A Study of Power Losses in A Two Stage Power Supply For Telecommunication Systems

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Abstract – This paper presents the design and the implementation of a power supply for telecommunication applications. The main focus of this work is to find the optimum operation frequency of the converters that compose it. A simple methodology of comparison between the volume of the heatsinks and the volume of the magnetic plus capacitive elements is used. As the increase of the switching frequency reduces the volume of the passive elements (inductors, transformers and capacitors), on the other hand it makes higher the volume of the heatsinks, since the commutation losses in the semiconductor elements (diodes, switches) get also higher. The power supply is composed of two stages: a power factor correction stage and a DC-DC converter to isolate and adapt the output voltage. In the AC-DC stage the high power factor continuous conduction mode boost converter is used. In the DC - DC stage, the full-bridge converter, with zero-voltage-switching and phase shift controller is used. By means of laboratory tests, an efficiency of 97% is obtained for the boost converter, and 94% efficiency for the full-bridge converter.

I. Introduction

This work presents, the design of a power supply for telecommunication systems, where the goal is the determination of optimum switching frequency of the converters that composes them. The methodology consists of the evaluation of the losses in the switches, diodes, resistors, capacitors, inductors and transformers, when the switching frequency is changed. As the switching frequency is increased, the volume of the passive elements (inductors, transformers and capacitors) is reduced. On the other hand the commutation losses in the semiconductor elements (diodes, switches) are higher. The optimum efficiency is defined when there is a volumetric equivalence between the volumes of the magnetic plus the capacitive elements and the volume of the heatsinks [7].

II. Topologies in Study

The structure presented in Fig. 1, is composed of two stages: in the first, the boost converter in continuous conduction mode (BOOST – CCM), [1], [2], [4], [11], is employed as a power factor correction. In the second stage, the Full-bridge Zero Voltage Switching, Pulse width Modulated, Phase Shift power flux control (FB-ZVS-PWM-PS) [1], [3], [5], [11], is used. High efficiency, reduced EMI and RFI interference as well as low harmonic distortion in the input current, are the main characteristics of this type of structures.

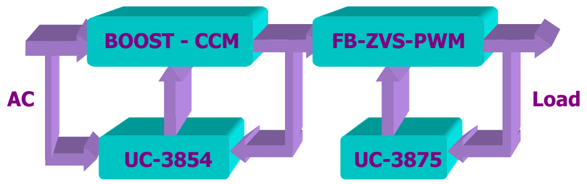


Fig. 1 - Power supplies for telecommunication systems.

A. *Power Factor Correction Stage*

Fig. 2 presents the Boost AC-DC converter in continuous conduction mode of input current. Both the command and control circuits are made by the UC-3854 [4]. Average current mode control is easily implemented. To minimize the switching loss component related to reverse-recovery of the diode D_b, a passive turn-on snubber circuit (L_s, C_s, D_{s1} D_{s2}) [1],[12], is used.

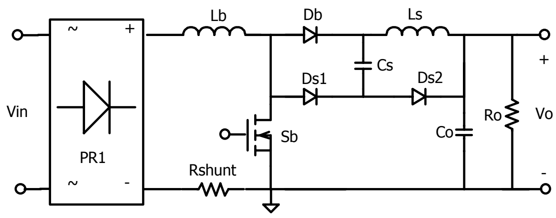


Fig. 2 - Boost converter with passive turn-on snubber circuit.

B. *DC-DC Converter stage*

Fig. 3 presents the FB-ZVS-PWM-PS converter. Among the several isolated DC-DC converter options, the Full-Bridge converter is the best choice when compared to other topologies as *forward, push - pull and half-bridge converters*. It presents the best use of the transformer, with the smallest voltage and current stresses.

Besides the natural features of the topology, the zero voltage switching technique (ZVS) has become a very attractive topology for this type of application. Parasitic capacitances and undesirable inductances in most of the applications can be used to propitiate the "soft commutation" of the switches [10]. Characteristics as high efficiency, reduced volume and low levels of electromagnetic and radiofrequency interference, makes the FB-ZVS-PWM-PS converter one of the best and most used topology in DC-DC stage applications for telecommunication power supplies.

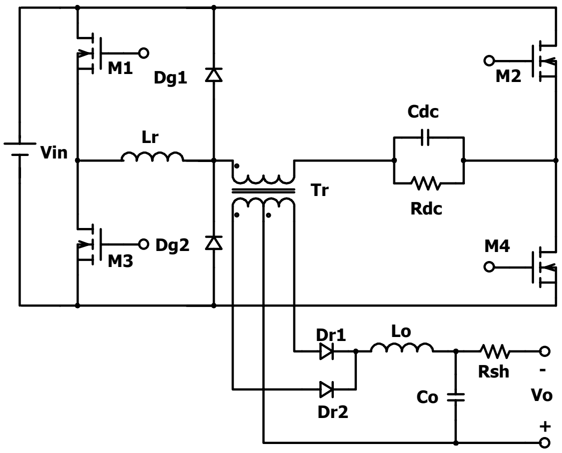


Fig. 3 - FB-ZVS-PWM-PS converter [3].

The turning on of the switches occurs under zero voltage. Switches M1 and M3 are turned on/off favorably, because the charging and discharging of the parallel capacitances is made with the output nominal current referred to the primary side of the transformer. The switches M2 and M4 commute with a smaller current magnitude, provided by the energy storage in the commutation inductor L_r.

III. Study of Losses in the Structure.

Most part of the components in these topologies is determined by the switching frequency. In this section is presented the main characteristics of the magnetic elements, capacitors and semiconductors that can provide better results for the power supply efficiency and volume with the variation of the switching frequency. It is desired in this application the maximum reduction of the loss energy with a minimum components volume.

C. *Strategy of determination of the losses*

In the semiconductor devices, switches and diodes, the increase of the switching frequency, causes an increase in the commutation losses. Thus, will be necessary heatsinks with small thermal resistances and with larger volumes. In the energy storage components such as inductors, transformers and capacitors, the increase of the commutation frequency results in the reduction of the volume. In the magnetic elements, beyond of reduction of the volume, there is an increase of the losses in the magnetic cores. It is evident here a trade off between the volume of magnetic material and the amount of the core losses. Therefore, an excessive increase of the operation frequency can result in a higher increase of the losses. In a capacitive element, the increase of the frequency results in a smaller value of capacitance with a reduction of its volume. Due to its constructive characteristics, the increase of the frequency results an increase in the equivalent impedance of the capacitor, increase of losses and a larger output ripple voltage. As presented, it is necessary a study of a methodology that considers the point of the volumetric equivalence between heatsinks and storage energy elements. Fig. 4 presents the point of maximum efficiency considering the volumetric analysis.

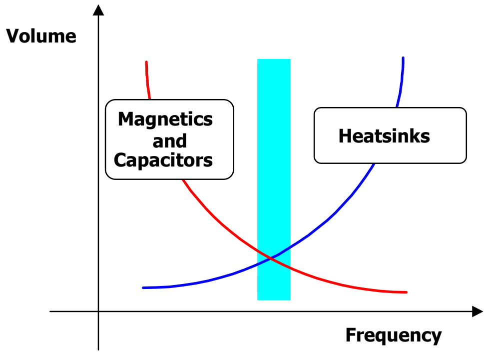


Fig. 4 - Determination of the area of maximum efficiency.

IV. Analysis of the Volumetric Equalization

As defined previously, the optimum switching frequency for the power converters that compose telecommunication power supplies will be defined by a comparison between the volume of the heatsink and the volume of the magnetic plus the capacitive elements. In sequence, the criteria used for the determination of the volume of the heatsink and magnetic plus capacitive elements are presented.

D. *Volume of the magnetic elements*

At magnetic elements the losses are defined by,

$$P_{mag} = \rho_{Cu(°C)} \cdot V_{Cu} \cdot J_{max}^{\;2} + V_e \cdot C_m \cdot f_s \cdot \Delta B_{max}^{\;y} \qquad (1)$$

Where, ρ_{Cu}, is copper resistivity, V_{Cu}, is the winding volume, V_e is the effective core volume, ΔB is the magnetic flux density variation and C_m, x and y are parameters that depends of the type of magnetic material.

Here the utilized material is IP12®[9], which, $C_m=7,9292x10^{-3}$, $x=1,4017$ and $y=2,3294$ [6]. The ΔB choice consists in a very important decision for designers. Fig. 6 presents the variation of ΔB when the switching frequency is changed. This curve is utilized whenever the limitation of the core losses is expected.

From (2), the excursion of magnetic flux density as functions of volumetric core losses can be determined. PV_{core} (mW/cm³) for each step of switching frequency and a determined B_{max}, can be obtained, by the manufacture datasheets,

$$\Delta B_{max} = \left(\frac{PV_{core}}{C_m \cdot f_s^{\,x}} \right)^{\frac{1}{y}} \qquad (2)$$

The graphic in Fig. 5 shows the variation of the volumetric core loss density, PV_{core}, with peak flux, for a range of frequencies from 20kHz to 100kHz, obtained by a characterization process of material described in [6].

The magnetic flux excursion design parameter is different for each magnetic element. In Fig. 7 some curves of magnetic flux density are presented. For each type of magnetic element of the power supply: (a) L_r, T_r and (b) L_b, L_o magnetic flux densities excursion. In both L_b and L_o inductors, core losses can be usually be negligible at frequencies below 500 kHz because ΔB is a small fraction of the DC flux level (Fig. 7 (b)). In these cases, $B_{\max}$ can be almost B_{sat}, with a small safety margin.

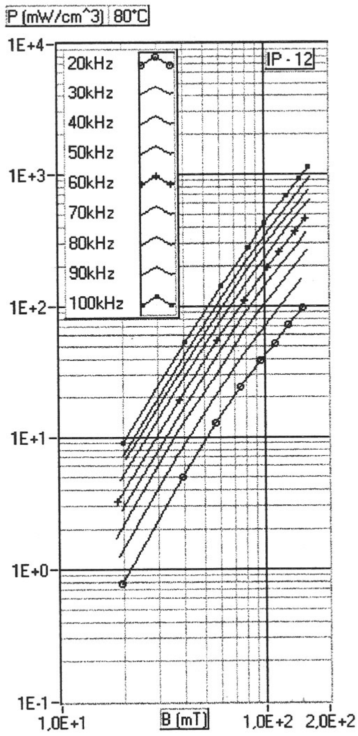


Fig. 5 – Experimental magnetic core losses as function of flux density and frequency for IP12 material.

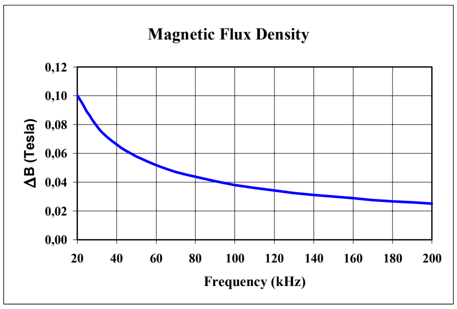
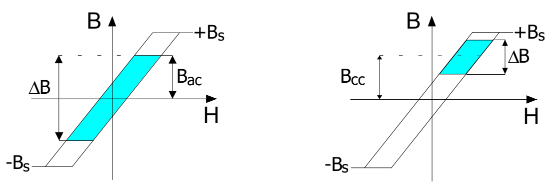


Fig. 6 – Magnetic flux density limitation.



(a) (b)

Fig. 7 – Magnetic flux density excursion.

In L_r and T_r designs, flux density swings all the way from $-Bs$ to $+Bs$ (Fig. 7 (a)). At high frequencies, ΔB will be usually limited by core losses, so that B_{max} will be less than B_{sat}, as in Fig. 6.

The volume of the magnetic elements was obtained by adding the effective volume of the cores from the manufacturer data sheets to the volume of the coil former obtained through the external dimensions. Considering that the whole useful area of the coil former is being used, a simplification can be reached, implying the resulting volume in approximately twice the effective volume of the core[8], [11], this facilitates the analysis procedure. Therefore, Table 1 presents the approximate volumes for the standard cores as in Fig. 8, from [9].

E. Volume of the capacitive elements

For the capacitive elements the determination of the volume is simple. In general, the diameter, and the length are manufacturer's data. So far, the volume of the capacitor can be determined.

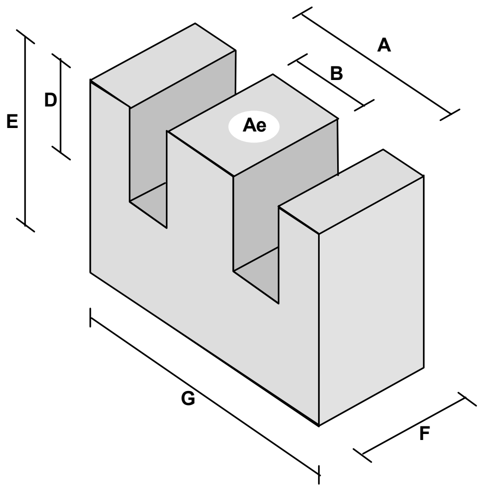


Fig. 8 – EE cores.

TABLE 1

APPROXIMATE VOLUME OF MAGNETIC ELEMENTS

Volume of the Magnetic Elements		
Cores EE	Ve (cm³)	Mag (cm³)
30/7	4,00	8,00
30/14	8,00	16,00
42/15	17,60	35,20
42/20	23,30	46,60
65/13	39,10	78,20
55/21	42,50	85,00
65/26	78,00	156,00
65/39	117,30	234,60
76/2	140,45	280,90

F. Volume of the heatsinks

Using the value of the thermal resistances from the heatsink to the ambient, Rth_{ha} in Fig. 9, the heatsink can be determined. The volume of an imaginary surrounding box is determined employing its external dimensions. In summary, the ideal switching frequency of the power supply in study can so far be determined:

- Initially, the average thermal resistance from heatsink to ambient Rth_{ha}, is determined for each design as a function of the step variation of the switching operation frequency. Where,

$$T_{hn(fs)} = T_{jn} - P_{totn(fs)} \cdot (Rth_{jcn} + Rth_{chn}) \tag{3}$$

is the heatsink temperature for each device. Thus,

$$T_h = \frac{T_{h1} + T_{h2} + \ldots + T_{hn}}{n} \tag{4}$$

is the average temperature for n device at same heatsink, so that the average thermal resistance heatsink to ambient is determinates.

$$Rthha = \frac{Th - Ta}{\sum_{1}^{n} P_{totn}} \tag{5}$$

- With the average thermal resistance of the heatsink to ambient, the heatsink are chosen and the volume of the heatsink for the n projects is determined.
- The total volume of passive elements is the sum of the volume of the magnetic elements plus the capacitive elements.

$$V_{pas}(f_s) = V_{cap}(f_s) + V_{mag}(f_s) \tag{6}$$

The comparison between the volume of the heatsink and the volume of passive elements defines the maximum efficiency point according to the methodology of the volumetric equivalence.

V. Theoretical Analysis

A completely procedure for determination of all elements of power supply unit are presented in [11]. Where are executed, n projects of each structure where the switching frequency ranges from 20 kHz to 200 kHz with the ideal switching frequency determination strategy defined.

Hence, the equivalence point between the volumes of magnetic plus the capacitive elements and the volume of the heatsink is presented, for both employed topologies.

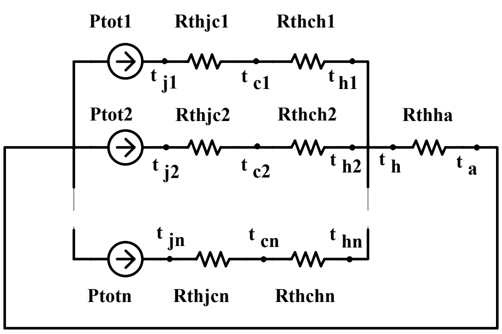


Fig. 9 - Thermal resistances for any semiconductors devices.

G. *AC-DC Stage, Boost-CCM Converter*

From the volumetric analysis between the heatsink and the magnetic plus capacitive elements, the optimization strategy leads to a point of volumetric equivalence for the AC-DC stage. Fig. 10 presents this point. It is observed that ideal theoretical frequency of operation is placed between 40 and 60 kHz, The dashed curve represents an interpolation, which makes possible the definition of the frequency of 50 kHz as the ideal switching frequency of the AC-DC converter.

From Fig. 10, it can be observed that magnetic volume for switching frequency above 50 kHz and once the determination of the output capacitor C_o, is independent of switching frequency, the volume of magnetic elements no more decreases [11]. For 50 kHz the Fig. 11, presents the theoretical losses distribution in the AC-DC stage, it is observed that rectifiers diodes are responsible by the major part of the losses.

H. *DC-DC Stage, Converter FB-ZVS-PWM-PS*

Through Fig. 12, it can be defined the point or the area of maximum efficiency, in a switching frequency interval between 100 kHz to 140 kHz. It can be observed that the volume of the passive elements remains constant after 100 kHz. Therefore the point of maximum efficiency should be taken at 100 kHz. By the way, the semiconductor losses due to commutation, will be the smallest ones. For 100 kHz the Fig. 13, presents the theoretical losses distribution in the DC-DC stage, where it is observed that output rectifiers diodes are responsible by the most of the losses.

VI. Experimental Results

In order to confirm the theoretical study, a 900W - 15A, power supply was implemented. The input stage should present high power factor and reduced harmonic content for the input, besides a stable output voltage under load variations.

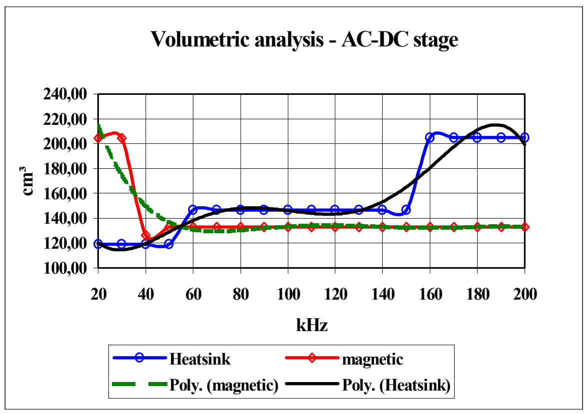


Fig. 10 - Point of volumetric equivalence in the AC-CC stage.

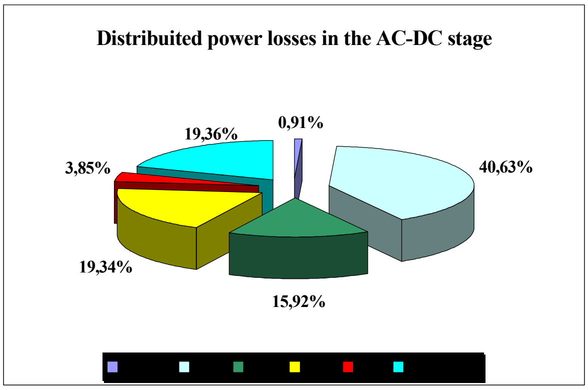


Fig. 11 – Theoretical power losses in the AC-DC stage.

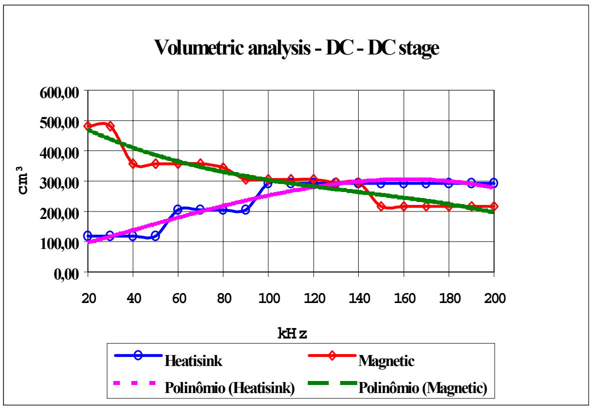


Fig. 12 - Point of volumetric equivalence in the DC-DC stage.

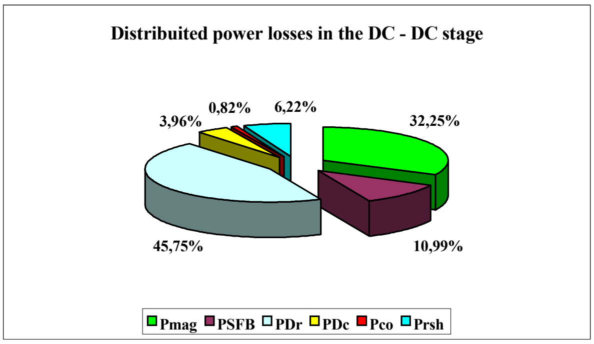


Fig. 13 - Theoretical power losses in the DC-DC stage.

I. Specifications of the power supply

The tested prototype presents the following specifications: output power, Po = 900 W, output voltage, Vo = 60 Vdc, expected efficiency, >91%, input voltage, Vin = 220 Vrms +/-15%, frequency = 60 Hz, output 120 Hz ripple voltage, ΔVo = 220mVpk.

J. AC-DC stage, experimental results

Two prototypes of the Boost converter were developed. The 50 kHz topology presented the largest efficiency. In the 100 kHz prototype, switch and main diode turning-off losses were higher. The losses in the magnetic elements are less influenced by the variation of the switching frequency, because it influences more in the core losses, due to low ripple of the input inductance current and the magnetic flux is also smaller. Hence, most of the losses happen in the copper winding, where the influence of the switching frequency is smaller. Finally, it is observed the conformity between the data obtained through theoretical analysis and the results obtained through the experimentation, according to Table 2.

K. DC-DC stage, experimental results

Two prototypes of the FB-ZVS-PWM-PS converter were developed. The 100 kHz switching frequency was the one that presented the largest efficiency, even so in the theoretical analysis, the 120 kHz topology presented better efficiency results than the 100 kHz topology.

The tendency presented in the theoretical analysis is observed in the experimental results, where it is noticed a reduction of the structure efficiency as the frequency increases. Trough the elevation of temperature measured in the passive elements and in the heatsinks, total losses in the FB-ZVS-PWM-PS converter can be separated, according to Table 3.

TABLE 2

EXPERIMENTAL LOSSES COMPOSITION IN THE BOOST CONVERTER, FOR 50 KHZ.

Element	50 kHz - Experimental Tamb = 31,8 °C				50 kHz - Theoretical Tamb = 40 °C			
	R_{th} (°C/W)	Δt (°C)	Losses (W)	η	R_{th} (°C/W)	Δt (°C)	Losses (W)	η
Inductor	7,713	38,5	4,99	97,7	7,713	52,76	6,84	97,3
Heatsink	1	16,8	16,8		3,56	53,6	17,48	

TABLE 3

APPROXIMATED DIVISION OF THE LOSSES IN THE CONVERTER FB-ZVS-PWM-PS, FOR 100 KHZ.

<table>
<tr><th rowspan="2">Element</th><th colspan="4">100 kHz - Experimental
Tamb = 30,8 oC</th><th colspan="4">100 kHz - Theoretical
Tamb = 40 oC</th></tr>
<tr><th>R_{th} (°C/W)</th><th>Δt (°C)</th><th>Losses (W)</th><th>η</th><th>R_{th} (°C/W)</th><th>Δt (°C)</th><th>Losses (W)</th><th>η</th></tr>
<tr><td>Tr</td><td>4,44</td><td>62,2</td><td>14,1</td><td rowspan="4">94,4</td><td>4,44</td><td>53,1</td><td>11,7</td><td rowspan="4">95</td></tr>
<tr><td>Lr</td><td>19,1</td><td>90,5</td><td>4,7</td><td>19,1</td><td>15,2</td><td>0.8</td></tr>
<tr><td>Lo</td><td>10,7</td><td>28,2</td><td>2,6</td><td>10,7</td><td>12,8</td><td>1</td></tr>
<tr><td>Heatsink 1500/25</td><td>1</td><td>22,2</td><td>22,2</td><td>2,7</td><td>77,9</td><td>28,9</td></tr>
</table>

VII. CONCLUSIONS

The presented methodology was able to provide an optimum project of the converters according to laboratory results. In the Boost converter the ideal switching frequency stays in 50 kHz and in the DC-DC converter it is about 100 kHz for the rated power of the prototypes. The efficiency obtained in the Boost converter was excellent, for both implemented prototypes, with advantage for the prototype of 50 kHz (97,7%). Besides the great efficiency, the 50 kHz operating frequency presents also the advantage of less electromagnetic and radiofrequency emissions, when compared with higher switching frequencies.

For the FB-ZVS-PWM-PS converter the obtained efficiency was 94,4%. The tendency of smaller efficiency was observed with the increase of the operation frequency, what confirms to the theoretical analysis. As presented also, the largest losses happened in the output rectifier diodes.

During the prototype's tests a greater temperature elevation was observed, in both *Lr* and *Tr* elements. This can be attributed to losses due to proximity effect, skin effect or both. So the DC-DC converter efficiency was lower than expected.

The obtained results, explains that the methodology is good enough to establish the point of maximum efficiency of the converters once the obtained efficiency as in theoretical analysis and experimental results presented great consistence.

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