Scientific Journal of Riga Technical University
Telecommunications and Electronics

2011

Volume11

Reducing Negative Effect of Frequency Modulation on Switching Power Converter Efficiency

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***Abstract* - In the paper, the effect of frequency modulation (FM) on efficiency of classical dc/dc switching power converters (SPC) is examined. The results obtained show that FM can decrease the efficiency of SPC. A procedure and expressions to calculate the efficiency and total power losses in the basic SPC topologies (buck, boost, buck-boost) are presented. Recommendations to improve the efficiency are also proposed.**

***Keywords:* power converter, frequency modulation, efficiency.**

I. INTRODUCTION

Nowadays switching power converters (SPC) are often used for electric power conversion, because of their advantages, mainly high efficiency and high specific power. Nevertheless SPCs have also their disadvantages, mainly high electromagnetic interference (EMI), which can be harmful to other electronic equipment. Despite the fact that filters, shielding, etc are classical ways to mitigate the problem, they usually increase weight, size and cost of SPC [1,2].

Spread spectrum approach, which is usually based on frequency modulation (FM), is one more successful technique to reduce EMI. In fact, the technique usually does not require the increasing size and cost of electronic equipment [2,3].

Nevertheless the use of FM has also several drawbacks, mainly, it can increase output voltage ripples significantly and reduce efficiency of SPC [4,5]. By analyzing the publications [5-7] about adverse effects of FM on SPC losses and efficiency (η), it is revealed that the problem is not well understood, mainly because examination of the problem in the publications is experimentally substantiated without relevant theoretical explanation. For example, it is found out experimentally in [7] that efficiency of FM 600W boost power factor corrector decreases by several percent due to the use of FM. In [7] this was explained by the increased losses in power inductor core. However the experimental investigation of the same PFC in [5] showed that FM does not affect efficiency. It is also found out experimentally in [6] that FM has no influence on efficiency of FM 600W SPC. The theoretical investigation of the problem was only presented in [4,8]. Despite a detailed study of the effect of FM on SPC efficiency presented in [4], a boost converter was only investigated. Moreover, for power inductor magnetic core loss analysis traditional Steinmetz equation is used in [4]. This can be a major source of errors because the equation is only useful when triangular-like power inductor current duty ratio is 50% [9]. That it is why in this paper a modified Steinmetz equation proposed in [9] for unmodulated SPC is used to get much more precise loss calculation for FM SPC.

Thus, the main aim of the paper is to examine classical FM dc/dc SPCs (buck, boost, buck-boost) operating in continuous conduction mode (CCM), to develop a simplified procedure to calculate losses and the efficiency of the basic converters, and to propose some recommendations to improve the efficiency.

II. GENERAL EXPRESSIONS TO CALCULATE LOSS OF FM SPC

As it has been mentioned before, a detailed study of the effect of FM on boost SPC losses in continuous conduction mode is done in [4]. General expressions to calculate losses ($P_{lossmod}$) and the efficiency (η) can be derived as follows [4]:

$$P_{loss\,\mathrm{mod}} = \frac{1}{T_m}\int_0^{T_m} p_{loss}(t)dt = \frac{1}{T_m}\sum_{k=1}^{T_m/T_{sw}} P_{loss}(T_{sw,k})T_{sw,k} \tag{1}$$

$$\eta = P_{out}/(P_{out}+P_{loss}) \tag{2}$$

where $p_{loss}(t)$ are instantaneous losses of FM SPC; $P_{loss}(T_{sw,k})$ are average losses at k-th switching period $T_{sw,k}$; T_{sw} is unmodulated SPC switching period; T_m is modulation signal period; P_{out} is output power. Note that the expression is only useful when T_m/T_{sw} is an integer number.

Assuming that T_m is higher than T_{sw} at least by an order of magnitude and that f_{sw} is periodically modulated by $m(t)$ (e.g. sine or triangular), (1) can be shown to be:

$$P_{loss\mathrm{mod}} = \frac{1}{T_m}\int_0^{T_m} P_{loss}(f_{sw}(t))dt \tag{3}$$

where $f_{sw}(t)$ is instantaneous switching frequency according to:

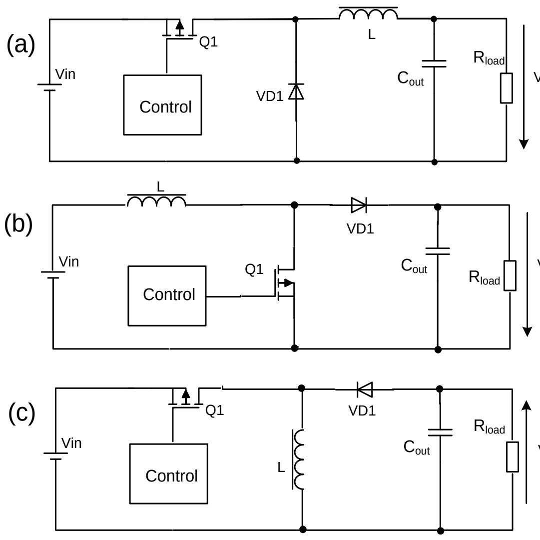

Fig. 1.Classical SPC examined: (a) buck; (b) boost; (c) buck-boost.

$$f_{sw}(t) = f_{sw} + \Delta f_{sw} m(t) \qquad (4)$$

where *m(t)* is the modulating signal; Δf_{sw} is frequency deviation; f_{sw} is the central switching frequency. As it can be seen from (1) - (3), the expressions can be used for various FM SPC topologies.

III. EFFECT OF FM ON SPC EFFICIENCY

A. Losses of unmodulated SPC

It is assumed in the analysis that the power transistor is MOSFET but the free-wheeling diode is the Schottky one. The three basic converters examined (see Fig.1) operate in CCM. The power MOSFET loss in the converters is mainly conduction loss (P_{Tcon}) and switching loss (P_{sw}) [10] as follows:

$$P_{Tcon} = R_{DS} I_{Drms}^2 \qquad (5)$$

$$P_{sw} = (1/2)B_2[(I_{Lavg} - \Delta i_L/2)t_r + (I_{Lavg} + \Delta i_L/2)t_f)]f_{sw} \qquad (6)$$

Where R_{DS} is power MOSFET on-resistance; I_{Drms} is RMS drain current of MOSFET; V_{out} is output dc voltage; I_{Lavg} is average inductor current; t_r and t_f are the power MOSFET rise and fall times respectively; Δi_L is the power inductor current peak-to-peak ripples. After several simplifications of (5) and (6), simple expressions to calculate power MOSFET losses of the converters can be derived:

$$P_{Tcon} = R_{DS} D I_{Lavg}^2 + \frac{R_{DS} D^3 B_1^2}{12 L^2 f_{sw}^2} \qquad (7)$$

$$P_{sw} = 0.5 B_2 I_{Lavg} (t_r + t_f) f_{sw} \ , \qquad (8)$$

where D is duty ratio; B_1 and B_2 are topology-dependent coefficients listed in Table 1. For precise calculations of I_{Lavg} real components should be taken into account.

Since Schottky diode switching losses are usually small, only conduction losses are considered as follows [4,11]:

$$P_{dcon} = (1-D) R_d I_{Lrms}^2 + V_d I_{Lavg} (1-D) \qquad (9)$$

where V_d is diode threshold voltage; R_d is diode forward resistance. For the topologies examined the formula (9) can be rewritten:

$$P_{dcon} = (1-D) R_d I_{Lavg}^2 + \frac{(1-D) R_d D^2 B_1^2}{12 L^2 f_{sw}^2} + V_d I_{Lavg} (1-D) \qquad (10)$$

Power inductor loss can be subdivided into winding losses (P_w) and magnetic core losses (P_{mc}). The winding losses are:

$$P_w = R_L I_{Lrms}^2 = R_L I_{Lavg}^2 + \frac{R_L D^2 B_1^2}{12 L^2 f_{sw}^2} \qquad (11)$$

where R_L is the power inductor DC resistance.

In the analysis, magnetic core losses are derived using modified Steinmetz equation [9] as follows:

$$P_{mc} = C_m \left[\frac{2}{\pi^2} \left(\frac{1}{D} + \frac{B_3^2 (1-D)}{B_1^2 D^2} \right) \right]^{\alpha - 1} \left(\frac{B_1 D}{2NS} \right)^{\beta} \frac{V_c}{f_{sw}^{\beta - \alpha}} \qquad (12)$$

where C_m, α, β are Steinmetz equation empirical coefficients that are usually listed in magnetic core material datasheets; N is number of turns of power inductor; S is the magnetic core cross-section area; V_c is the magnetic core volume; B_3 is topology-dependent coefficient from Table 1. Note that for magnetic core loss calculation (12) is much more precise than the expression used in [4] for different D values.

TABLE1
TOPOLOGY-DEPENDENT COEFFICIENTS FOR LOSS CALCULATIONS

	B_1	B_2	B_3	B_4	B_5	B_6	B_7
Buck	V_{in}-V_{out}	V_{in}	-V_{out}	D	1-D	1	0
Boost	V_{in}	V_{out}	V_{in}-V_{out}	1	0	1-D	D
Buck-Boost	V_{in}	V_{in}+V_{out}	-V_{out}	D	1-D	1-D	D

Input and output capacitor losses for the three topologies are the following:

$$P_{Cin} = r_{Cin} B_4 (B_5 I_{Lavg}^2 + \Delta i_L^2 / 12) \qquad (13)$$

$$P_{Cout} = r_{Cout} B_6 (B_7 I_{Lavg}^2 + \Delta i_L^2 / 12) \ , \qquad (14)$$

where B_4 - B_7 are topology-dependent coefficients listed in Table 1.

As it can be deduced from (7) - (14) and as it is also proved in [4], the losses can be rewritten in the form:

$$P_{loss} = P_{const} + P_{lin}(f_{sw}) + P_{nonlin}(f_{sw}) \ , \qquad (15)$$

where P_{loss} is total power losses of unmodulated SPC; P_{const} are independent on f_{sw} losses; $P_{lin}(f_{sw})$ are linearly dependent on f_{sw} losses and $P_{nonlin}(f_{sw})$ are nonlinearly dependent on f_{sw} losses. The total power loss components therefore are the following:

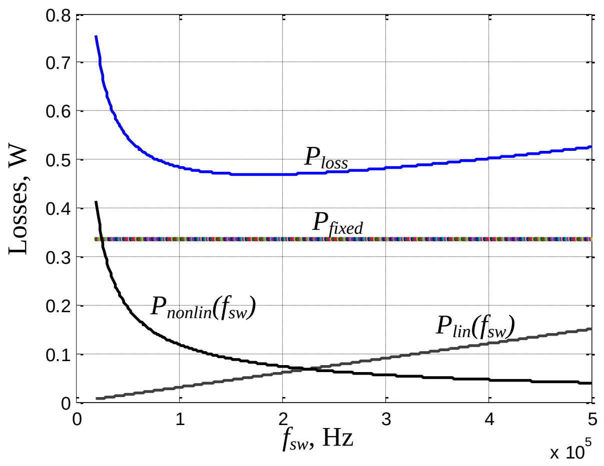

Fig.2. Calculated P_{loss} and its components dependence on f_{sw} for unmodulated boost SPC in CCM with the powdered-iron-core power inductor (L=46μH; C_{out}=330μF; V_{in}=5V;R_{load}=12.7Ω).

$$P_{const} = I^2_{Lavg}[R_L + DR_{DS} + (1-D)R_d + V_d(1-D)/I_{Lavg} + + B_6B_7r_{Cout} + B_4B_5r_{Cin}] \tag{16}$$

$$P_{lin}(f_{sw}) = \frac{1}{2}B_2I_{Lavg}(t_r + t_f)f_{sw} \tag{17}$$

$$P_{nonlin}(f_{sw}) = \frac{B_1^2D^2[R_L + DR_{DS} + (1-D)R_d + B_6r_{Cout} + B_4r_{Cin}]}{12L^2f_{sw}^2} + + C_m\left[\frac{2}{\pi^2}\left(\frac{1}{D} + \frac{B_3^2(1-D)}{B_1^2D^2}\right)\right]^{\alpha-1}\left(\frac{B_1D}{2NS}\right)^{\beta}\frac{V_c}{f_{sw}^{\beta-\alpha}} = \frac{A_1}{f_{sw}^2} + \frac{A_2}{f_{sw}^{\beta-\alpha}} \tag{18}$$

As an example unmodulated boost SPC losses versus f_{sw} are shown in Fig.2 [4]. As it can be seen $P_{lin}(f_{sw})$ are more pronounced at higher f_{sw}, while $P_{nonlin}(f_{sw})$ are more pronounced at lower f_{sw}.

B. Losses of FM SPC

As it was proved in [4] FM can only affect $P_{nonlin}(f_{sw})$, as it can also be deduced from (1), (3), (15)-(18). That is why the total power losses of FM SPC ($P_{lossmod}$) are:

$$P_{lossmod} = P_{const} + P_{lin}(f_{sw}) + P_{nonlinmod}(f_{sw}), \tag{19}$$

where $P_{nonlinmod}(f_{sw})$ are nonlinearly-dependent on f_{sw} losses of FM SPC. So the losses of FM SPC examined, for example, for triangular or sawtooth FM are the following:

$$P_{nonlinmod}(f_{sw}) = A_1/(f_{swc}^2 - \Delta f_{sw}^2) + + A_2\frac{(f_{swc} + \Delta f_{sw})^{\alpha-\beta+1} - (f_{swc} - \Delta f_{sw})^{\alpha-\beta+1}}{2\Delta f_{sw}(\alpha - \beta + 1)} \tag{20}$$

where A_1 and A_2 are coefficients from (18).

As an example calculated FM boost SPC losses and efficiency versus f_{sw} are shown in Fig.3. But in Fig.4 experimental results for the same boost FM SPC are depicted. As it can be seen, the theoretical results are in a good agreement with the experimental ones. This clearly shows that the expressions derived for FM SPC are very useful. The same conclusion was also deduced from comparison of theoretical and experimental results for buck and buck-boost converters.

It should be noted that triangular or sawtooth FM gives better results than the sinusoidal one, as it can be seen in Fig. 3 and Fig. 4.

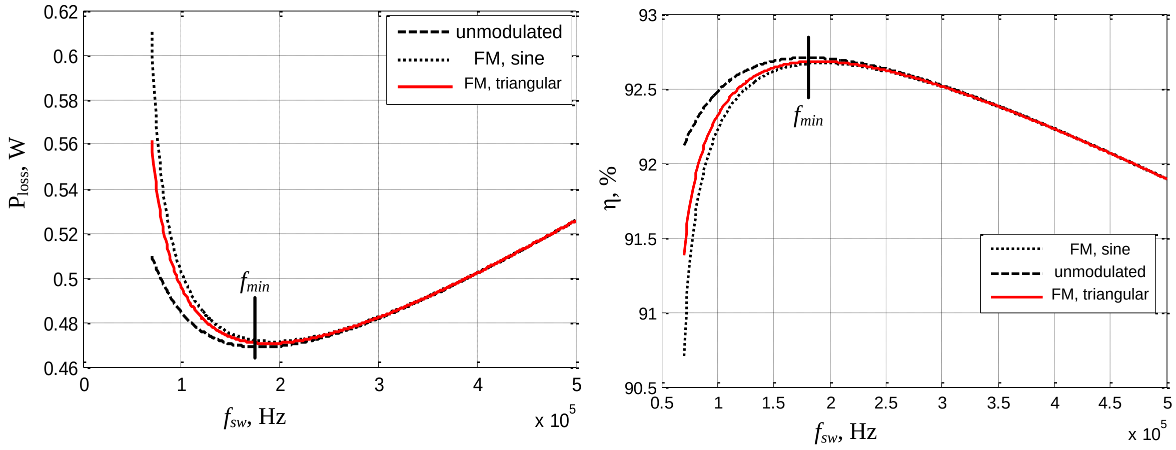

Fig.3. Calculated $P_{lossmod}$ and η versus f_{sw} for unmodulated and FM boost SPC. FM parameters: f_{swc}=70...500kHz; Δf_{sw}=60kHz; f_m=1kHz; *m(t)* is sine and triangular.

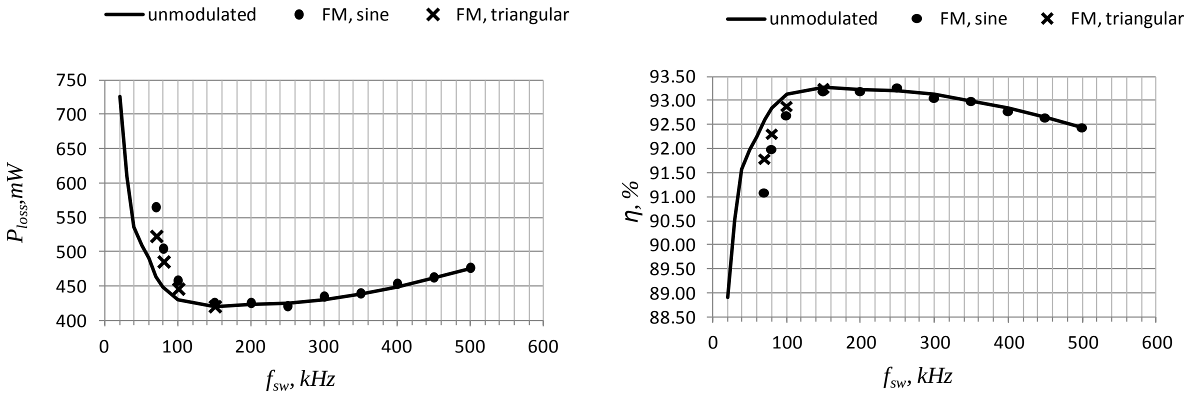

Fig. 4.Experimental η and the total losses versus f_{sw} for unmodulated and FM boost SPC. Parameters are the same as for Fig. 3.

IV. PROCEDURE TO CALCULATE EFFICIENCY OF FM BUCK, BOOST AND BUCK-BOOST SPC

Despite the procedure to calculate losses and efficiency was also proposed in [4], it is not so useful for the topologies examined. Using the procedure developed in [4], we propose a new simplified one:

- depending on SPC topology, write down coefficients from Table 1;
- calculate losses $P_{lin}(f_{sw})$ and P_{const} of unmodulated SPC using Eq. (16), (17);
- derive the expression for $f_{sw}(t)$ for a given $m(t)$;
- derive $P_{nonlin}(f_{sw})$ using Eq. (18);
- calculate FM SPC $P_{nonlinmod}(f_{sw})$ using Eq. (3);
- finally, using Eq. (2) and (19) calculate the total power loss and the efficiency of FM SPC.

V. RECOMMENDATIONS

Based on the results obtained in the paper for the basic FM SPC examined, now we can propose some useful recommendations to reduce the negative effect of FM on SPC efficiency. As losses of unmodulated SPC ($P_{nonlin}(f_{sw})$), which are nonlinearly-dependant on f_{sw}, usually decrease as f_{sw} increases and FM can increase only $P_{nonlin}(f_{sw})$, minimum switching frequency $f_{swmin}=f_{sw}-\Delta f_{sw}$ should be chosen so that $f_{sw}(t)$ changes in the region where $P_{nonlin}(f_{sw})$ is much lower than $P_{const}+P_{lin}(f_{sw})$. This condition is usually satisfied when f_{swmin} is higher than f_{min} (frequency at which total power loss of unmodulated SPC (P_{loss}) has its minimum; see also Fig. 2 and Fig. 3).

VI. CONCLUSIONS

The use of FM in SPC to mitigate EMI can decrease the efficiency of SPC, if instantaneous switching frequency $f_{sw}(t)$ changes in the region where $P_{nonlin}(f_{sw})$ is comparable with $P_{const}+P_{lin}(f_{sw})$. This is because FM can only affect $P_{nonlin}(f_{sw})$.
In order to calculate the efficiency and total power losses of basic FM SPC (buck, boost, buck-boost) procedure developed and expressions derived in the paper can be used. The expressions are very useful and can be used for different *D* and load resistance values. The results obtained in the paper can be used not only for the basic SPC investigated but also for other single-ended ones. If the recommendations proposed are considered, FM has almost invisible impact on the efficiency. This gives a designer a possibility to design high-quality FM SPC without sacrificing the efficiency.

REFERENCES

[1] K. Mainali, R. Oruganti, „Conducted EMI Mitigation Techniques for Switch-Mode Power Converters: A Survey," *IEEE Transactions on Power Electronics*, vol. 25, no.9, pp. 2344 – 2356, Sep. 2010.

[2] H. Li, Z. Li, B. Zhang, K. Tang, W. Halang, "Suppressing electromagnetic interference in direct current converters," *IEEE Circuits and Systems Magazine*, no.4, pp.10-28, 2009.

[3] A. Santolaria, "SSCG methods of EMI emissions reduction applied to switching power converters," Ph.D. dissertation, Electron. Eng. Dept., Polytechnic University of Catalonia, Barcelona, Spain, July 2004.

[4] D. Stepins, "Study and quality improvement of frequency modulated switch-mode power converters," Ph.D. thesis, Department of Electronics and Telecommunications, Riga Technical University, Riga, Latvia, June 2011.

[5] D. Gonzalez, J. Balcells, A. Santolaria, J. Bunetel, J. Gago, D. Magnon, S. Brehaut, "Conducted EMI Reduction in Power Converters by Means of Periodic Switching Frequency Modulation," *IEEE Transactions on Power Electronics*, vol.22, no.6, pp. 2271-2281, Nov. 2007.

[6] J. Balcells, D. Gonzales, J. Gago, A. Santolaria, J.C.L. Bunetel, D. Magnon, S. Brehaut, "Frequency modulation techniques for EMI reduction in SMPS," *Proceedings of the 9th European Conference on Power Electronics and Applications, EPE'05*, Dresden, 2005, P. 1 – 6.

[7] J.-C. Bunetel, D. Gonzalez, J. Balcells, "Impact of periodic switching frequency modulation control to reduce conducted EMI in power factor converters," *32nd Annual Conference of IEEE Industrial Electronics Society (IECON2006)*, Paris, France, Nov. 7-10, 2006, pp. 2541-2545.

[8] J. Jankovskis, D. Stepins, D. Pikuļins, "Efficiency of PFC Operating in Spread Spectrum Mode for EMI Reduction," *Electronics and Electrical Engineering*, no. 7, pp.13 – 16, 2010.

[9] J. Reinert, A. Brockmeyer, R.W. de Donker, "Calculation of losses in ferro- and ferrimagnetic materials based on the modified Steinmetz equation," *IEEE Transactions on Industrial Applications*, vol. 37, no.4, pp.1055-1061, July 2001.

[10] "MOSFET Power Losses Calculation Using the Data-Sheet Parameters", Infineon Application Note, V 1.1, July 2006, pp. 1-23.

[11] "The Conduction Losses in a Power Rectifier", STMicroelectronics AN604 APPLICATION NOTE, 2004.

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He has been involved in several research projects on examination of spread spectrum technique for switching power converters and improvement of power magnetic components. His research interests include spread spectrum techniques applied to switching converters, reduction of electromagnetic interference, control of power electronic converters and planar inductors.
He is currently the IEEE member.

Deniss Stepins. Frekvences modulācijas negatīvās ietekmes samazināšana uz impulsveida sprieguma pārveidotāja lietderības koeficientu
Šajā darbā ir izpētīta frekvences modulācijas (FM) ietekme uz klasisko vientakta impulsveida sprieguma pārveidotāju (ISP) lietderības koeficientu. Izpētītie klasiskie ISP ir pazeminošais, paaugstinošais un pazeminoši-paaugstinošais ISP. Enerģijas zudumu analīzes rezultātā ir pierādīts, ka vispārējā gadījumā pilnie FM ISP enerģijas zudumi sastāv no trim sastāvdaļām: neatkarīgie zudumi, lineāri atkarīgie un nelineāri atkarīgie no komutācijas frekvences. Iegūtie rezultāti liecina par to, ka FM var samazināt ISP lietderības koeficientu, tāpēc ka FM ietekmē no komutācijas nelineāri atkarīgus frekvences zudumus. Ir pierādīts, ka nelineāri atkarīgie zudumi ir galvenokārt saistīti ar spēka induktora magnētisko serdi. Ir izstrādāta efektīva metodika un ir izvērstas analītiskās izteiksmes lietderības koeficienta un pilno enerģijas zudumu aprēķiniem klasiskajos ISP. Izvērstās analītiskās izteiksmes ņem vērā arī magnētiskās serdes zudumus. Šim nolūkam tika izmantota modificēta Šteinmeca izteiksme, kas ļauj iegūt precīzākus rezultātus nekā tradicionālā izteiksme. Teorētiski iegūtie rezultāti ir arī eksperimentāli pārbaudīti, izmantojot frekvences modulētos klasiskos ISP. Ir piedāvātas dažas efektīvas rekomendācijas enerģijas zudumu samazināšanai un lietderības koeficienta uzlabošanai frekvences modulētos ISP. Ir pierādīts, ka, ja minimālā komutācijas frekvence ir lielāka par frekvenci, pie kuras nemodulētam ISP ir pilno zudumu minimums, tad FM praktiski nepasliktina lietderības koeficientu un nepalielina enerģijas zudumus. Ir arī pierādīts, ka enerģijas zudumi FM ISP ir atkarīgi arī no modulācijas signāla formas: modulācijas signāli ar mazāko vidējo taisngriezto vērtību dod mazākus zudumus. Rekomendācijas un iegūtos rezultātus, kas arī bija eksperimentāli pārbaudīti, var pielietoti kvalitatīvu frekvences modulēto ISP projektēšanai, optimizācijai un t tālākai attīstībai.

Денис Степинс. Уменьшение вредного влияния частотной модуляции на коэффициент полезного действия импульсных силовых преобразователей
В данной статье изучено влияние частотной модуляции (ЧМ) на коэффициент полезного действия (КПД) классических однотактных импульсных силовых преобразователей (ИСП): понижающего, повышающего и повышающе-понижающего преобразователей. В ходе исследования потерь энергии

в ЧМ ИСП было выяснено, что в общем случае полные потери ЧМ ИСП можно разделить на три вида: потери, которые независят, линейно зависят и нелинейно зависят от частоты коммутации. Полученные результаты показывают, что ЧМ может уменьшить КПД ИСП, потому что ЧМ влияет на ту часть полных потерь, которая нелинейно зависит от частоты коммутации. Выяснено, что потери, нелинейно зависимые от частоты коммутации, главным образом связаны с потерями в сердечниках силовых дросселей и трансформаторов. Методика и выражения для расчета КПД и потерь в этих преобразователях также представлены. Выведенные выражения для расчета потерь принимают во внимание также потери энергии в сердечниках. Для получения более точных результатов при расчете потерь в сердечниках используется модифицированное уравнение Штейнмеца. Теоретически полученные результаты также экспериментально проверены. Рекомендации по улучшению КПД и уменьшению потерь в ЧМ ИСП также предложены и экспериментально проверены. В статье доказано, что если минимальная частота коммутации выбрана больше, чем частота на которой полные потери немодулированного ИСП минимальны, то ЧМ практически не влияет на КПД и потери ЧМ преобразователя. Выяснено также, что применение модулирующих сигналов с уменьшенными средневыпрямленными значениями, дает возможность увеличить КПД в ЧМ ИСП. Рекомендации и полученные результаты могут быть применены для проектирования качественных ЧМ ИСП, а также для их дальнейшего развития.