harmonic voltages at 16kHz and 24kHz are still detectable, but their amplitudes have significantly decreased. After adding the filter, the harmonic voltage values are 45mV (RMS) at 16kHz and 73mV (RMS) at 24kHz.

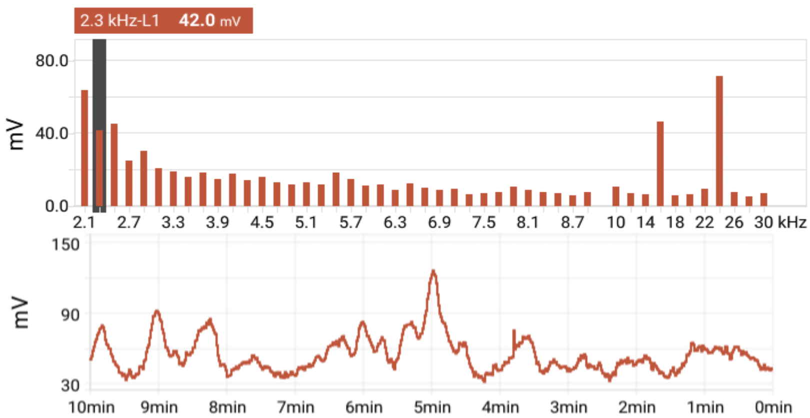

Fig. 6. Voltage harmonic measurements were taken after the EMI filter installation. The upper panel shows two harmonic components at frequencies of 16kHz and 24kHz, while the lower panel presents the voltage total harmonic distortion over a 10-minute period.

Based on the measurements, we can estimate the filter's performance using the following equation. The equation provides the voltage attenuation value ($A_V(dB)$) in decibels (dB) [12]:

$$A_V(dB) = 20\log\left(\frac{U_{no\_filter}}{U_{filter}}\right) \quad (3)$$

where U_{no_filter} is harmonic voltage RMS value before filter installation and U_{filter} is harmonic voltage RMS value after filter installation. The attenuation results, after the filter installation, in decibel scale are following:

$$\begin{aligned} A_{V,16kHz}(db) &= 35.6\ dB \\ A_{V,24kHz}(db) &= 23.3\ dB \end{aligned} \quad (4)$$

A direct comparison between the measurement results and simulations is not possible due to the unknown source/load impedance values. Additionally, the parasitic values of the EMI filter were not included in the simulation model. These factors primarily explain the observed differences. The simulation results and manufacturer's datasheet can only provide preliminary assumptions about the filter's suitability for the application. The results emphasize the importance of measurements in actual installations, as the parasitic values of the filter affect its performance, including filter stability [12].

4. CONCLUSIONS

We can conclude that the performance of the selected filter is sufficient for this application. However, a more detailed analysis would require additional information, such as source and load impedances, as well as the parasitic values of the filter components. The first step in improving the analysis is to obtain more accurate equivalent circuit values for the EMI line filter. Even then, several uncertainties remain.

Due to various uncertainties, this study highlights the importance of real measurements. Voltage and current harmonic measurements are relatively straightforward when using the proper and suitable measurement device, as was done in this work. For higher harmonic frequencies, traditional spectrum analyzer-based measurements are essential.

The following procedure is recommended for selecting an EMI line filter:

1. Measure the harmonic voltage frequencies before the EMI filter is installed. The lowest voltage harmonic frequency $f_{v,min}$ is determined based on the measurements.
2. Find a suitable filter whose cut-off frequencies ($f_{c,CM}$, $f_{c,DM}$) are smaller than $f_{v,min}$
3. To gain a better understanding of the filter's performance, simulating the filter is recommended. The simulation, for instance, reveals the attenuation slope of the filter. The accuracy of the simulation results depends entirely on the accuracy of the created model. To further understand the filter's functionality, different source and load impedance values could be used in the simulations.

4. Install the selected EMI filter for the application and repeat the harmonic (voltage/current) measurements
5. If the attenuation and/or cutoff frequency are insufficient, consider selecting an EMI line filter with larger C_x and C_y capacitor values. Larger capacitor values typically improve the attenuation profile and lower the cut-off frequency. You can verify your selection again through simulations.

The advantages of the simulation tool and model become particularly evident when a commercial EMI line filter is unavailable, and a filter must be designed from scratch. The results of this study could also serve as educational material for bachelor-level students. It provides a straightforward method for approaching EMI line filter selection and analysis. Based on this work, the following practical exercises could be presented to bachelor-level students: harmonic voltage and current measurements in different type applications, EMI line filter selection, detailed analysis, and filter design from scratch as the most challenging exercise. Various EMI issues are becoming more common in the future; thus, it is important that EMI theory and practices are studied comprehensively, including at the university level.

BIBLIOGRAPHY

[1] Novak, J., Simanek, J., Cerny, O., Dolecek, R. (2008) "EMC of Frequency Controlled Electric Drives". RADIOENGINEERING, VOL. 17, NO. 4, DECEMBER 2008
[2] Zare, F. (2009) "EMI in modern AC motor drive systems". IEEE EMC Society Newsletters, summer(222). pp. 53-58.
[3] Yang, L., Wang, S., Feng, J. (2018) "Electromagnetic interference modeling and suppression techniques in variable-frequency drive systems". Front. Mech. Eng., 2018, 13(3): 329–353 https://doi.org/10.1007/s11465-018-0466-1
[4] Post, C. F. (2014) "EMC design considerations for medium to large variable speed drives in industry," 2014 XXXIth URSI General Assembly and Scientific Symposium (URSI GASS), Beijing, China, 2014, pp. 1-4, doi: 10.1109/URSIGASS.2014.6929538.
[5] Charishma, P. V. S., Jayasree, P. V. Y (2023) "Estimation of Common Mode noise and Differential Mode noise generated by DC-DC Power Converters". IJEER 11(3), 836-843. DOI: 10.37391/ijeer.110330.
[6] Yuan, L., Zhang, J., Liang, Z., Hu, M., Chen, G., Lu, W. (2023) "EMI challenges in modern power electronic-based converters: recent advances and mitigation techniques". Front. Electron. 4:1274258. doi: 10.3389/felec.2023.1274258
[7] Zeghoudi, A., Bendaoud, A., Bechekir, S., Miloudi, H., Tilmatine, A., Miloua, F. (2022) "Common and Differential Mode Filter Used in SEPIC Converter", International Journal of Electronics and Electrical Engineering Systems (ISSN : 2602-7437) Volume 5, Issue 4 (December 2022)
[8] Genc, S., Sarma, N., Gundogdu, B., Ozgonenel, O., Gezegin, C.,Terzi, U. K. (2023) "Suppression of Conducted Emissions in Three-Phase Adjustable Drive Systems". Presented at 2023 14th International Conference on Electrical and Electronics Engineering (ELECO), Bursa, Turkiye

[9] Kostov, K. S., Sjöroos, J.-P., Kyyrä, J. J., Suntio, T. (2004) ”Selection of power filters for switched mode power supplies”. In: Proceedings of the 2004 Nordic Workshop on Power and Industrial Electronics (NORPIE 2004). Trondheim, Norway. 14-16 June 2004.

[10] Majid, A., Saleem, J., Bertilsson, K. (2012) "EMI filter design for high frequency power converters". 2012 11th International Conference on Environment and Electrical Engineering, Venice, Italy, 2012, pp. 586-589, doi: 10.1109/EEEIC.2012.6221444.

[11] Ma, Y., Feng, C., Li, C., Wang, L., Jia, Z., Chen. J. (2017) “A Precise Design Method of EMI Filter Based on Compound Common-mode and Differential-mode Inductance”. Proceedings of the 2017 2nd International Conference on Control, Automation and Artificial Intelligence (CAAI 2017), doi: 10.2991/caai-17.2017.26

[12] Kostov, K., Kyyrä, J., Suntio, T. (2003) ”Analysis and design of EMI filters for DC-DC converters using chain parameters”. In: Proceedings of the 10th European Conference on Power Electronics and Applications (EPE 2003). Toulouse, France. 2-4 September 2003.