COMPARISON AMONG ZVS ISOLATED PWM DC-DC CONVERTERS

J.E. Baggio, H.L. Hey, H.A. Gründling, H. Pinheiro, J.R.Pinheiro
Power Electronics and Control Research Group - GEPOC
Federal University of Santa Maria - UFSM
97105-900 - Santa Maria - RS - Brazil
baggio@nupedee.ufsm.br, renes@ctlab.ufsm.br - www.ufsm.br/gepoc

Abstract: **This paper presents a comparative study among ZVS isolated PWM dc-dc converters. The full-bridge converter, the neutral-point-clamped diode converter and the series arrangement of half-bridge converters are compared considering ZVS operation range, efficiency and cost. These converters are analyzed for three cases: (i) maximum efficiency at full load; (ii) the use of a series inductor to assure ZVS in a desired load range; (iii) ZVS in entire load range. Complete theoretical analysis and experimental results for 60V/25A are accomplished to demonstrate the presented theoretical analysis.**

I. INTRODUCTION

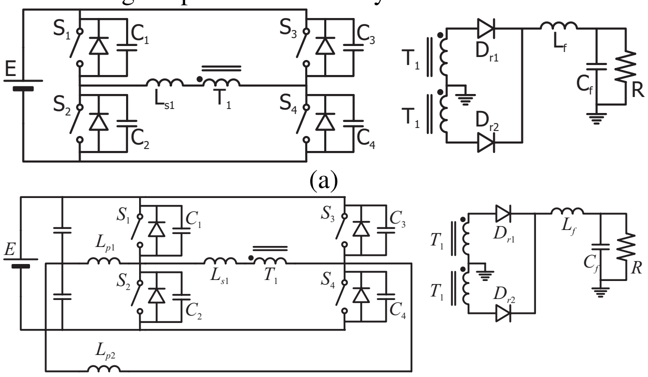
The full-bridge (FB) converter presented in Fig. 1a has been widely utilized by the industry as dc-dc isolated converter for high frequency high power applications. This converter presents industry-desired characteristics, such as robustness and capability to incorporate parasitic components to obtain soft commutation [1,2,12,13].

The full-bridge converter can operate with ZVS in a load-range due to the presence of transformer leakage and magnetizing inductances [1,2,3]. Like the ZVS-FB converter, many other isolated dc-dc converters can operate with ZVS in a load-range, only using the transformer leakage inductance [1,5,6,8,9,13,14].

The main drawback of this commutation technique is the increase of the conduction losses when ZVS is required in a wide load range. For this purpose, the inductance in series with the transformer must be enlarged, reducing the effective duty-cycle and penalizing the converter efficiency [1,2,3]. However, the designer can sacrifice the soft-commutation at light load to achieve higher efficiency at full load. Otherwise, the ZVS capability of these converters can be easily extended to full-load-range by the inclusion of an auxiliary commutation circuit (ACC) that performs ZVS at light load current. A simple way to implement this auxiliary circuit is the inclusion of an auxiliary inductor for each leg, as depicted in Fig. 1b.

This paper analyzes the Neutral-Point-Clamped Diode (NPC) presented in Fig. 2a with an ACC and the converters composed of series connection of two half-bridges (sHB) presented in Fig. 2b and 2c, which present the same commutations characteristics of the full-bridge converter. The series arrangement of the switches make these converters more appropriate for high voltage applications. However, even for low voltage applications, these converters can be an attractive choice, since they the use MOSFETs rated for half of dc bus voltage, which present reduced drain-source on-resistance.

Following are presented the analysis of the converters

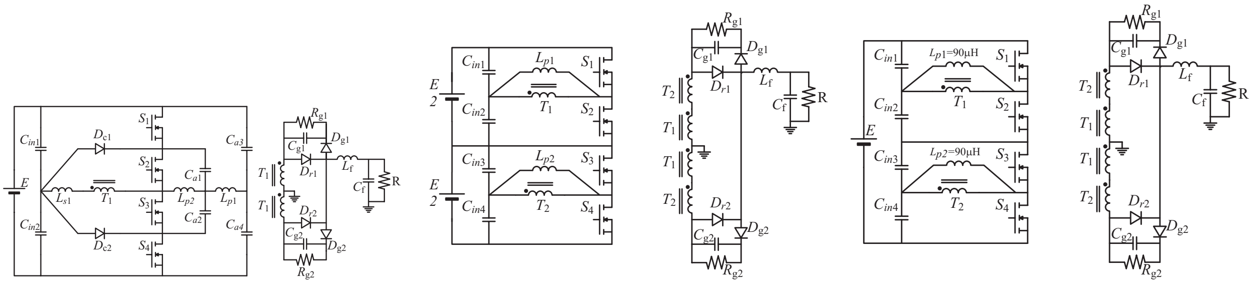


(b)

Fig. 2 - Dc-dc ZVS isolated Full-bridge converter: (a) ZVS in a wide load range; (b) ZVS in entire load range.

II. CONVERTERS ANALYSIS

In this section an analysis of the effects of the ACC on the efficiency of isolated converters is presented. It is well known that on isolated converters, the transformers leakages inductances can be seen as inductors in series with the transformer. Since the series inductors produces duty-cycle reduction, the transformer leakage becomes significant for high frequency high power converters. The relation between the effective duty-cycle and the series inductor is given by in (1) for the FB converter, and by (2) for the series converters. The relation between the series inductor and the duty-cycle



(a) (b) (c)

Fig. 1 – Converter with main switches rated to half of dc bus voltage: (a) NPC; (b) sHB with PSM; (c) sHB with PWM.

of the series converters is illustrated in Fig. 3a, for the set of specifications defined on Table 1.

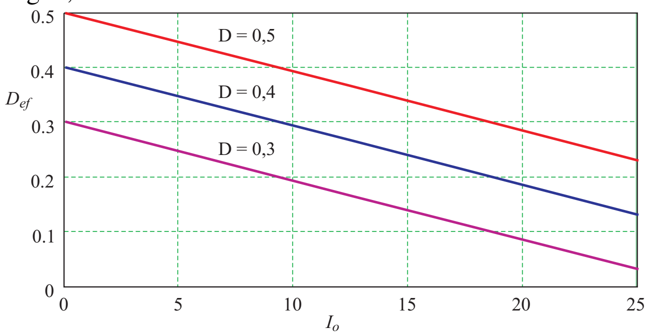
$$\Delta D_{FB} = \frac{4 f_s L_r i_o}{n.E} \tag{1}$$

$$\Delta D_{sHB} = \frac{8 f_s L_r i_o}{n.E} \tag{2}$$

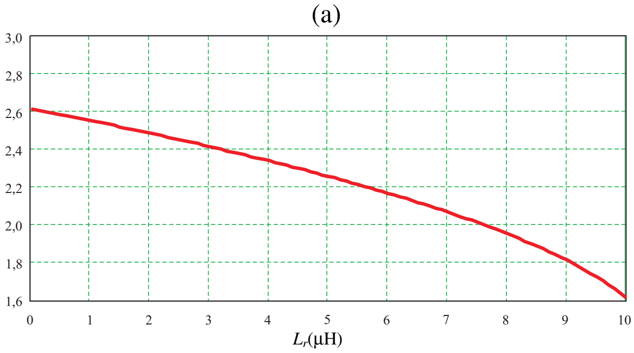
Table 1- Converter parameters.

Parameter	Value
Switching frequency - *fs*	100 *k*Hz
Resonant inductor - L_r	9µH
Transformer turns-ratio - *n*	1.67
Output current - I_o	25A
Input voltage - *E*	400V

The transformers design must consider this reduction in a way to guarantee the output voltage regulation. The transformer turns-ratio in function of the series inductor for the series converters is presented in Fig. 3b. It can be seen that as large as the series inductance, as small as the transformer turn-ratio, resulting in higher values of load current reflected to the primary side. As a consequence, for high values of resonant inductors, the conduction losses on the switches are increased. On the other hand, as large as the resonant inductor, as large as the parallel inductor necessary to guarantee ZVS in entire load range, resulting in reduced reactive circulating energy. The relation between the resonant inductor and the parallel inductor is illustrated on Fig. 4, for the sHB with PWM



(a)



(b)

Fig. 3 – (a) Effective duty-cycle versus series inductor value; (b) Transformer turns-ratio versus series inductance.

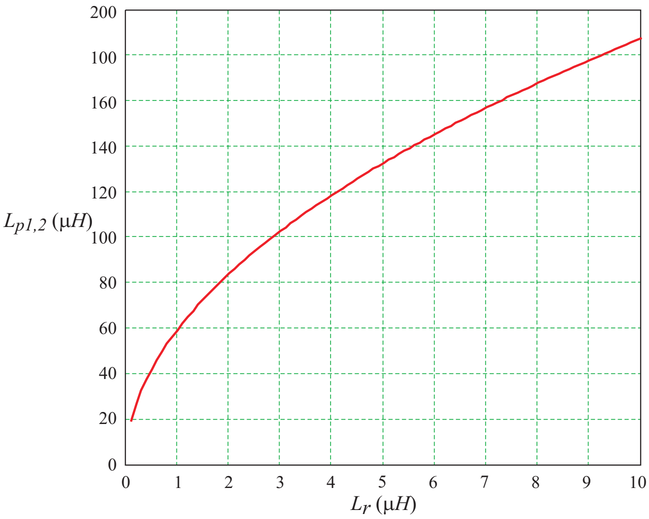


Fig. 4 – Relation between Parallel and series inductor for the sHB with PWM.

Infinite sets of series/parallel inductors can be utilized to guarantee ZVS in entire load range. However, the set of inductors which maximize the converters efficiency can be obtained by an optimization method, as present below.

Optimization Method and Simulation Results

A simple way to define the best set of series/parallel inductors to maximize the converter efficiency was presented in [14]. The optimization method consists of the evaluation of the converter main losses utilizing an iterative process.

The losses that are evaluated on the iterative process are:

- Switches conduction losses;
- Transformers losses (magnetic and conduction);
- Series and parallel inductors losses;
- Inductor filter losses;
- Rectifier diodes conduction losses;
- Reverse recovery losses on rectifier diodes.

Although the converters present other losses, the set above specified are enough to indicate the best design, since they represent the main converters losses

The losses above specified are well known and can be easily evaluated utilizing traditional equations. Simulation results are presented for the set of specifications presented on Table 2 .

Table 2 - Set of converters specifications.

Parameter	Value
Output power	P_{out} = 1,5kW
Input voltage	E = 400V
Minimum input voltage	E_{min}=360V
Output voltage	V_o = 60V
Switching frequency	f_s = 100kHz
Maximum duty-cycle	D_{max} = 0.45

For this application it is considered the use of MOSFETs as main switches, since its parasitic components can be utilized for the ZVS. The set of components utilized for simulations are presented on Table 3.

Table 3 – Devices utilized for simulation and experimental results.

Component	Parameter
$S_{1\text{-}4}$	MOSFETs IRFP264 for the sHB and NPC. MOSFETs IRFP460 for the FB.
$D_{1\text{-}4}$	MOSFETs intrinsic diodes
$C_{1\text{-}4}$	MOSFETs intrinsic capacitors
$T_{1\text{-}2}$	Ferrite core EE55/21 – Thornton (sHB)
T_1	Ferrite core EE65/26 – Thornton (FB/NPC)
$L_{p1,2}$	Ferrite core EE 30/07 - Thornton
$L_{s1,2}$	Ferrite core EE 30/14 - Thornton
$D_{r1\text{-}2}$	30CPH03 (300V/30A).
$D_{g1,2}$	BYV26E – Phillips.
$R_{g1,2}$	10kΩ/5W
$C_{g1,2}$	1μF

Fig. 5 presents the relation between the efficiency of the FB converter at full load versus the resonant inductor. As it can be seen in this figure, the maximum efficiency of the converter occurs when resonant inductors around 5μH are utilized, where the efficiency can be up to 2% higher than when non-optimized set of inductors are utilized. Similar results are obtained for simulation of the sHB and NPC converters, as depicted on Fig. 6, however with resonant inductor values around 1μH.

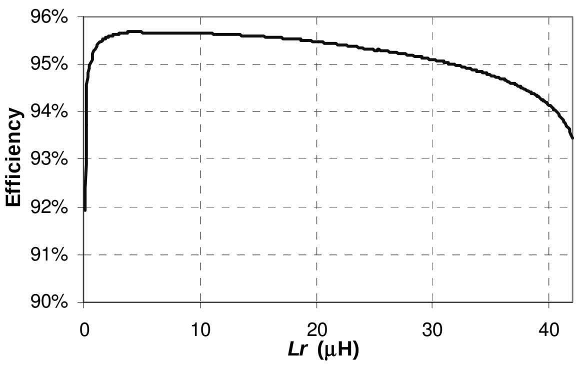


Fig. 5 - Theoretical efficiency of the FB converter versus the resonant inductor for E=400V.

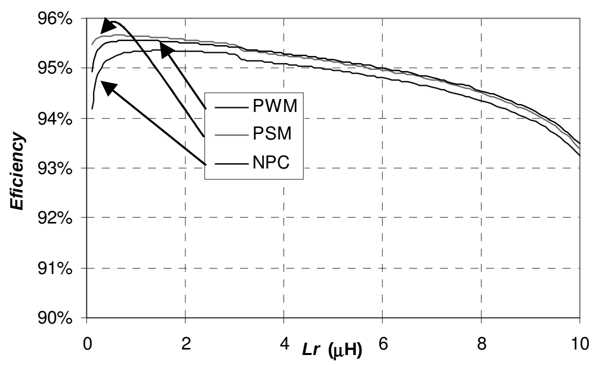


Fig. 6 - Theoretical efficiency of the series converters versus the resonant inductor for E=400V.

When 3ϕ utility grid are utilized, the dc bus voltage can reach voltage as high as 800V. Taking into account these applications, simulations for E=800V were performed. In this case, the same output characteristic and switching frequency were adopted, and, it was considered the use of MOSFETs IRFPG50 for the FB converter and the MOSFETs IRFP460 for series converters. The theoretical results for the converters are presented on Fig. 7 and Fig. 8. It can be seen that an optimized design of the FB converter can present efficiency up to 4% higher than a non-optimized design. For series converters, the difference between the optimum and non-optimum design is around 2%.

Another important characteristic that must be highlighted is that, in high voltage applications, the series converter present higher efficiency than the FB converter, considering the actual technology.

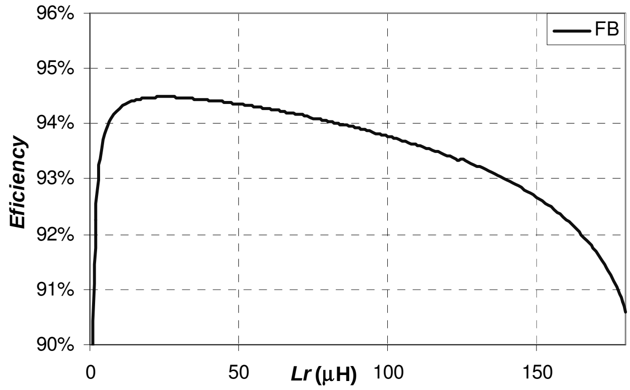


Fig. 7 - Theoretical efficiency of the FB converter versus the resonant inductor for E=800V.

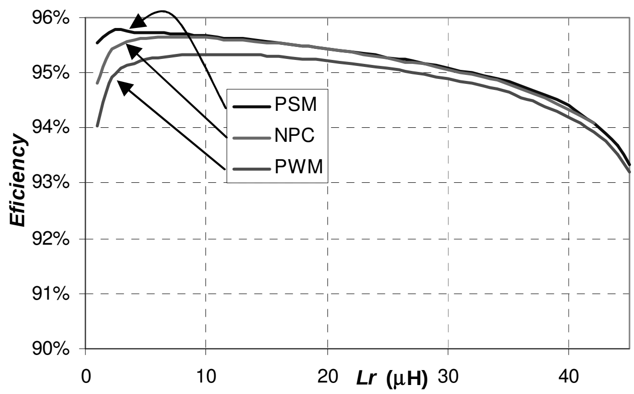


Fig. 8 - Theoretical efficiency of the series converters versus the resonant inductor for E=800V.

III. Experimental Results

To validate the theoretical analysis, experimental results were obtained from prototypes of the FB and sHB converters for a dc bus of 400V, according the specifications and components utilized on simulations.

However, it was necessary to round the transformers turns-ratio for transformers implementation. Fig. 9 and Fig. 10 present the ideal and the implemented turn-ratios n for the sHB converter and for the FB converter, respectively.

Fig. 12 presents experimental results and theoretical results of the sHB converter with PSM and PWM operating at full-load taking into account the rounded turn-ratios. In a similar manner, the theoretical and experimental results of the FB converter are presented on Fig. 11. A good agreement between the theoretical and experimental results can be seen in these figures. In spite of the difference in their absolute values, the relation between theoretical and experimental allows do define the best set of series/parallel inductors which produce the maximum efficiency. The difference on absolute values occurs due to some losses that are present in the converter and was not considered on the mathematical model.

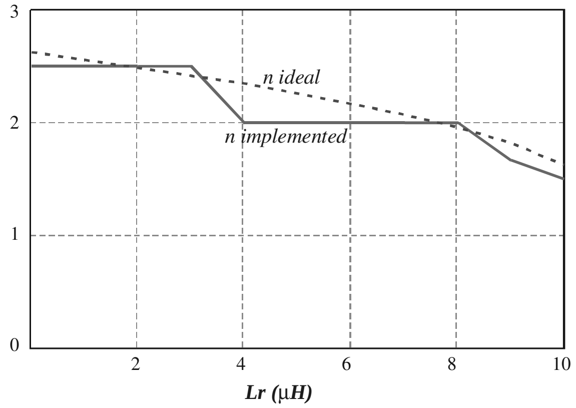


Fig. 9 - sHB transformers turn-ratio versus resonant inductor.

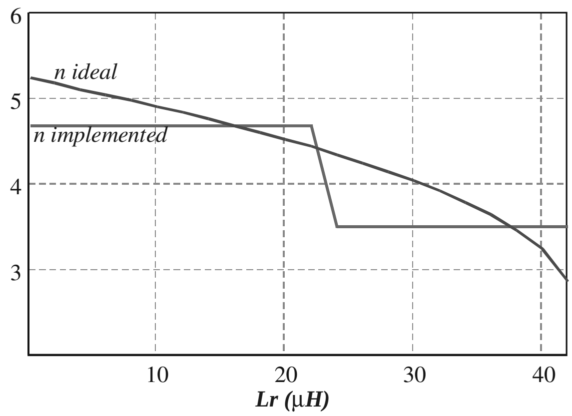


Fig. 10 – Full-bridge transformer turn-ratio versus resonant inductor.

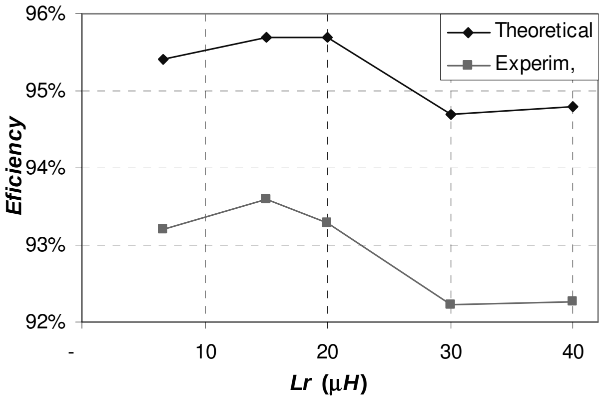
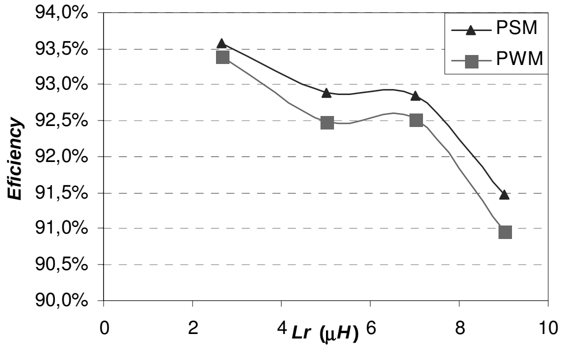
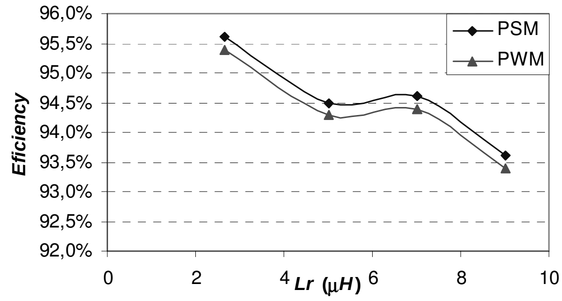


Fig. 11 – Efficiency of the FB converter at full-load versus the resonant inductor for E=400V.



(a) Experimental results.



(b) Theoretical results.

Fig. 12 – Efficiency of the sHB converters at full-load versus the resonant inductor for E=400V.

The minimum value of L_r utilized on Fig. 11 and 12 are the minimum values that can be used, since these values are the transformer leakage inductances.

Experimental results demonstrate that an optimized design allows obtain efficiency 2% higher than a non-optimized design, as it was predicted on the theoretical and simulation analysis. Moreover, it can be seen that the optimum design of series converter utilizes only the transformers leakage inductance and parallel inductors, while the FB converter optimum design includes series and parallel inductors, for the utilized specifications set.

A comparison between the efficiency of the sHB converter with PSM utilizing an optimized ACC and without the ACC (with ZVS from 30% of the full load to full-load) is presented in Fig. 13. Further the converter with ACC present ZVS in entire load range, it presents efficiency higher than the converter without ACC, becoming more attractive on the point of view of efficiency and electromagnetic interference.

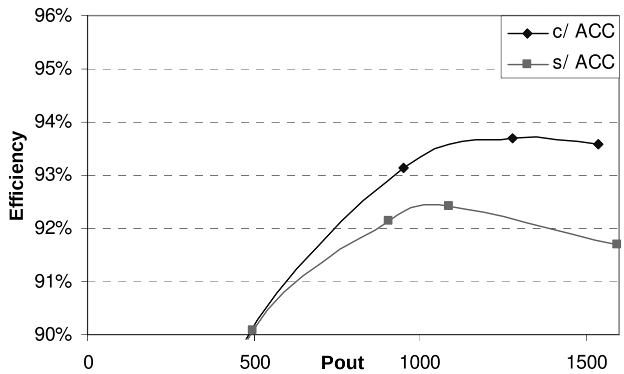
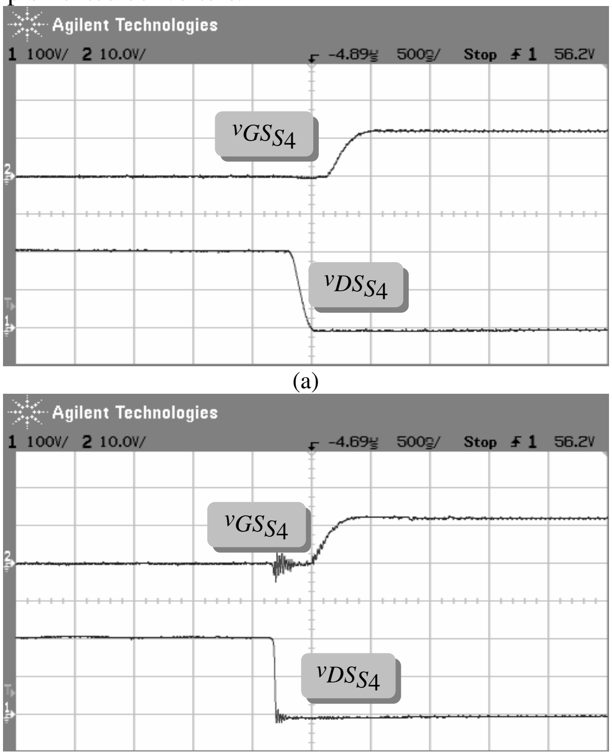


Fig. 13 Efficiency of the sHB with ACC and withou ACC.

Voltage waveforms are presented to demonstrate the ZVS converters capability at no-load and at full-load due to the use of the ACC. Fig. 14 presents the gate-source signal and the drain-source voltage on switch S_4 of the sHB converter with PSM. It can be seen that the gate voltage is applied only after the drain-source voltage reaches zero, characterizing the ZVS. Similar characteristics were observed on the other implemented converters.



(a)

(b)

Fig. 14 – Drain-source and gate-source voltages on switch S_4 of the sHB converter with PSM: (a) operation at no-load; (b) operation at full-load.

IV. Converters Comparison

In this section, some comparisons among the converters are performed, taking into account the previously presented experimental and theoretical results.

Experimental results demonstrate that the sHB and the FB converters with optimum design present nearly the same efficiency. This way, to define the best converter for this application, other parameters must be included on the comparison. Following are presented the cost of the main devices of the converter. Here are not included some components of the converter, such as drives, control circuits, sensors, circuit boards, etc, which costs are difficult to be estimated. However, the costs of power elements are analyzed and can indicate which converter tends to present smaller cost.

Table 4 presents the prices in dollars of the main devices utilized on the power stage of the converters. It can be seen that the switches utilized on FB converters are cheaper than that utilized on series converter. Moreover, the FB converter utilizes less dc bus sharing capacitors, resulting in a cheaper converter.

Considering that the FB converter presents the lowest price and the same efficiency of the series converters, it becomes the more indicate for applications at low voltage, considering the actual technology.

However, as presented on Table 5, the sHB presents the lowest cost for dc bus of 800V. Moreover, as previously demonstrated, the sHB presents the highest efficiency at high voltage, becoming a natural choice for high voltage applications.

Table 4 – Cost of components of implemented converters for E=400V.

	FB converter			sHB converter			NPC converter		
	unit. price	Q	total	unit. price	Q	total	unit. price	Q	total
MOSFETs	3,16	4	12,64	3,24	4	12,96	3,24	4	12,96
Transf. core	8,37	1	8,37	4,02	2	8,04	8,37	1	8,37
Rectifier diode	1,10	1	1,10	1,10	1	1,10	1,10	1	1,10
Clamper	2,45	2	4,90	2,45	2	4,90	2,45	2	4,90
Output Filter core	4,02	1	4,02	4,02	1	4,02	4,02	1	4,02
ZVS inductors	0,63	3	1,89	0,63	2	1,26	0,63	2	1,26
Output filter capacitor	0,48	1	0,48	0,48	1	0,48	0,48	1	0,48
Input sharing capacitor	0,95	2	1,90	1,34	4	5,36	1,34	4	5,36
Clamper diode							0,30	2	0,60
Auxiliary capacitor	0,95	1	0,95				0,95	1	0,95
TOTAL			**36,25**			**38,12**			**40,00**

Table 5 – Cost of components of implemented converters for E=800V.

	FB converter			sHB converter			NPC converter		
	unit. price	Q	total	unit. price	Q	total	unit. price	Q	total
MOSFETs	4,51	4	18,04	3,16	4	12,64	3,16	4	12,64
Transf. core	8,37	1	8,37	4,02	2	8,04	8,37	1	8,37
Rectifier diode	1,10	1	1,10	1,10	1	1,10	1,10	1	1,10
Clamper	2,45	2	4,90	2,45	2	4,90	2,45	2	4,90
Output Filter core	4,02	1	4,02	4,02	1	4,02	4,02	1	4,02
ZVS inductors	0,63	3	1,89	0,63	2	1,26	0,63	2	1,26
Output filter capacitor	0,48	1	0,48	0,48	1	0,48	0,48	1	0,48
Input sharing capacitor	0,95	2	1,90	1,34	4	5,36	1,34	4	5,36
Clamper diode							0,30	2	0,60
Auxiliary capacitor	0,95	1	0,95				0,95	1	0,95
TOTAL			**41,65**			**37,80**			**39,68**

Considering the converter volume, the FB converter can be considered the most compact, if there is commercial transformer ferrite core to attend the power demand. However, when one ferrite core is not sufficient to attend the output power, and two transformers must be used, the sHB or the NPC converter becomes more attractive than the FB, since the series converters utilizes less inductors than the FB converter. In this case, comparing sHB and NPC, the sHB stand out since it utilizes less capacitor and dispenses with the use of clamp diodes.

V. CONCLUSIONS

This paper presented a comparative study among some dc-dc ZVS isolated converters. The full-bridge converter, the neutral-point-clamped diode and the series arrangement of two half-bridge, using PWM and PSM are compared. All these converters operate with ZVS in a load range due to the transformer leakage inductance. However, the load range with ZVS can be enlarged with the inclusion of an inductor in series with the transformer, or even extended to entire load range by the inclusion of auxiliary shunt inductors.

Theoretical and experimental results demonstrate that the use of an optimization method to design the converter allows obtaining converter efficiency 2% higher than converters with non-optimized designs. Moreover, it was demonstrated that optimized designs allow the converters with ZVS in entire load range present efficiency higher than the converters with ZVS in only a load range.

The comparison among converters is not simple and it depends on the technology and application in which the converters are being compared. For the set of specifications defined on the paper, a comparison among the studied converters demonstrates that for low voltage (400V) applications, the converters efficiencies are almost the same, for the optimized designs. However, the FB converter presents the lowest cost, being elected the best choice for low voltage, high frequency applications, confirming its preference on industry production.

On the other hand, for higher voltages the use of series converters become more appropriate, since they present higher efficiency and lower cost than the FB converter.

For high voltage and high power applications, the sHB converter presents the most attractive characteristics, since it can process the double of power of the FB or NPC converter, without making use of transformers parallelism connection techniques.

REFERENCES

[1] R.A.Fisher, K. D. T Ngo and M. H. Kuo, “A 500kHz, 250W Dc-to-DC Converter with Multiple Outputs Controlled by Phase-Shift PWM and Magnetic Amplifiers”, *High Frequency Power Conversion Conference Proceedings*, pp. 100-110, 1998.

[2] J.A. Sabaté, V. Vlatkovic, R.B. Ridley, F.C. Lee and B.H. Cho, “ Design Considerations for High-Power Full-Bridge ZVS-PWM Converter”, *IEEE APEC Conference Proceedings*, pp. 275-284, 1990.

[3] L. Mweene, C. Wright and M.F. Schlecht, “A 1kW, 500kHz Front-End Converter for a Distributed Power Supply System”, *IEEE APEC´89 Proceedings*, pp. 423-432.

[4] S. Nagai, T. Yamamoto, M. Nakaoka and S. Hamada, “Zero-Voltage Soft-Switching PWM High-Frequency AC-Link DC-DC Converters Incorporating Saturable Reactor-Assisted Capacitive Lossless Snubber Topology for Distributed Power Supply Systems”, *Proceedings of the European Space Conference*, pp. 165-171, September 1991.

[5] P.G. Maranesi, “The Switch In-Line Converter”, *IEEE PESC´*93 Proceedings, pp. 185-188.

[6] E. Deschamps and I. Barbi, “An Isolated ZVS-PWM DC-to-DC Converter with Half of the Input Voltage Across the Switches”, *IEEE PESC´*99 Proceedings, pp 289-294.

[7] R. Ayyanar and N. Mohan, “A Novel Soft-Switching DC-DC Converter with Wide ZVS-Range and Reduced Filter Requirement”, *IEEE PESC´*99 Proceedings, pp 433-438.

[8] R. Ayyanar and N. Mohan - “Full-Load-Range-ZVS Hybrid DC-DC Converter with Two Full-Bridges for High-Power Battery Charging”, INTELEC´99 Proceedings.

[9] J.R. Pinheiro and I. Barbi, “The three-level ZVS-PWM dc-to-dc Converter”, *IEEE Trans. on Power Electronics*, vol. 8, n. 4, pp.486-492, 1993.

[10] J.R. Pinheiro and I. Barbi, “Wide Load Range Three-Level ZVS PWM dc-to-dc converter”, *IEEE PESC*’93 Proceedings, pp. 171-177.

[11] D.B. Dalal – "A 500khz multi-output converter with zero voltage switching", *Applied Power Electronics Conference*, pp. 265-274, 1990.

[12] M. M. Jovanovic – "Merits and limitations of resonant and soft-switched converters", *INTELEC Proceedings*, pp. 51-58, 1992.

[13] J. R. Pinheiro, J. E. Baggi, “Isolated Interleaved-Phase-Shift-PWM dc-dc ZVS Converters”, *IAS annual meeting proceedings*, pp. 2383-2388, 2000.

[14] J.E. Baggio, H.L. Hey , J.R. Pinheiro, “An improved full-load-range isolated ZVS-PWM DC-DC converter”, *Applied Power Electronics Conference*, pp. 265-274, 2001.