Electromagnetic Interference (EMI) which is also called as Radio Frequency Interference (RFI) refers to the undesired generation of radiated or conducted energy in electrical systems. This provides an inevitable problem in switching power supplies. In order to increase the efficiency of switching power supplies, fast switching is applied which leads to the generation of noise over a wide range of frequency. Electromagnetic Compatibility (EMC) has recently gained a new importance in power electronics, therefore the analysis of EMI and its measurement is one of the main concerns of switching power supply designers.

To minimize post-development modification costs, it is important to take EMC aspects into account already in the design phase. There are products which, not complying with the EMC regulations, fail to make them to the market. This paper analyses the conducted EMI emission due to the usage of Pulse Width Modulation (PWM) in a Buck switching power supply. PWM is widely used to control switching power supplies. In this study the pulse-width of the control signal of the electronic switch in the converter varies according to the variation of source voltage, reference voltage and load. This will cause the variation of the switching duty-cycle around a constant value. We consider the situation where the duty cycle of the nth PWM cycle \( d_n \) consists of a constant value \( D \) and a time-varying component.

Not similar to a large number of references, which have considered low harmonics generated by the converters, this paper analyses the noise spectrum in Radio Frequencies (RF). The EMI spectrum measurement process is based on the introduction of a Line Impedance Stabilization Network (LISN). Therefore a simplified representative model is used.

A computerized simulation and some associated softwares have been used to calculate the noise spectrum. It is to be mentioned that the noise spectrum at the LISN output has been considered as the compliance measurement. In order to reduce the undesired noise effect, a filter should be applied at the input of the switching power supply. Considering the nonideal behaviour of its elements, application of this filter is taken into account in the simulation. The differential mode noise circuit model used in the calculation in which the input current of the converter is considered as the noise source \( I_{ex} \). The transfer function of the noise signal over the input current can easily be established.

Duty cycle, amplitude of duty cycle variation and modulation frequency are most important parameters affecting the output spectrum which maximum level of conducted noise can be reduced via them. Experimental sample of such a converter has been designed and implemented. Practical measurement has been in accordance with the theoretical results.
ABSTRACT

The conducted Electromagnetic interference (EMI) emission due to the usage of a fixed frequency Pulse Width Modulation (PWM) controller in a buck switching power supply is studied. The study is based on the variations of PWM waveform due to those of input Voltage, reference Voltage, and load. Line Impedance Stabilization Network (LISN) is introduced to be employed in EMI measurement. An equivalent noise circuit is presented to model Differential Mode (dm) conducted noise emission. The noise spectrum of LISN output is computed in Radio Frequencies (RF), and the effect of different parameters is analysed using appropriate simulations.

1-INTRODUCTION

High speed switching, recently possible in power supplies reduces their weight and volume, somehow, provides good efficiency, however causes Radio Frequency Interference (RFI) emission. This makes it a problem for the producers to present their products to the market, they can not comply to Electro-Magnetic Compatibility (EMC) regulations. Post-development modification would be too costly, so it is important to take EMC aspects already in design phase into account Kneath(1), Nave(2). Fixed Frequency PWM controllers are widely applied for output voltage regulation in switching power supplies. This paper studies the noise generation in a power supply due to this method. As a sample, buck type DC/DC converter is chosen which has a high ability of noise production. In order to limit noise generation, certain filters are utilized at the input of the converter. Their parameters are considered in the simulations. It is to be mentioned again that not similar to other studies concerning low frequency analysis of noise spectrum, this paper analyses the output noise spectrum in Radio Frequencies (RF).

2-FIXED FREQUENCY PWM

A simple fixed frequency PWM controller applied to a buck DC/DC converter and the corresponding waveforms are showed in Fig.1.

Assuming the error Voltage $v_e$ to change slow with respect to the switching frequency, the pulse width and hence the duty cycle can be approximated by equation (1), where $V_p$ is the sawtooth voltage amplitude.

$$d = \frac{v_e}{V_p}$$

(1)

This type of controller, which utilizes voltage information in order to regulate output voltage, is called voltage mode controller.
3-PWM WAVEFORM SPECTRAL ANALYSIS

The normalized pulse train \( m(t) \) of Fig.2 represents PWM waveform. The nth pulse of PWM waveform consists of a fixed component \( \frac{D}{f_s} \), in which D is the steady state duty cycle, and a variable component \( \frac{d_n}{f_s} \), in which n represents the variation of duty cycle due to that of source, reference and load.

![Fig.2 PWM Waveform](image)

Representing switch current in the Buck DC/DC converter, PWM waveform contains useful information concerning noise in the power supply. Doing the spectrum analysis in RF bands, one can ignore the small variations of pulses during the time period of \( \frac{n}{f_s} \) to \( \frac{n+d_n}{f_s} \). Thus the error Voltage variation is considered as equation (2).

\[
v_e = V_e + V_e \sin 2\pi f_m t
\]  

(2)

\( f_m \) represents the frequency of error voltage variation due to the variations of source, reference and load. The interception of the error voltage variation curve and the PWM sawtooth with switching frequency results equation (3) for the computation of duty cycle coefficients.

\[
d_n = D + D_t \sin 2\pi f_m \frac{(n + d_n)}{f_s}
\]  

(3)

It is considerable that the maximum variation of the pulse width around its steady state value of \( D \) is determined by \( D_1 \). In a period of \( T_m = \frac{1}{f_m} \), there will be \( r = \frac{f_s}{f_m} \) pulses with duty cycles of \( d_n \). Equation (4) presents the Fourier series coefficients \( C_n \) of the PWM waveform \( m(t) \). Which have the frequency spectrum of Fig.3.

\[
C_n = \sum_{k=1}^{r} d(k) \text{Sinc}(n\Delta f(k)) e^{-jn\Delta f(k)} e^{-j2\pi k l_r / r}
\]  

(4)

4-cm & dm MODES OF CONDUCTED NOISE

The connection of elements, source lines and cabling provide the path for conducted noise emission. Conducted noise has two components, Differential Mode (dm) which considers the noise between two lines of power supply and Common Mode (cm) existing between each line and common ground. The dm conducted noise current path \( I_{dm} \), in an electrical circuit is shown in Fig.4. In the case of a connection between load and chassis, or a leakage current between load and ground in high frequencies, the voltage difference of different ground nodes can be modeled by a voltage source. This is shown in Fig.5 that specifies the cm conducted noise current paths \( I_{cm1} \) and \( I_{cm2} \) Fluke(3).

![Fig.4 Differential Mode Conducted Noise](image)
The input current of a buck converter performs as a noise source for the DC network. Therefore, in this case dm conducted noise is particularly important. The discussion will be continued considering this mode only.

5-CONDUCTED NOISE ANALYSIS

5-1-Line Impedance Stabilization Network (LISN)

LISN is an industrial element that should have following characteristics to satisfy measurement conditions:

1-Transferring power from source to converter, LISN must provide a low impedance path for noise measurement.

2-The effect of source impedance in noise measurement must be reduced by LISN.

According to Fig.6, LISN is placed between power supply and converter, and noise is measured at its output.

The analysis of an industrial LISN would be too complicated, therefore a simple model with sufficient accuracy is used Mahdavi et al(4,5). The noise source is the converter input current that has the PWM waveform studied in previous section.

5-2-Equivalent noise circuit and output noise spectral analysis

In the equivalent circuit of Fig.7 the voltage source \(V_S\) is replaced by short circuit and the input current of the converter is represented by a noise current source. This will be useful in the analysis of dm conducted noise.

The transfer function is defined as the ratio of the output voltage to the current noise. Taking the effect of the filter at the converter input into account, the transfer function is derived as equation (5).

\[
H(S) = \frac{V_{LISN}(S)}{I_{ex}(S)} = \frac{n_0 + n_1 S + \ldots n_5 S^5}{d_0 + d_1 S + \ldots + d_5 S^5}
\]

The coefficients \(d_i, n_i\) (i = 1, 2, ..., 5) correspond to the parameters of the equivalent noise circuit. \(R_c\) and \(L_c\) are respectively the effective series resistance (ESR) and inductance (ESL) of the filter capacitor \(C_f\) and model the effect of its nonideality. Fig.8 demonstrates the transfer function \(H(j\omega)\) in the frequency domain, with following parameters for the LISN and the filter:
6-2-Amplitude of duty cycle variation (D1)

The maximum pulse width variation is determined by D1. The noise spectrum was computed with different values of D1 = 0.0001, 0.05, 0.1, 0.45. Increasing of D1 causes the expansion of the noise spectrum in frequency domain, which produces a small reduction in the maximum level of conducted noise. Practically the appropriate value of D1 is limited by control aspects of the power supply design.

6-3-Modulation frequency (f_m)

Reference voltage can be regulated using appropriate electronic design, and load variations are too slow, thus the main factor in the variation of duty cycle is the source voltage. The 100 Hz ripple in source voltage is the inevitable consequence of the usage of rectifiers. The output noise spectrum is computed in the frequencies of f_m = 100, 500, 5000 Hz. According to the results in higher frequencies the noise spectrum expands in frequency domain but causes small variation in the maximum level of conducted noise.

6-4-Filter parameters (L_c, R_c)

Filter has an important effect in the reduction of conducted noise. As the simulation show in the electronic design the elements of the filter should be chosen as large as possible. The nonideality of the elements, specially C_f reduces the noise reductive effect of the filter. Fig.10 shows the effect of R_c and L_c in equation (5).

Fig.8 LISN Frequency Response

The output noise spectrum is derived by multiplication of the transfer function and the source noise spectrum. In the mentioned condition of parameters, the output noise spectrum will be as Fig. 9.

Fig.9 Noise spectrum versus f/f_m

6-PARAMETERS AFFECTING THE OUTPUT SPECTRUM

6-1-Duty cycle (D)

The pulse width in PWM waveform varies around a steady state D. The output noise spectrum was computed with different values of D=0.5, 0.9, 0.1. With D = 0.1 and D = 0.9 even harmonics are added to odd ones, but these latters show a small reduction in their amplitudes. However D = 0.5 has the highest level of noise production. The effect of other parameters will be studied in the condition of D = 0.5.
6-5-Nonideal performance of switch

The nonideal performance of switch affects the falling and rising edges of the converter input current therefore the analysis of rise time and fall time values must be considered in the computations. Fig.11 shows the variations of $C_n$ in the ideal condition ($t_r=t_f=0$), the symmetrical condition, $(t_r=t_f=0)$ the practical condition, $(t_f < t_r < 0)$ for normalized waveform.

Considering the practical condition, equation (4) changes to equation (6).

$$C_n = \sum_{k=1}^{\infty} d(k) \text{Sinc}(nt_r) \text{Sinc}(n\pi) e^{-j2\pi(k-1)/r}$$

(6)

For typical switches, such as power MOSFETs, the practical values of $t_r$ and $t_f$ are less than 100 ns. Therefore the reduction of $C_n$ occurs in high frequencies.

7-CONCLUSION

Conducted RFI emission was studied in a switching power supply. Avoiding the complexity of an industrial LISN analysis, a simple but sufficiently accurate model was used. Considering its high ability of noise generation, a step down converter was chosen, in which the input current was assumed as the origin of conducted noise and was modeled by a noise current source. In this study, the variation of duty cycle around its steady state is considered in the noise spectrum computation. As the results show, the highest level of noise production occurs in the duty cycle $D=0.5$ with small variations. According to the nonideality analysis of the LC filter at the input of the converter, in high frequencies the capacitor shows inductive characteristics, causing weak performance of the filter.

The primitive laboratory results, which confirm the study, will be subsequently published.

8-REFERENCES

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