Impact of Periodic Frequency Modulation on Power Quality of Switching Power Converter

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***Abstract* – In this paper power quality of switching frequency modulated (SFM) power converters is analyzed in details. Careful attention is paid on the effect of SFM parameters on switching power converter input current total harmonic distortion (THD) and power factor. Theoretical analysis, simulations and experiments show that SFM used for electromagnetic interference reduction in switching power converters has almost invisible impact on input current THD and power factor of conventional switching power converters.**

***Keywords:* frequency modulation; power converter; electromagnetic interference; power quality.**

I. INTRODUCTION

Switching power converters (SPC) are widely used for electric power conversion in modern electronic equipment. Conventional AC-mains-connected SPC usually consists of diode bridge rectifier, large capacitance filtering capacitor C_{in} and DC/DC SPC (Fig.1.). Input current of conventional AC-mains-connected SPC is usually highly distorted and therefore the input power quality (PQ) is bad.

Input PQ of SPC is characterized by power factor (PF) and input current total harmonic distortion (THD) [1]. PF by definition is the real power P_{real} ratio to apparent power P_{app} [1], [2]. Input current THD is directly related to PF as follows [2]

$$PF = P_{real} / P_{app} = \cos(\varphi) / \sqrt{1+THD^2} \quad , \qquad (1)$$

where φ is phase angle between input voltage and current fundamental harmonics. The higher THD of SPC input current is, the lower PF is and the worse PQ is. In an ideal case AC line current is purely sinusoidal, so it has only one spectrum component at mains frequency (f_{mains}). In a real case of course AC line current is distorted and harmonics of f_{mains} appear in its spectrum.

SPC are major sources of electromagnetic interference (EMI). Various EMI suppression techniques have been proposed and used over the last decades including EMI filters, ferrite beads, etc [3] - [6]. One of the novel yet simple and cheap techniques known today for EMI reduction in SPC is so called spread spectrum technique [4] – [8]. Spreading the spectrum of SPC voltages and currents and consequently noticeable peak EMI levels reduction can be easily achieved through the modulation of switching frequency f_{sw} periodically, randomly or even chaotically [7], [8]. Periodic switching frequency modulation (SFM) is widely used in practice because it is very cheap and simple method. To implement periodic SFM usually simple periodic modulating waveforms (such as sine, triangle, sawtooth, etc) are often used. The main parameters of periodic SFM are switching frequency deviation Δf_{sw}, modulation frequency f_m and modulating waveform.

Although SFM is very useful to reduce EMI, it is reported in several papers that the technique can increase THD of SPC input current and reduce PF [5], [6], [9]. For example in [6] and [9] it is experimentally verified that SFM can increase THD of power factor correctors (PFC) appreciably. Appearance of modulation frequency f_m harmonics in the PFC input current spectrum was also observed in the papers. But in [5] experiments and simulations of resonant inverter for induction heating appliances show that mains input current THD increases by several %.

Despite the fact that the effect of SFM on AC-mains-connected SPC input current THD and PF was studied in [5], [6] and [9], clear and detailed explanation why SFM can degrade the input PQ and increase input current THD is not presented in the papers. Moreover the effect of SFM on PQ of conventional AC-mains-connected SPC with large capacitance filtering capacitor following diode bridge are not examined in the papers.

In this paper the effect of periodic SFM on PQ and THD of conventional AC-mains-connected flyback

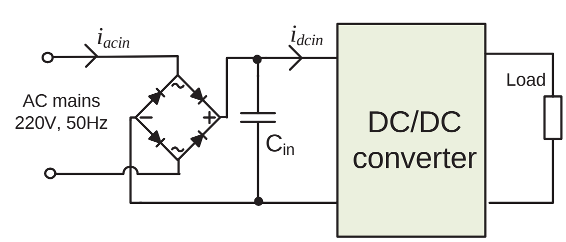

Fig.1. Block diagram of a conventinal AC-mains-connected SPC.

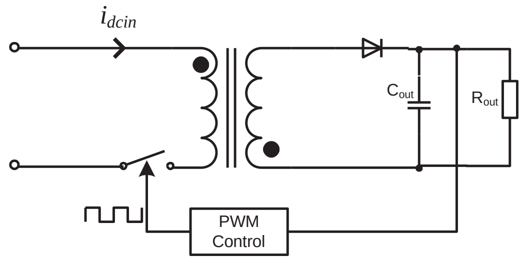

Fig.2. Schematic diagramm of flyback DC/DC converter.

converter will be studied in details theoretically, using SIMULINK simulations and experimentally.

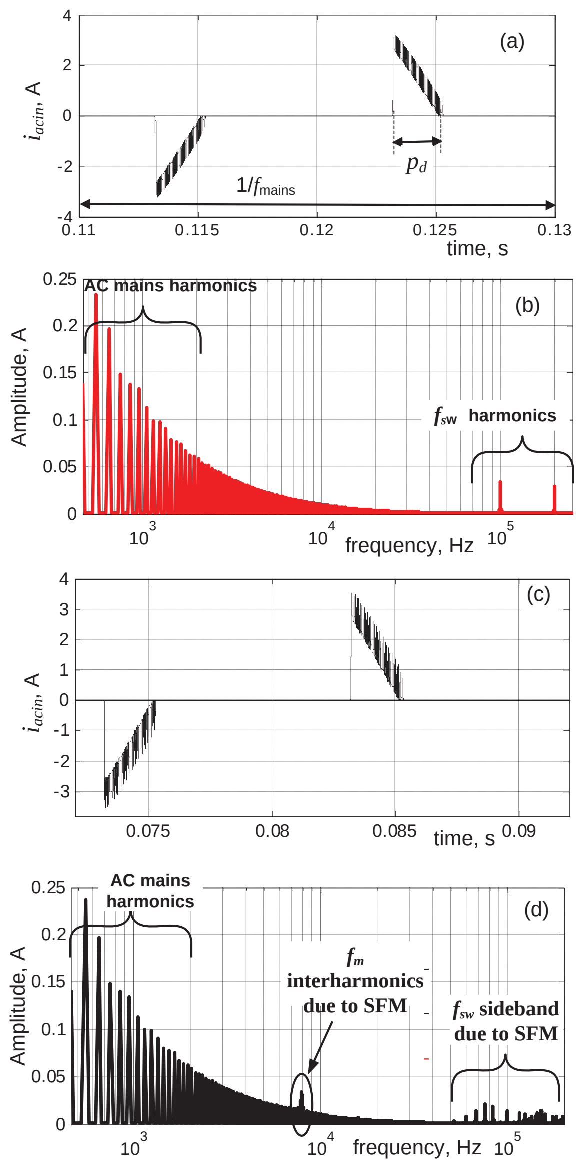

Fig.3. Simulated i_{acin} of AC-mains-operated flyback SPC in DCM: (a) in time domain without SFM; (b) in frequency domain without SFM; (c) in time domain with SFM; (d) in frequency domain with SFM. (Parameters: f_m=8kHz; Δf_{sw}=30kHz; f_{sw}=100kHz; V_{inrms}=220V; f_{mains}=50Hz; D=0.2; C_{in}=50μF; L_m=200μH).

II. Analysis of Input Current Spectrum of SPC

In this section spectrum of conventional AC-mains-connected SPC AC input current i_{acin} will be analyzed with and without SFM. It is assumed in the paper that the DC/DC converter is flyback (Fig. 2).

A. Without SFM

As an example simulated i_{acin} waveform and its spectrum without SFM depicted in Fig.3(a,b).When SFM disabled then input AC current consists of two components: narrow pulses with AC mains frequency f_{mains} and high frequency (HF) switching ripples with f_{sw}. In frequency domain i_{acin} consists of f_{mains} harmonics and spectrum components at f_{sw} and its multiples.

B. With SFM

When SFM enabled i_{acin} consists not only of the narrow current pulses and HF switching ripples but also of low frequency (LF) ripples with f_m caused by SFM (Fig. 3(c)). Moreover SFM causes interharmonics with frequencies $nf_m \pm mf_{mains}$ (where m=1, 2, 3…. and n=1, 2, 3….) in the LF region of i_{acin} spectrum. The LF interharmonics can increase THD of i_{acin} if they appear in the frequency range of a power analyzer. Moreover the LF interharmonics can be regarded as EMI in the LF region (this is because several standards, e.g. CISPR16 require EMI measurements from 9 kHz).

Now it is of importance to find out the cause of the LF interharmonics in i_{acin} spectrum. For this purpose flyback converter DC input current i_{dcin} will be analyzed first. In Fig. 4 simulated i_{dcin} of flyback SPC with and without SFM in time and frequency domains is shown. When SFM is not used then there are no LF components in i_{dcin} spectrum (Fig. 4(b)). However when SFM is used then noticeable LF components at f_m and its multiples appear in i_{dcin} spectrum (Fig. 4(d)). It is logically that these LF components in i_{dcin} spectrum are responsible for f_m interharmonics in i_{acin} spectrum.

It is rather well known from power electronics that for the analysis of SPC in the LF region method of averaging can be used [3]. In fact the method is also used in [10] to calculate LF output voltage ripples due to SFM and in [11] to analyze the effect of SFM on boost DC/DC SPC input current in the LF region. Input DC current of flyback converter averaged to switching period T_{sw} is

$$\langle i_{dcin} \rangle = \frac{D^2 V_{dcin}}{2 L_m f_{sw}} \qquad (2)$$

where D is duty ratio; V_{dcin} is flyback converters DC input voltage; L_m is flyback transformer magnetizing inductance. Since f_{sw} is modulated then instantaneous switching frequency

$$f_{sw}(t) = f_{sw0} + \Delta f_{sw} m(t) \ , \qquad (3)$$

where *m(t)* is the modulating waveform (e.g. sine) with unitary amplitude; f_{sw0} is central switching frequency; Δf_{sw} is switching frequency deviation. This means that

$\langle i_{dcin} \rangle$ of SFM flyback converter is switching frequency dependent as follows

$$\langle i_{dcin} \rangle = \frac{D^2 V_{dcin}}{2L_m f_{sw}(t)} \quad . \tag{4}$$

Assuming that Δf_{sw} is much lower than f_{sw0} then 1st order-Taylor-series-approximation can be used

$$\langle i_{dcin} \rangle \approx \frac{D^2 V_{dcin}}{2L_m f_{sw}} - \frac{D^2 V_{dcin}}{2L_m} \frac{\Delta f_{sw}}{f_{sw0}^2} m(t) \quad . \tag{5}$$

Eq. (5) clearly shows that SFM results in f_m harmonics in i_{dcin} spectrum, because input DC current of flyback converter in DCM is f_{sw} dependent. The amplitudes of the LF harmonics for open-loop flyback SPC with SFM can be calculated as follows

$$C_{dcn} \approx \left| d_{mn} \frac{\Delta f_{sw}}{f_{sw0}^2} \frac{D^2 V_{dcin}}{2L_m} \right| \tag{6}$$

where d_{mn} is $m(t)$ Fourier series complex coefficients (for sine $m(t)$ d_{mn} is 1). Since SFM induces LF ripples in output voltage of SPC [10], then PWM control changes instantaneous duty ratio to minimize the LF variations when $f_m < f_c$ (where f_c is open loop crossover frequency). So for closed loop SFM flyback SPC the amplitudes of the LF harmonics can be calculated as follows

$$C_{dcn} \approx \left| d_{mn} \frac{\Delta f_{sw}}{f_{sw0}^2} \frac{D^2 V_{dcin}}{2L_m} \frac{1}{1+T(s)} \right| \quad , \tag{7}$$

where $T(s)$ is open loop gain in DCM. In (7) $s = j2\pi n f_m$.

SFM flyback SPC input AC current i_{acin} spectrum components can be calculated assuming that the LF f_m harmonics in i_{dcin} interact with f_{mains} harmonics. As a result SFM causes f_m interharmonics with frequencies $nf_m \pm mf_{mains}$ in i_{acin} spectrum. So, SFM SPC i_{acin} amplitudes of spectrum components in LF region can be derived as follows

$$C_{acm} = \left| \frac{\dot{C}_{dcn}}{1 + \dfrac{\underline{Z}_s + R_{br}}{\underline{Z}_{cin}}} \otimes d_{en} + I_{mainsm} \right| \tag{8}$$

where I_{mainsm} is f_{mains} harmonics complex amplitudes without SFM; where d_{en} is complex amplitudes of spectrum of equivalent rectangular pulse train with unitary amplitude (the duration of the pulse trains is equal to p_d (Fig.3(a))); $\underline{Z}_{Cin}$ is input capacitor complex impedance; $\underline{Z}_s$ is power source complex impedance; R_{br} is diode bridge forward resistance; $\otimes$ means convolution. It is clearly seen in Fig. 3(d) and Fig. 4(d) that f_m inetrharmonics amplitudes in i_{acin} spectrum caused by SFM are several times lower than amplitudes of f_m harmonics in i_{dcin} spectrum. This is due to two reasons: firstly, input filtering capacitor C_{in} partly reduces the amplitudes of the LF components; secondly, the AC input current i_{acin} flows only short time interval $2p_d$ (Fig. 3(a)). The same conclusion can also be deduced from (8).

Simulation results revealed that THD of i_{acin} with SFM (f_m=1kHz; Δf_{sw}=30kHz) increases only by 0.5 % due to SFM when f_m=1kHz. For other f_m values increase in THD was even lower.

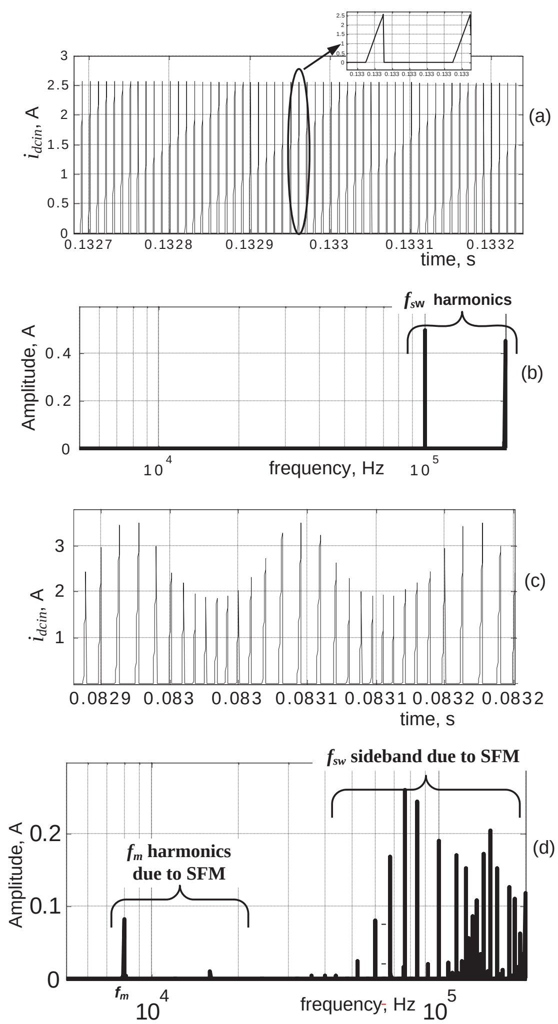

Fig.4. Simulated i_{dcin} of DC/DC flyback SPC in DCM: (a) in time domain without SFM; (b) in frequency domain without SFM; (c) in time domain with SFM; (d) in frequency domain with SFM. (Parameters: f_m=8kHz; Δf_{sw}=30kHz; f_{sw}=100kHz; D=0.2).

III. Experiments

For experimental investigation conventional AC-main-connected flyback switching power converters have been designed and experimented. The flyback converter operates in DCM and its nominal output power 40W. The experimental SPC can operate in both modes: with and without SFM. The simplified schematic

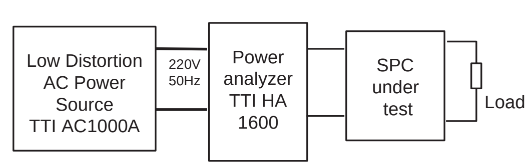

Fig.5. Block diagram of the experimental setup.

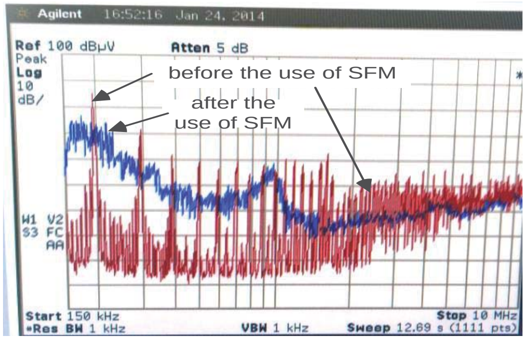

Fig.6. Experimental conducted EMI spectrum of SFM AC-mains-connected flyback SPC operating in DCM. (Parameters: f_m=2kHz; Δf_{sw}=30kHz, f_{sw}=80kHz).

diagram of the experimental setup is shown in Fig. 5. AC input current THD and power factor have been measured with and without SFM using high quality power and harmonics analyzer TTI HA1600. The measurement results are tabulated in Table 1 and Table 2 for different values of Δf_{sw}, and f_m.

The results presented in Tables 1 and 2 confirm theoretical predictions that increase in THD is negligible (<0.5%) for conventional SPC due to the use of SFM. Moreover PF remains constant even for high Δf_{sw}. Slight increase in THD is due to f_m interharmonics in input AC current spectrum. For higher values of Δf_{sw} THD is slightly higher. Choice of f_m slightly affect THD: when f_m-f_{mains} higher than power analyzer maximum analysis frequency f_{max} (e.g. TTI HA1600 measure harmonics up to f_{max}=2kHz) then the power analyzer cannot see the interharmonics of f_m due to SFM and measured THD is the same as for SPC without SFM. When f_m<1kHz then THD is the same as for unmodulated case. This can be described by (7): for lower f_m open loop gain $T(s)$ is higher and therefore C_{dcn} are lower.

After the power quality has been measured conducted EMI of the experimental flyback SPC was also measured using a spectrum analyzer (with a peak detector and resolution bandwidth (RBW) of 1kHz) and line impedance stabilization network. As an example experimental conducted EMI spectrum in the frequency range 150kHz – 10MHz is shown in Fig.6. As it can be seen from Fig. 6 and Tables 1 and 2 SFM can lead to noticeable conducted EMI reduction in SPC without degrading input power quality of conventional SPC.

TABLE I. FLYBACK CONVERTER THD AND PF VS MODULATION FREQUENCY (NOMINAL LOAD; Δf_{sw}=30KHZ; f_{sw}=80KHZ).

f_m, kHz	THD, %	PF
unmodulated	91.5	0.414
0.5	91.5	0.414
1	91.8	0.414
2	91.8	0.414
5	91.5	0.414

TABLE 2. FLYBACK CONVERTER THD AND PF VS SWITCHING FREQUENCY DEVIATION (NOMINAL LOAD; f_m=1KHZ; f_{sw}=80KHZ).

Δf_{sw}, kHz	THD, %	PF
10	91.5	0.414
30	91.8	0.414

IV. CONCLUSIONS

Comprehensive study of the effect of SFM on power quality of conventional AC-mains-connected SPC shows that SFM is very effective technique for conducted EMI reduction without noticeable degradation of input power quality characterized mainly by THD and PF. This is because conventional AC-mains-connected SPC have inherently high current THD and slight increase in THD is not a problem. Moreover THD cannot increase significantly due to SFM because they have large capacitance filtering capacitor following a rectifier and due to the fact that the AC input current flows only short time interval. Obviously in PFC which inherently has small input current distortion and which do not have large capacitance input filtering capacitor, the use of SFM is much more problematic.

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