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Research Article

EMI Generated by Switched DC-DC Converters in Automotive Applications

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Abstract

This research paper give you picture to deals with electromagnetic interference that can arise from switched DC-DC converters intended for low-power applications, e.g. automotive industry. It analyzes measures and methods that can applied when a reduction of EMI directly at the source without using any additional means such as shielding and filtering is desired. By investigating the physical properties of the two most important ingoing components, the diode and the MOSFET, an improved MOSFET model and a new gate voltage control method is proposed. This method is referred to as active gate control with an operating principle where a controller circuit shapes the desired output to a sinusoidal trajectory during the entire switching event. By doing this, it is shown that the harmonic content in the output signal can be reduced.

Keywords: *Electromagnetic compatibility, DC-DC converter switching, MOSFET switches*

1. Introduction

Power electronic converters can be found wherever there is a need to modify the electrical energy form (i.e. to modify its voltage, current or frequency). Power electronics are used in widely different automotive areas such as fuel injection control, NOX control system, traction control for electric drives and connection of wind power plants to the grid, therefore, the power range from varies few milliwatts to hundreds of watts. This paper focuses on the usage of low power DC-DC converters intended for onboard power. Modern electronic devices, e.g. processors, often make use of several different voltage levels in the same application which gives a demand of power electronics.

2. Hard Switching Converters

By definition, a hard switching converter, eg. a step down converter, is a converter in which the switching element carries the whole input voltage and current as it changes state at e.g. turn-on. In the beginning of a turn-on interval, the transistor begins to conduct which gives that the voltage will start to fall at the same time as current begins to flow. A similar event occurs as the transistor turns off; the full current starts to fall as the voltage over it increases. In such a converter, the simplest way of reducing EMI is by turning the device on and off during a longer time interval in order to reduce dv/dt and di/dt. However, the simultaneous presence of voltage across the transistor and current gives increased switching losses. The final solution of converter performance becomes a tradeoff between switching losses, EMI performance and component cost. To improve the EMI performance without having to increase the switching losses, a snubber can be added across the switching element that reduces dv/dt and di/dt of the power device.

In the hard switched converters with a transformer, the primary causes of harmonics in the output are the leakage inductance of the transformer and the heat sink applied to the switching element. If a heat sink is used, it is often grounded due to safety reasons and must then be isolated from the semiconductor by a dielectric washer since the terminal of the MOSFET that connects to the heat sink is usually connected to the drain. This causes a high potential to be applied over the stray capacitor formed between the drain terminal and the grounded heat sink. The applied voltage gives rise to the flow of a common mode current in the converter, see Figure 1.

One way to reduce the problems caused by stray capacitance is to use the technique proposed in Figure 1, where a copper sheet is used in combination two isolating sheets. The copper sheet is connected to the source terminal of the MOSFET and acts as a Faraday shield that reduces the stray capacitance.

It also effectively reduces the stray capacitance to the heat sink and allows for several semiconductors to be mounted on the same flange.

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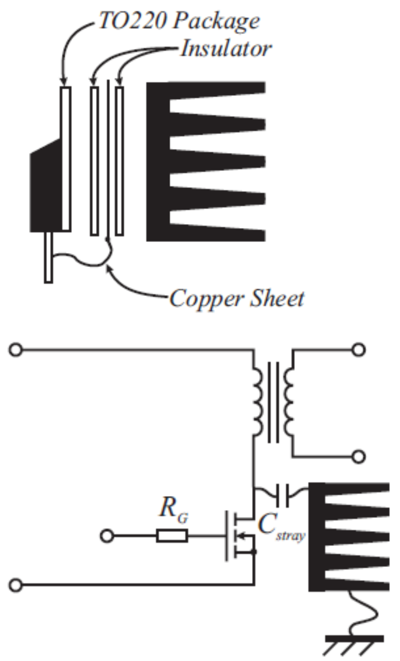

Fig.1 Proper way of isolating a heat sink to minimize EMI

Heat sink may affect the radiated emission of a switched DC/DC converter. The electric field amplitude spectrum at certain frequency ranges is generally enhanced by the application of a heat sink acting as an antenna which makes the antenna effect necessary to take into consideration in certain cases.

Another common cause of EMI is the stray inductance and capacitance of the transformer that often is used in a SMPS, an equivalent circuit is shown in Figure 2. The equivalent circuit models the interwinding capacitance as CW. This capacitance causes the problem of common mode emissions in isolated power supplies in a similar way as for the heat sink. One effective way of decreasing the intern winding capacitance is by applying a faraday shield between the windings. The shield usually consists of a copper sheet connected to the primary ground of the transformer.

The intra-winding capacitances, CP and CS are small and usually negligible at the operating frequencies of switching power supplies and controllers. A large magnetizing inductance, LM, causes a large magnetizing current which may lead to saturation of the transformer core. As for inductors, saturation of a transformer will increases the magnetic-field emission due to the higher current, gives higher core losses that in turn causes higher temperature with the possibility of thermal runaway, and a degradation of coupling between the windings.

The last parameter that needs to be accounted for in the equivalent circuit is the leakage inductance of the primary and secondary winding, LLP and LLP respectively that creates a magnetic field between the windings. While some of this field is captured by the core, the rest acts as a magnetic dipole radiating out into surrounding space with an intensity which decays as the cube of the distance. Examples of techniques for reducing the leakage inductance is interleaving the windings or by applying a conductive flux strap.

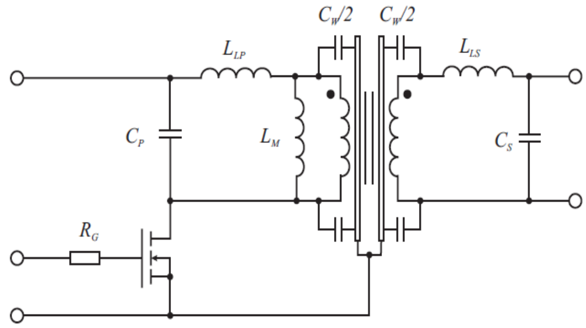

Fig. 2 Effective transformer shielding

The strap provides a path for the eddy currents that result from the leakage inductance magnetic dipole and then creates an opposing magnetic dipole which tends to cancel the original field at close proximity to the transformer. However, not only the winding capacitance needs to be taken into consideration. For lower frequencies, the ferrite core stray capacitance becomes a significant part of total stray capacitance of the magnetic component. Hence, the winding arrangement may not play a significant part in low frequency common mode current generation.

3. Transformer types and effects

In more and more modern converters, the use of planar transformers becomes more common. The usage has mainly two advantages, the possibility of achieving high power density and lowered leakage inductance. The most effective implementation of the layers is by interleaving the primary and secondary layers so that the stray magnetic flux induced by the eddy currents is canceled. From a production point of view, a wire wound transformer can show a large spread in the parameters from production run to production run. If considering a planar transformer, it is significantly more consistent and shows repeatable characteristics. In addition to this, planar technology gives the possibility of integrating a complete EMI-filter into one component that also may help to enhance the EMI performance of the converter. However, the planar transformer has the disadvantage of increased intra winding parasitic capacitances, CP and CS, and increased inter winding capacitance, CS. The increase of these capacitances gives rise to higher differential mode and common mode noise magnitude, respectively.

4. DC-DC Converter Modeling

When it comes to predicting the overall performance of a switched DC-DC converter, several factors complicate the results and the accuracy of the simulation. At first, the most common language for simulating electronic components is SPICE, is not originally intended as a simulator for switched elements. The second factor that contributes to difficulties in simulation is the large amount of parameters that affect the results and the difficulties to determine them. Need a basic approach with a model over the converter that considers both the parasitic capacitance in the transformer and from the heat sink. Once these parameters are known, equivalent circuits over both common and differential mode conducted emissions can be performed. However, the model shows significant discrepancies in simulation results and measurements for higher frequencies (1Mhz) and the versatility is drastically reduced due to difficulties in determining the parasitic capacitances in the circuit.

A more general approach for simulating EMI is, EMI prediction tool based on approximating the switching event has been implemented. The tool focuses on finding the correct current and voltage derivatives, di/dt and dv/dt, during the switching event by studying an behavioral model of the IGBT and approximate the switching transients with a piecewise linear function. By doing so, the practical switching characteristic can be reconstructed in the EMI noise quantification study. A comparison showed that this method improved the simulated EMI spectrum compared with trapezoidal switching events. This method vouches for a simple method to evaluate the EMI noise; however, the major deficit is it only can be quantified once the switching event is known in detail.

When radiated disturbances are to be modeled, much more complex simulation models are needed, often in full 3D. The method allows the study of geometrically complicated structures which are supposed to simulate a realistic electromagnetic environment in eg. a hybrid vehicle. The most advantageous benefit with the proposed method is that only a current measurement in the time domain is needed to predict the radiated emissions. However, the complexity of the FDTD-model makes it is advantageous since it requires a good knowledge of the environment where the converter is to be placed.

5. Random Switching

Several studies have been performed in the past that shows reduced levels of EMI from switched DC-DC converters that are using some kind of non-deterministic property applied to the switching pattern. The key property that differentiates random switching in a switch mode power converter from regular switching, which generates time-periodic switching functions, is that random switching produces switching functions that have a non-deterministic, random component. If a random switching converter is well designed, it can behave similarly to a regular converter, i.e., generating a switching function that allows the reference signal to be extracted by a low-pass filtering and transferred to the load. As a consequence of the non-repetitive switching functions, the frequency-domain spectra for randomized modulators are different from the spectra caused by a deterministic modulation strategy. For classic PWM modulation, the spectrum mainly consists of discrete frequency components clustered around multiples of the PWM carrier frequency, whereas a random modulator transfers the power carried by the harmonics into a continuous density spectrum.

A randomized modulation scheme is characterized by an invariant deterministic and probabilistic structure. If considering the reference switch pattern, dither is added that does not change from one switching cycle to the next. At each new cycle, the same probabilistic structure is used which means that there are no variations in the requirements on average quantities such as the duty ratio. Based on this, the stationary switching schemes can be further classified into three main categories:

- Randomized Pulse Position Modulation (RPPM)
- Randomized Pulse Width Modulation (RPWM)
- Asynchronous Switching Schemes, both simplified and regular

Figure 3 shows a switching function that consists of several consecutive random switching cycles. ξk is the time at which the cycle starts, Tk is the duration of the k'th cycle, ak is the duration of the on-state within this cycle, and ξk is the delay to the turn-on within the cycle.

Note that the duty ratio is dk = ak/Tk. All of the above mentioned switching schemes can be achieved by altering some of the parameters shown in Figure 3. In general, one can dither ξk, ak or Tk individually or simultaneously.

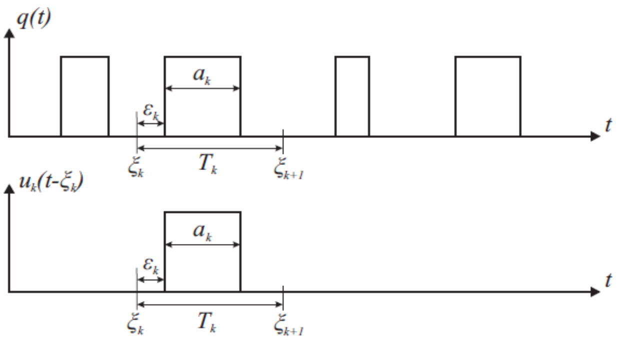

Fig. 3 The switching waveform q(t) and the pulse u (t − ξk)representing just the k:th cycle of q(t).

If randomized PPM is studied, each cycle has the same length Tk, and the pulse in each cycle has the same duration ak, but an independent random variation in the position ξk of the pulse in the k'th cycle is allowed. Randomized PWM triggers the pulse in the beginning of each period, i.e. ξk = 0, and varies the duration of the pulse ak. The total switching period Tk remains fixed. Not that in contrast to conventional switching that for eg. ak = 0.5 has only odd harmonics, randomized PWM yields discrete harmonics at even multiples of the switching frequency as well.

Both RPPM and RPWM are efficient ways of reducing the size of discrete harmonics and in satisfying narrowband constraints. However, due to its widespread nature, random switching techniques are much less effective in dealing with wide-band requirements. If the two previously mentioned techniques are compared, randomized PWM can reduce the fundamental frequency component in the power spectra more than randomized

PPM. On the other hand is randomized PPM more efficient at reducing higher discrete harmonics.

A true asynchronous modulation technique, adds a random variation to the period time of the pulse, Tk. The time delay at the beginning of each pulse, ξ_k = 0, is set to zero and the pulse width, ak, is also kept constant. This is done by varying the period time of the pulse, Tk, but keep the on-state at a constant length, i.e. ak. Both of these methods are proven to give lower power density spectrum. One of the main motivations for use of randomized modulation is the possibility of acoustic noise reduction in inverter-based motor drives.

A motor drive benefits from the randomized switching strategy by a better utilization of the available harmonic content of waveforms at the interface where the power supply connects to the motor. However, in the modern telecommunication systems, sensitive consumers such as radio applications can be interfered by high spectral power density concentrated to a certain frequency, this can be seen as a spurious on the carrier frequency.

Random switching schemes can for that reason offer a fairly wide range of waveform spectra to choose from. The added degrees of freedom allows for a more effective optimization of signal power at specific frequencies and frequency bands of interest. When compared with deterministic waveforms and switching schemes, the main effect of randomization is a reduction of the discrete spectrum and consequently also an introduction of a continuous spectrum.

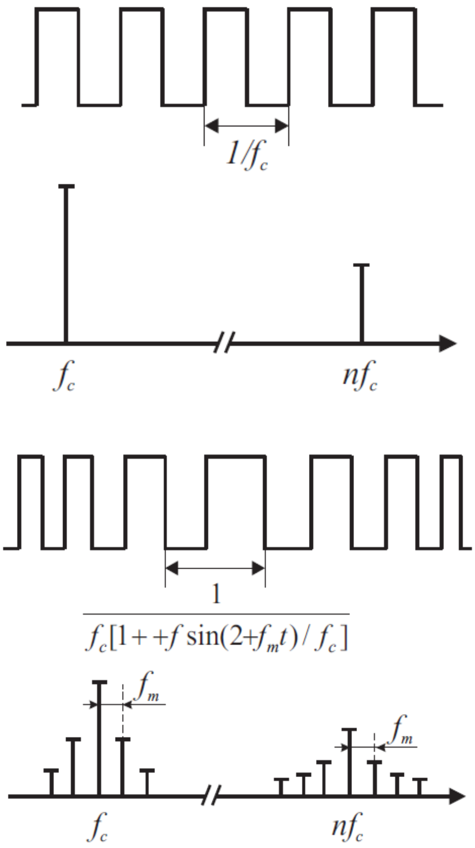

Fig. 4 Comparison of spectra from a square waveform and a frequency modulated square waveform.

Depending on what type of equipment that is connected to the power supply, the consequences of randomized introduction can vary. For instance, the damaging effect of harmonic torque pulsations in electric motors is more severe than that of wideband fluctuations of the same overall power. In general, the impact of randomization is likely to be positive for systems that are susceptible to narrow-band interference, like digital circuits, rotating machinery and communication systems. While many types of communication systems are sensitive to narrow-band interference, the actual performance is very much dependent on the particular communication method. Hence can randomized modulation can be seen as a part of emerging digital energy systems that aim to achieve efficiency while minimizing undesirable effects on the environment like EMI, vibrations and acoustic noise.

Note that not only random parameter modulation such as RPWM and RPPM can be of interest. The switching frequency, fc, is modulated with a frequency, fm, with an amplitude of frequency change Δf, that helps to spread out the spectrum. The principle of how the pectra is spread is shown in Figure 4.

The modulation frequency is typically selected much lower than the switching frequency. A modulation frequency, fc, of 200Hz for a converter that operates with 150kHz switching frequency. Note that the total power of the signal is unaffected by frequency modulation. The total power of a signal equals to the summation of the square of each harmonic amplitude.

The general tendency of frequency modulation is to spread out the power of each switching harmonic. The higher the harmonic number, the more even is the spread-out power. However, due to the fluctuations in the output voltage, the technique of carrier modulation is better suited for DC/AC applications that can tolerate these small fluctuations better than a DC/DC converter with high output tolerances. Another deficit stated in that needs to be taken into consideration is the interaction of the modulation frequency within the control-loop that might lead to a deteriorated EMI-performance.

6. Summary

It is a new approach to MOSFET modeling and the proposed model was used to show that it is possible to achieve better controllability of a system comprising of varying parameters with an adaptive control algorithm. Regarding the output of the system, the controllability is significantly better for a system where the drain current is selected as an output compared to a system where the drain source voltage is selected as an output. Nevertheless, certain problems still exist where the greatest problem to overcome is how the reference voltage shall be adapted to the present operating conditions.

The suggested procedure for extracting parameters, although not completely correct from a control theory point of view, gives the possibility to approximate suitable values already at the simulation stage of the development work. It is shown that a single operating point is not sufficient when the controller parameters are to be determined. The total system is a complex entity with many non-linear variables and a procedure for finding the adaptive control parameters is presented in this papers.

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