

Active Cancellation of Periodic Electromagnetic Disturbances for Passive Filter Reduction in Automotive dc-to-dc Converters

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Kurzfassung

Leistungselektronische Systeme können aufgrund der verwendeten schnellschaltenden Transistoren erhebliche Quellen für elektromagnetische Störungen darstellen. Zur Begrenzung dieser Störungen gegenüber der Umwelt werden üblicherweise passive Filter eingesetzt, welche jedoch häufig groß, schwer und teuer sind. Die aktive Störungsunterdrückung ist ein vielversprechender Ansatz zur Lösung dieser Probleme. Bereits existierende Methoden (aktive Filter) leiden unter unvermeidlichen Verzögerungszeiten, da diese das Gegenstörsignal direkt aus einem gemessenen Signal erzeugen. Die systematische Verzögerungszeit durch Störmessung, Signalgenerierung und Gegenstörinjektion sorgt dafür, dass Störungen und Gegenstörungen niemals gleichzeitig anliegen. Daher sind die erzielbare Störungsreduktion und der entstörbare Frequenzbereich systematisch eingeschränkt. Zur Lösung dieses Problems können synthetisierte Gegenstörsignale eingesetzt werden. Da diese künstlich erzeugt wurden, besteht keine systematische Verzögerungszeit und alle problematischen Effekte, wie Phasendrehungen oder Betragsgänge, können kompensiert werden. Für die destruktive Interferenz zwischen den Signalen muss ein synchroner Betrieb zwischen Leistungselektronik und dem Entstörsystem gewährleistet werden, was jedoch in den meisten digitalen Systemen realisiert werden kann. Die Methode wurde bereits erfolgreich bei DC/DC-Wandlern für Automotive-Anwendungen eingesetzt. In diesem Beitrag werden der Stand der Technik und die Störungsunterdrückung mithilfe von synthetisierten Signalen vorgestellt. Es wird ein Demonstrator präsentiert und Messergebnisse werden diskutiert. Weitere potenzielle Einsatzbereiche werden dargestellt.

Abstract

The electromagnetic compatibility (EMC) of power electronic systems is a severe issue since the switching of transistors can cause high levels of electromagnetic interferences (EMI). To reduce the EMI, passive filters are commonly applied that tend to be bulky, heavy and expensive. Active noise cancellation is a promising approach to get rid of these problems. Existing methods, namely active EMI filters, suffer from unavoidable delay times since they inject a cancellation signal that originates from a measured signal. These delay times limit the suppressible frequency range and the achievable EMI reduction. To resolve this issue, synthesized cancellation signals can be applied. Since the signal is artificially generated, there is no systematic delay and all bothersome effects, like phase-shifts or magnitude responses, can be compensated. It is only required that the cancellation signal can be synchronized with the power electronic system to maintain a destructive interference. However, this can be realized in most digital controlled systems. The method has already been successfully applied to automotive DC/DC converters. In this contribution, the state of the art and the innovation are described, a demonstrator and measurement results are presented, and the potential field of application is evaluated.

1 Introduction

Power electronics is a key technology of the 21st century due to the possibility of very efficient energy conversion. Usually, power electronics achieve this efficiency by switching transistors that may be considerable sources of electromagnetic interferences (EMI). These interferences may harm the operation of other systems, such as communication or broadcasting services or susceptible sensors, which steadily gain more significance due to digitization. To ensure the functionality of sensitive systems in proxim-

ity to power electronic devices, electromagnetic compatibility (EMC) is a major enabler for electrification with power electronics.

At first, the state of the art of conducted EMI reduction is discussed. Afterward, a new concept using synthesized and synchronized cancellation signals is introduced. A digital prototype hardware is presented and the necessary programming process is discussed. The implemented algorithm is briefly described. Then, the realized cancellation system is applied to a stationary operating dc-to-dc converter in an exemplary automotive application. The device

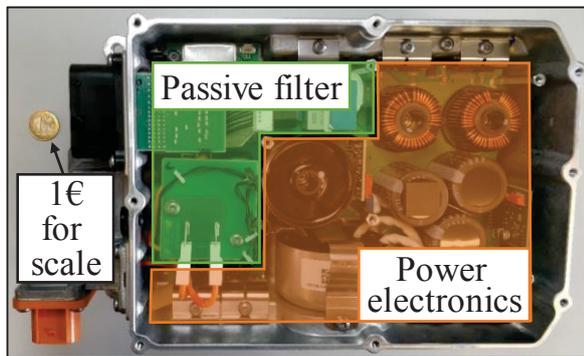


Figure 1: Exemplary on-board charger (3.6 kW) of KOSTAL

under test is described and measurement results are discussed. Afterward, other potential applications are depicted. The work is closed by a conclusion.

2 State of the Art

In this chapter, the state of the art of conducted EMI reduction is summarized. The most common solution are passive filters. However, there is also an established method for active cancellation in the form of active EMI filters.

2.1 Passive EMI Filters

Passive line filters consisting of coils and capacitors are commonly applied to attenuate the conducted EMI of power electronic devices. Since the disturbances as well as the operating voltages and currents of the converters are typically quite high, filters tend to be bulky and heavy. In Figure 1, an automotive on-board charger is depicted. Here, the passive filter takes up approximately one third of the volume of the electronics. In many applications, this can be a serious problem. In e.g. hybrid vehicles, there is not much volume for the power electronic systems since the combustion engine and its components take up basically all of the available space. In electric vehicles, there is more free space since there is no combustion engine anymore. Nevertheless, there are very high requirements regarding the vehicle's total mass to improve the driving range. So, there are many reasons to shrink the passive filter components.

2.2 Active EMI Filters

To resolve the mentioned issue, active EMI filters have been developed (Figure 2) [1]-[4]. In contrast to passive filters, active EMI filters inject cancellation signals that cause a destructive interference with the disturbances of the power electronics to reduce the EMI of the system. Active EMI filters consist of a small circuit for sensing the disturbances, an amplifier (e.g. operational amplifier) to generate the cancellation signal from the disturbances, and a small circuit for injecting the cancellation signal. The major limitation for active EMI filters is the inevitable delay time introduced by the analog (or recently also digital) circuitry. Due to this delay time, noise and anti-noise can never be exactly simultaneous. This effect systematically

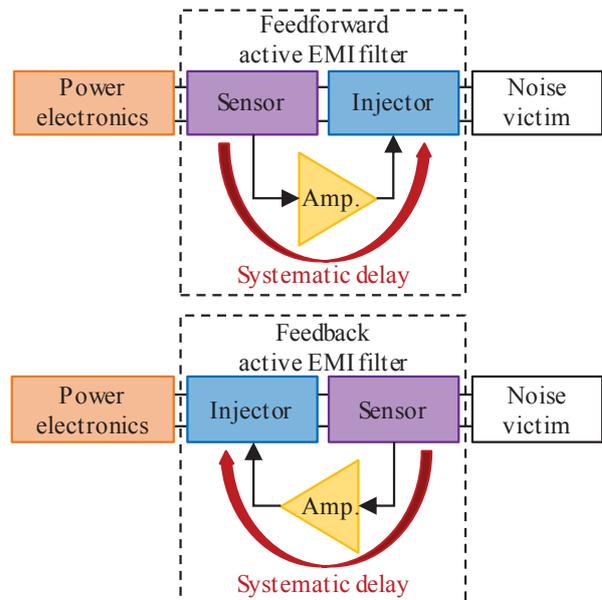


Figure 2: Fundamental topologies of active EMI Filters (top: feedforward-type, bottom: feedback-type)

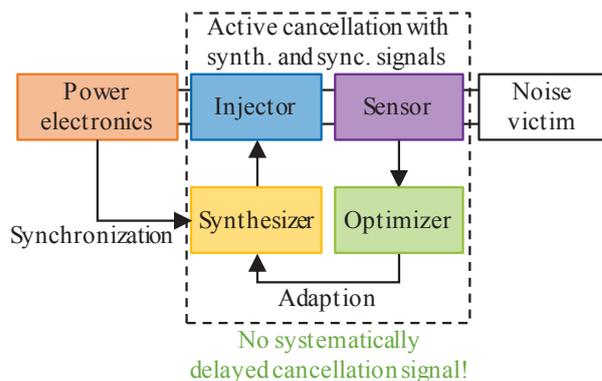


Figure 3: Active cancellation with synthesized and synchronized signals

limits the achievable EMI reduction and the suppressible frequency range as analyzed exemplary for feedforward-types in [7].

3 New Concept

In this chapter, the new cancellation concept is presented. The systematic limitations of active EMI filters are resolved by artificially synthesizing the cancellation signal. A convenient method for signal synthesis is presented for the application to (quasi-)periodic disturbances of, e.g., a dc-to-dc converter in stationary operation.

3.1 Active EMI Cancellation with Synthesized and Synchronized Cancellation Signals

To resolve the issue of a systematically delayed signal path, the cancellation signal can be artificially synthesized and applied in synchronicity with the disturbances (Figure 3) [5]-[8]. Remaining magnitude responses, phase-shifts and delays are compensated by the shape of the synthesized

signal. So, the cancellation signal can be simultaneous with the disturbances improving the effectivity of the method widely.

However, finding the right shape of the cancellation signal is no trivial task. So, an optimizer is applied that adapts the signal in regard to the residual disturbances at the output. Obviously, this optimization needs some time and may limit the dynamic response of the system. This can be an issue for power electronic devices in transient modes of operation, but not in stationary states.

In stationary operating systems, power electronic systems generate disturbance spectra consisting of discrete harmonics. So, the cancellation signal can easily be synthesized from harmonic sine waves. An appropriate method is depicted in the following section.

3.2 Adapted Harmonics Cancellation

The fundamental concept of adapted harmonics cancellation (AHC) is illustrated in Figure 4. The power electronic system in stationary operation is the source of disturbing harmonics that must be cancelled out. A dc-to-dc converter would be a typical example of a system that creates harmonic disturbances due to the periodic switching of the transistors. The cancellation signals can be generated by digital hardware (e.g. by an FPGA-system with analog-to-digital converters [ADCs] and digital-to-analog converters [DACs], Figure 5).

The digital hardware comprises an optimizer and a synthesizer. For cancellation, the synthesizer generates a sine wave for each disturbing harmonic. The optimizer is used to find the right amplitudes and phases for cancellation. The synchronicity of the generated sine waves and the disturbances is maintained by a suitable synchronization signal. In power electronic systems, binary control signals are convenient for synchronization.

To link the power electronic system and the cancellation system, interfaces are necessary. A sensor consisting of an analog circuit and an ADC is used to measure the disturbances. An injector is applied to couple the cancelling waveforms into the power electronic system. This injector consists of an injecting circuit and a DAC. These components can be very small, especially in comparison to passive EMI filters.

4 Digital Hardware

In this section, the prototype hardware and the necessary programming process is summarized. Furthermore, the implemented algorithm is stated.

4.1 Prototype Hardware for the Active Cancellation Method

The FPGA-system Red Pitaya STEMLab 125-14 is used as a powerful and flexible development tool. The STEMLab 125-14 mainly consists of a System-on-Chip (SoC), two ADCs, two DACs and several GPIOs. The SoC includes a

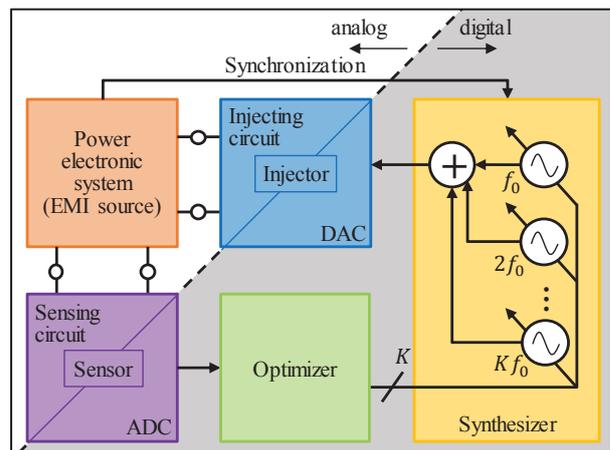


Figure 4: Concept of adapted harmonics cancellation



Figure 5: FPGA evaluation system with high-speed DACs and ADCs (Red Pitaya STEMLab 125-14)

FPGA (Xilinx Zynq 7010 SOC) and a dual-core ARM Cortex A9 CPU running a Linux operating system which enables programming of the FPGA and communication via Ethernet. The two ADCs and the two DACs have a resolution of 14 Bit and a sample rate of 125 MS/s. Therefore, RF analog input signals can be passed through the analog frontend, digitalized by the ADCs and processed inside the FPGA while digital output signals can be passed to the DACs and injected into the setup. The main reasons for using STEMLab 125-14 are the fast and precise ADCs and DACs as well as the flexibility given by the FPGA itself.

4.2 Programming Process

To minimize the development time, it is desirable to provide a convenient modeling environment and a fast processing of the necessary tool chain. Therefore, MATLAB Simulink is used as a development environment for the FPGA's logic that also enables a prior simulation of the functionality. Based on this Simulink Model, HDL (Hardware Description Language) Models of the desired logic are generated by the HDL Coder. These HDL Models are embedded into a standard frame in Xilinx Vivado.

Based on a correct HDL description of the circuit, basically three steps are needed to realize logic on an FPGA: Firstly, during the synthesis step, a netlist of logic elements is generated based on the functional description in Verilog. Secondly, during the implementation step, the netlist is modified to fit the used FPGA and the maximum signal

transit times are reviewed. If the timing constraints are fulfilled and the implemented design still meets its description, the implementation step should be successful. Thirdly, a bit stream is generated that includes all necessary information to configure the FPGA corresponding to the intended design.

In a further step, a binary file is generated based on the bit stream. This binary file can be transferred over LAN from the developer's computer to the STEMlab's Linux OS via a FTP connection. The transferred logic can comfortably be activated using a SSH remote connection to the Linux OS.

The tool chain has been automated by a batch file. Thus, after system design in Simulink, only one batch file needs to be executed to program the FPGA. Furthermore, to enable the development from several different computers without the need of a bothersome installation process, the needed development software has been installed on a Virtual Machine (VM) which can easily be transferred to other computers.

4.3 Implemented Algorithm

The algorithm implemented on the FPGA-system is based on the "single-frequency adaptive notch filter" developed in [10] and [11]. This algorithm is well established for the active suppression of single tones in acoustics [12] and was successfully transferred to the suppression of switching harmonics in EMC [5]-[7]. In [13], the algorithm was extended for the successive application to a very large number of harmonics. So, a broadband cancellation signal can be generated from numerous sine waves by the FPGA-system.

5 Demonstrator

For demonstration, the disturbances of an automotive 48 V/12 V dc-to-dc converter are suppressed by the self-adapting algorithm. At first, the device under test is presented. Afterward, measurement results are discussed.

5.1 Device Under Test

The device under test (DUT) can be seen in Figure 6. The dc-to-dc converter is an evaluation board GS61008P-EVBHF with fast-switching GaN transistors. It steps down the input voltage of 48 V to 12 V. The switching frequency is chosen to 300 kHz. The converter transfers a power of approximately 144 W to a load resistor of 1 Ω . The converter is controlled by the FPGA-system to achieve a synchronous operation between the power electronic system and the cancellation system. The disturbances at the 48 V input line shall be suppressed.

The injecting circuit is a simple inductive transducer made of a toroidal ferrite with two turns for both windings. The sensing circuit is realized as a capacitive voltage sensor with a capacitor of 100 nF. Since the adaptive algorithm compensates the frequency response of the coupling circuits and the system, no further optimization is necessary.

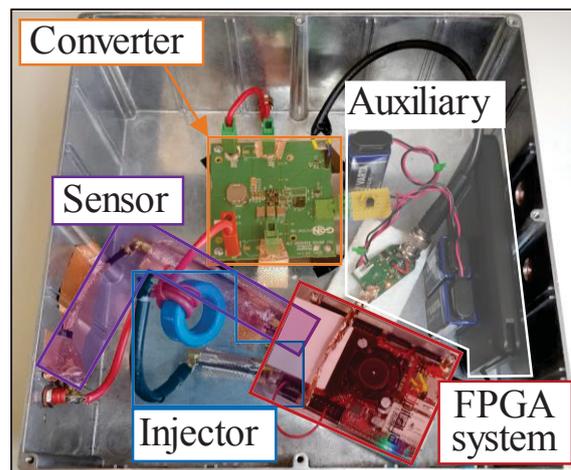


Figure 6: Photograph of the DUT

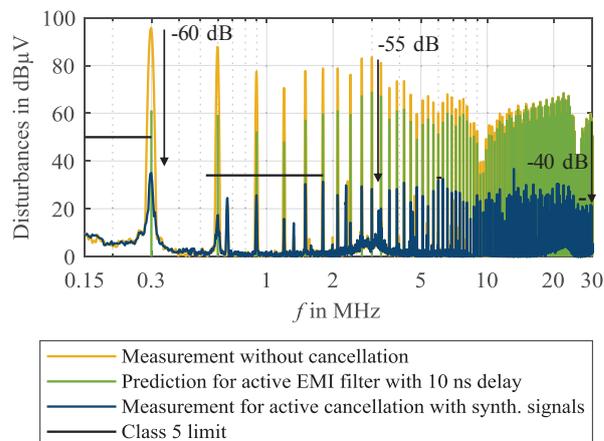


Figure 7: Measured disturbances at the artificial network

However, in practical realizations, the coupling circuits could be optimized and minimized.

The auxiliary circuits comprise power supplies for the transistor driver of the dc-to-dc converter and a digital isolator to avoid a ground loop that could close itself by the control connection for the dc-to-dc converter.

5.2 Measurement Results

In Figure 7, the disturbances at the artificial network are depicted. Obviously, the original disturbances are much higher than the class 5 limit of the standard CISPR 25 [9]. The resulting disturbances for a feedforward active EMI filter with a reasonable delay time of 10 ns are predicted with the formulas derived in [6] and [7]. Due to the systematic delay, the achievable reduction and the suppressible frequency range are severely limited for the active filter. Since there is no systematic delay between noise and anti-noise for the concept with synthesized cancellation signals, the noise suppression is widely improved. The complete frequency range from 150 kHz to 30 MHz is suppressed successfully and complies now with the standard. The fundamental wave at 300 kHz is reduced by nearly 60 dB, and even the 100th harmonic at 30 MHz is suppressed by approximately 40 dB. The power consumption caused by the

cancellation signal is estimated to 3 mW. This value is extremely low since only a high-frequency ripple is compensated that has already been filtered by the stabilizing capacitors of the dc-to-dc converter. Therefore, little power is sufficient for active suppression. More details and further demonstrations can be found in [5]-[8] and [13].

6 Potential Applications

Until now, the presented method of active EMI suppression with synthesized and synchronized cancellation signals has been successfully applied to stationary operating dc-to-dc converters. Currently, the method is being extended for the application on motor inverters that play a key role in modern automotive and power electronics in general. By injecting exactly synchronous cancellation signals without any uncompensated delay, there is an extraordinary potential for the active EMI suppression. Another interesting application are power factor corrections (PFCs) that are important components in many devices like on-board chargers.

Furthermore, the method is being extended to be applicable to multiple terminals of arbitrary power electronic systems. In [14], all lines of a stationary operating dc-to-dc are actively suppressed by a central cancellation system that injects multiple synthesized cancellation signals.

7 Conclusion

A new method has been developed to eliminate disturbing voltages or currents by injecting synthesized and synchronized cancellation signals. In comparison to other known active methods, there is no systematic delay time that limits the achievable performance of the system. The effectivity of the method has been shown for dc-to-dc converters and is currently being extended for other important power electronic systems, namely motor inverters. The authors expect a considerable reduction of the necessary passive filter effort that can lead to power electronic systems with very high power densities.

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