DSP Control of Gyrator-Behaved Switch Mode Converter

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Abstract

Recent advances in DSP technology, such as those found in the TI C2000 family, make possible the practical exploration and eventual economical implementation of switch mode converters topologies that, until now, were conceived as a curiosity or at best, of theoretical value only. Applying the DSP capabilities, we explored in this study the characteristics and advantages of a double-bridge, Gyrator-behaved switch-mode DC-DC converter. This paper introduces the Gyrator behaved topology, proposes a user-friendly method for simulation-based DSP code development and debugging, and demonstrates the agreement between theoretical predictions and experimental results that were obtained on a laboratory prototype.

1. Introduction

A Gyrator, presented symbolically in Fig. 1, is defined as a two port network, characterized by an identical trans-conductance function between the two ends:

$$\begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} 0 & g \\ -g & 0 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \quad \text{or} \quad \begin{matrix} i_1 = gV_2 \\ i_2 = -gV_1 \end{matrix} \tag{1}$$

Such a characteristic allows the realization of a wide range of applications of the device such as voltage to current converters, step up and step down voltage to voltage converters, inductance to capacitance conversions and back. Hardware Gyrator realizations were proposed by Tellegen [1]. Further development and analog implementation of the element as an impedance inverter were demonstrated in [2]. The first demonstration of a power Gyrator (as opposed to signal Gyrator) using switch mode converters was given in [3]. In this case the Gyrator function was realized by applying classical buck, boost and buck-boost switch mode converters in closed loop. Double bridge topology power Gyrator implementation was described and analyzed in [5]. Some recent studies, [6], suggest new control methods that improve efficiency of the double bridge converter for a wide operation range. The double bridge topology was chosen in this study due to its simplicity and relatively low components count and bi-directional power transfer ability. In previous works, the control issue and especially control development process were only partially covered and the treatment was based on mathematical equations or block diagrams, lacking the details of control implementation.

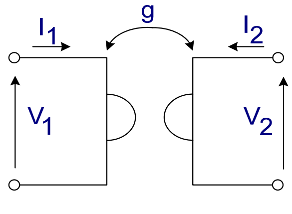


Figure 1: Symbolic representation of the Gyrator

In this study, we present a DSP based control realization of the double bridge Gyrator and propose a new, user friendly simulation guided code development procedure. The main catalyst of the DSP selection was the recent technological advancement in this field and the resulting availability of powerful and yet relatively low cost DSP products. By utilizing the advantages of multifunctional digital controllers, the overall on-board component count is reduced considerably, as compared to an analog control implementation, while still maintaining acceptable switching frequency, approaching the speed and flexibility of a dedicated FPGA based design.

The investigated Gyrator topology (Fig. 2), is based on the "AC inductor" concept, defined as an inductor that operates with zero average current [7]. An "AC inductor" based topology, as used in this study, enjoys zero voltage switching with no need for a resonant tank and associated resonant, high current capacitor. The investigated topology is relatively simple and exhibits a bi-directional gyration behavior where the direction of the energy flow is determined by the relative phase lag between the two bridges. Frequency control is another level of freedom for tuning system performance. This study, however, concentrates on the fixed frequency, phase control approach.

2. Gyrator implementation using double bridge "AC Inductor" topology

The theoretical analysis of proposed topology is carried out under the assumption that each of the bridges is connected to DC voltage source and can thus be represented by square wave voltage sources V_{AB}, V_{CD}, having amplitudes that are equal to the DC voltages V_1 and V_2 respectively, as shown in Fig. 3(a). To better understand the nature of inductor's current and derive the conversion ratio of the double bridge circuit, we employ the superposition approach. This is accomplished by connecting each of the square wave voltage sources to its own inductor (Fig. 3(b)). It is evident that the actual current that flows in the physical inductor is the sum of the currents in the two separate inductors. That is:

$$i_{L(AB)} + i_{L(CD)} = i_L \qquad (2)$$

The current waveforms $i_{L(AB)}$ and $i_{L(CD)}$, forced by the two square wave voltage sources, are shown in Fig. 4. The duty cycle D which corresponds to the phase φ between the two square waves is defined as:

$$D = \frac{T_{on}}{T_s} = \frac{\varphi}{2\pi} \qquad (3)$$

where T_S is the switching frequency and T_{on} is the time lag between the phases. The power delivered to or from V_{AB} of the original circuit (Fig. 3(a)) can be calculated by considering the total average current flowing into it during $T_S/2$. Since the average of current $i_{L(AB)}$ is zero (bottom trace of Figure 4) its contribution to V_{AB} average power flow is also zero. The contribution of V_{CD} is found by deriving the average $i_{L(CD)}$ current during the first $T_S/2$ (Figure 4) which should be

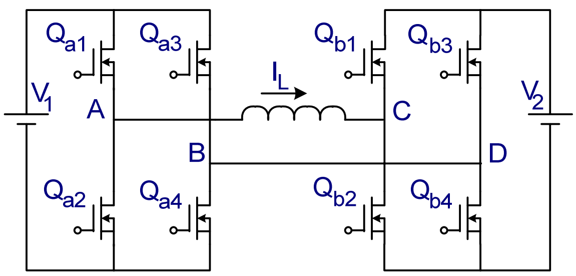


Figure 2: Double bridge "AC inductor" circuit.

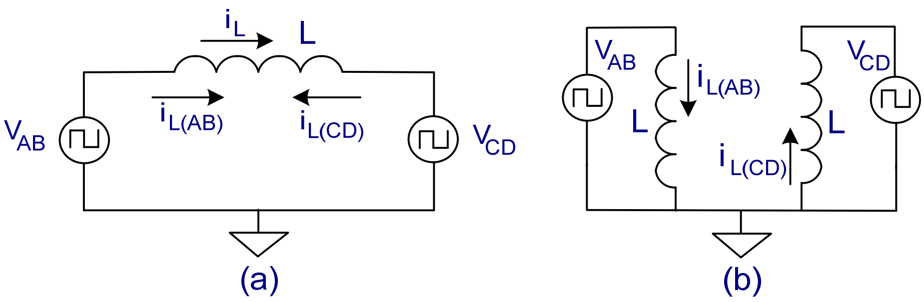


Figure 3: Inductor' current decomposition:

(a) Bridges representation; (b) Superposition of inductor current.

identical to the contribution of the second half cycle due to the symmetry of the square wave. The $i_{L(CD)}$ current at the beginning of $T_S/2$, X, (Fig. 4) (t=0) is found to be:

$$X = \frac{q}{2} \cdot \frac{T_s \cdot V_2}{L} \tag{4}$$

where:

$$q = \frac{1}{2} - 2D \tag{5}$$

which yields:

$$X = \frac{T_s V_2}{2L} \left[\frac{1 - 4D}{2} \right] \tag{6}$$

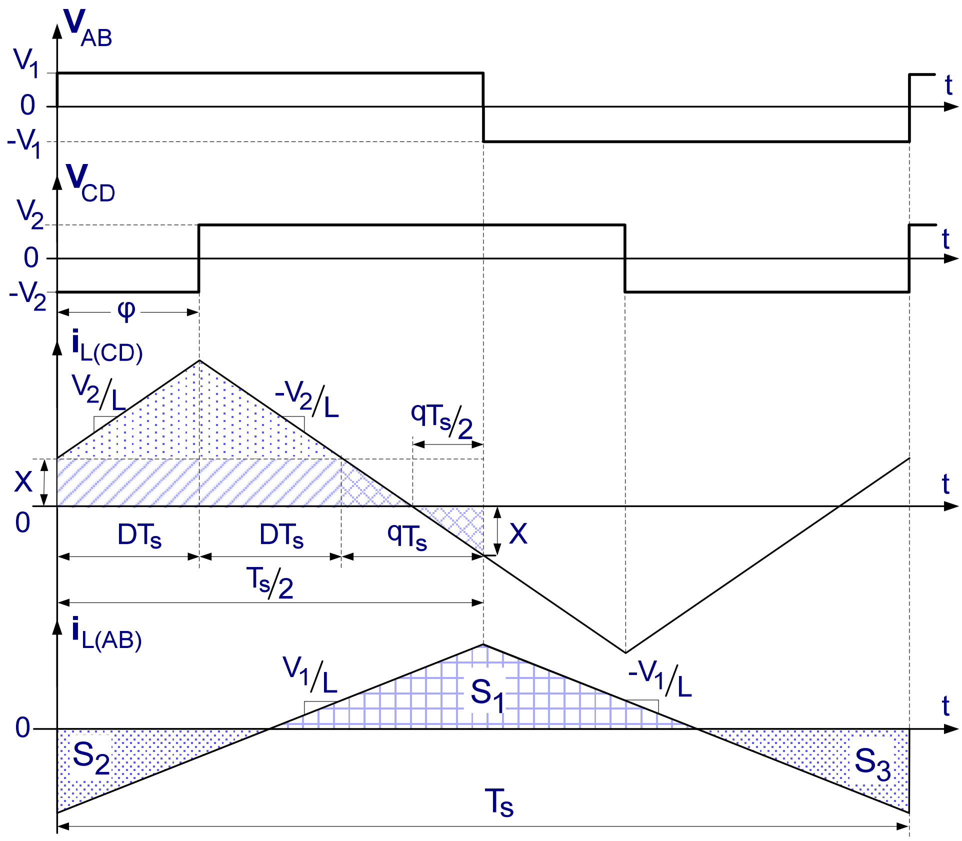


Figure 4: Contribution of the two bridges to the inductor current waveform.

The average input current $i_{L(avg)}$ into V_{AB} is defined as:

$$i_{L(avg)} = \frac{S_{total}}{T_s/2} \tag{7}$$

where S_{total} is the total area enclosed by the $i_{L(CD)}$ waveform during $T_s/2$ which is found to be:

$$S_{total} = X \cdot 2DT_s + \frac{DT_s V_2}{L} \cdot \frac{2DT_s}{2} \tag{8}$$

substituting Eq. 6 into Eq. 8 and rearranging yields:

$$S_{total} = \frac{DT_s^2 V_2}{2L}[1 - 2D] \tag{9}$$

Now, substituting Eq. 9 into Eq. 7 we obtain the average input current $i_{L(avg)}$ into V_{AB} :

$$i_{L(avg)} = \frac{S_{total}}{T_s/2} = \frac{DT_s V_2}{L}[1 - 2D] \tag{10}$$

And the gyration ratio "g" (1) is thus equal to:

$$g = \frac{DT_S}{L}[1 - 2D] = \frac{\varphi}{2\pi\pi_S L}\left[1 - \frac{\varphi}{\pi}\right] \tag{11}$$

where $f_S = 1/T_S$ is the switching frequency. Although derived for V_{AB}, it is obvious that, due to the complete symmetry of the circuit, the gyration ratio for V_{CD} will be identical. Fig. 5 represents phase dependence of a gyration ratio as derived in Eq. 11. Gyration ratio equals zero at $\varphi = 180°$ and maximum at $\varphi = +/- 90°$. It is evident that energy transfer is bidirectional depending on the phase between excitation of the bridges.

3. Simulation guided DSP control development

The required control for the double bridge Gyrator can be easily accomplished by a DSP. In this study we have used the TI TMS320F2808. The high flexibility of this DSP is very helpful during the research period, enabling real-time computations, and easy and fast switching between algorithms and control methods.

Another important aspect of the DSP control implementation, as developed in this study, is the simulation assisted algorithm development and debugging. This was accomplished by applying a power electronics simulator (PSIM Professional version 7.1.2.121; Powersim, USA). This tool was especially designed for power electronics, motor control, and dynamic system simulation. Some of

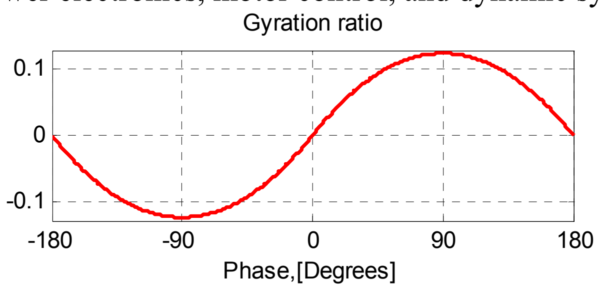


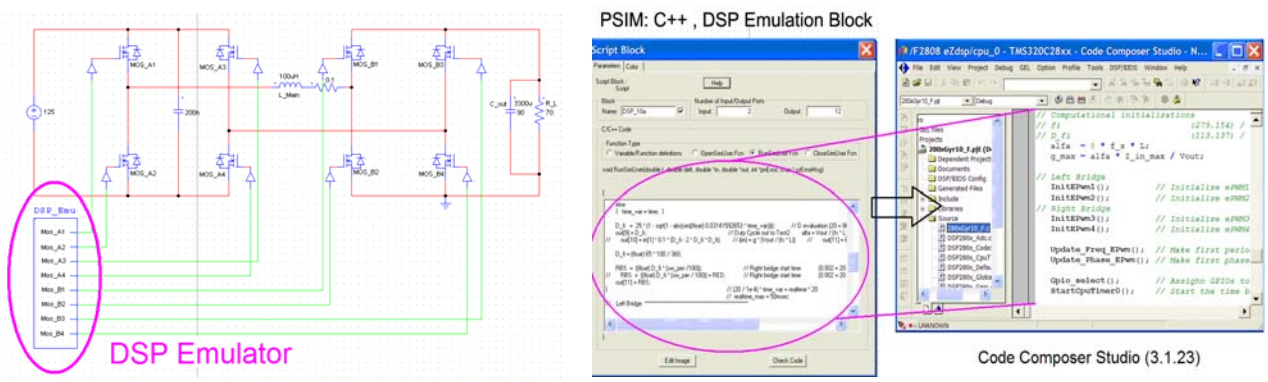
Figure 5: Theoretical gyration ratio.

its advantages include fast simulation and lack of convergence problems when simulating switch mode systems. Fig. 6(a) shows the simulation model of the double bridge Gyrator implemented in PSIM. The model contains two MOSFETs bridges, one connected to the input voltage and the other to a resistive load in parallel to a filter capacitor. These two bridges are interconnected by an inductor and controlled by a PSIM C++ block which emulates the DSP operation. This block controls all the MOSFETs via isolated floating driver units. The code for the PSIM C++ block was implemented by a "SoftIntegration" Inc. compiler which is part of PSIM. The C++ window is shown on the left side of Fig. 6(b). Applying this C++ control feature, the control algorithm can be debugged and optimized by running PSIM, time domain simulations. Once ready for hardware testing, the C++ code was transferred, as is, to the Code Composer Studio (3.1.23) by copy and paste (left of Fig. 6(b)), and then compiled and embedded into the DSP. This user friendly approach shortens considerably the algorithm debugging process, reducing the number of hardware trials, and makes the development process more efficient. The ability to simulate the control process of the power stage by using the exact C++ code that is eventually transferred to the Code Composer minimizes the gap that usually exists between the simulation of pure mathematically models and digital control implementation on a DSP.

4. Control Strategy

It follows from section 2, that the objective of the control is to generate two square waves, which are phase shifted one with the respect to the other, to drive the two bridges. That is, each of the bridges (Fig. 2) needs to be driven by a square wave of 50% duty cycle, and there is a need for a delay between the two drives to generate the phase shifted square waves at the output of the bridges. This square wave output is obtained by operating the diagonal MOSFETs in each bridge simultaneously and complementary to the transistors in the other diagonal. For example, each of the pairs Q_{a1},Q_{a4} and Q_{a2}, Q_{a3} (Fig. 2) need to be operated simultaneously and complementary to the other pair. The same goes for the 'b' bridge that comprises the pairs Q_{b1},Q_{b4} and Q_{b2},Q_{b3}, except that the drive needs to be delayed with respect to 'a' bridge. In addition to the generation of the basic drive sequence, there is a need to provide a dead time between the drive of the transistors in each half bridge (Q_{a1},Q_{a2} ; Q_{a3},Q_{a4}; Q_{b1},Q_{b2} ; Q_{b3},Q_{b4}) to prevent a short circuit due to conduction overlap (Shoot Through).

The above drive requirements for the two bridges are compatible with the capabilities of the TI TMS320F2808 used in this study. The basic bridge drives where generated by two counters, PWM(1,2) for the left side bridge and PWM(3,4) for the right side bridge (Fig. 2), corresponding



(a) (b)

Figure 6: DSP emulation by a C++ block of "PSIM Professional 7.1.2.121: (a) PSIM simulation model. (b) The copy and paste process of the simulated C++ code into the code composer.

compare registers, CMPA(1,2) and CMPA(3,4) which were set to 50%, while the 'Active low complementary' function was activated (Fig. 8). Rising edge delays (RED) and falling edge delays (FED) were used to secure the dead time between the diagonal drive of each bridge. The delay between the drive of the two bridges (phase delay) was created by a third compare register CMPB2 (Fig. 8) that was set to the desired delay. The output signal of this comparison was used as a sync signal to start the delayed PWM counter PWM(3,4).

5. Simulation and Experimental Results

A prototype of the proposed Gyrator-behaved switch mode converter was built and tested experimentally. The control was carried out by the TI's eZdsp TMS320F2808 evaluation board, applying the setup of Fig. 9. The objectives of the tests done were to validate the practical implementation of the theoretical gyration ratio, the examine the possibility of obtaining a smooth control of the power stage by the DSP, to validate the soft switching operation and to evaluate the simulation-guided DSP control development as proposed in this study. The parameters of the experimental unit were: Input and output maximum voltage 400 VDC; nominal output power of 300W; maximum current of 5Arms; switching frequency 100 kHz; inductance of the main coil 100 µH. The typical waveforms of the experimental unit and simulation results for the same parameters, given in Fig.10, confirm soft switching behavior of the power stage. Load step response for load increase and load decrease situations are given in Fig. 11.

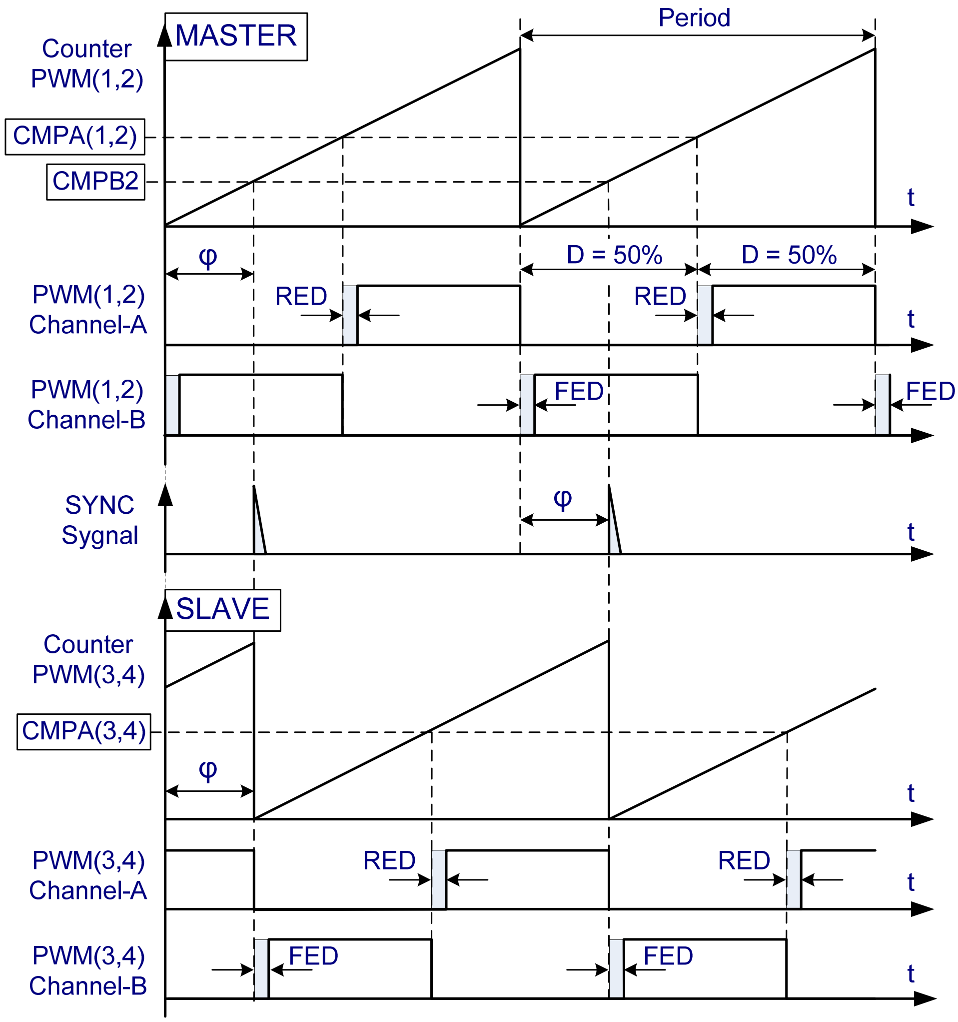


Figure 8: ePWM timing diagram. (CMPA/B(X) – Compare registers)

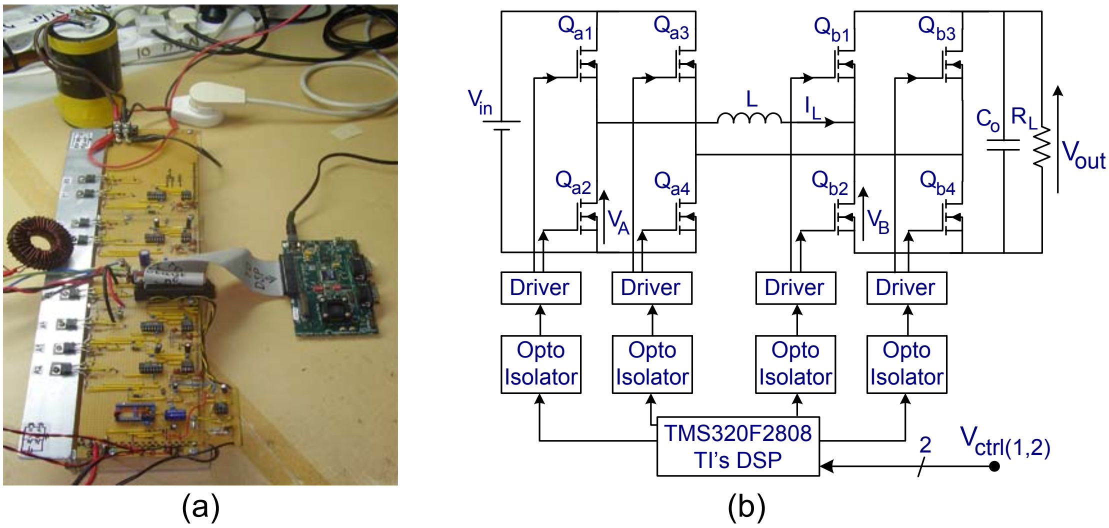


Figure 9: Experimental setup: (a) Prototype photo, (b) Setup block diagram.

The sudden change in output current (observed in Fig. 11) is due to the fixed voltage on the output capacitor that settles at a time constant of the output network, after which the load current returns to the magnitude it was before the excitation, while the output voltage is changed to a new value. The experimental gyration ratio (Fig. 12) follows the theoretically expected behavior. The difference is due to (primarily conduction) losses which were not taken into account in the theoretical computation.

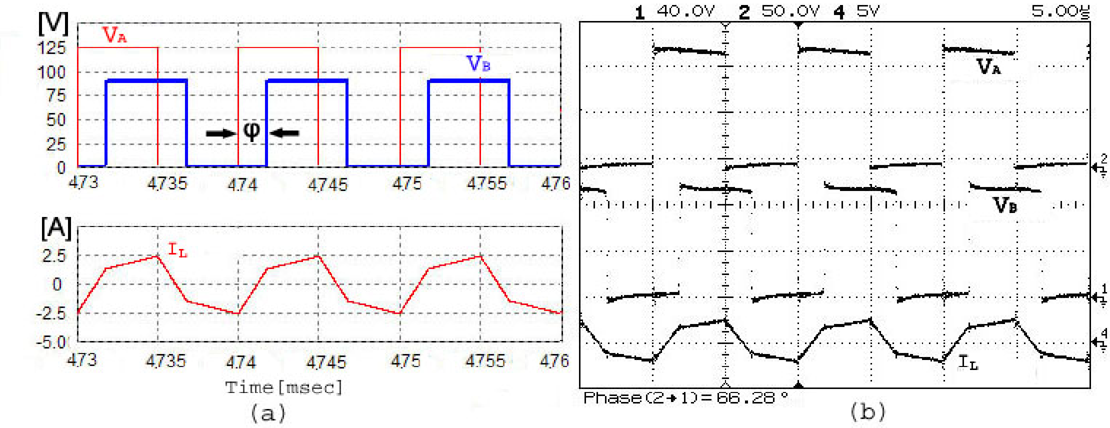


Figure 10: Typical waveforms: (a) Simulation, (b) Experimental.

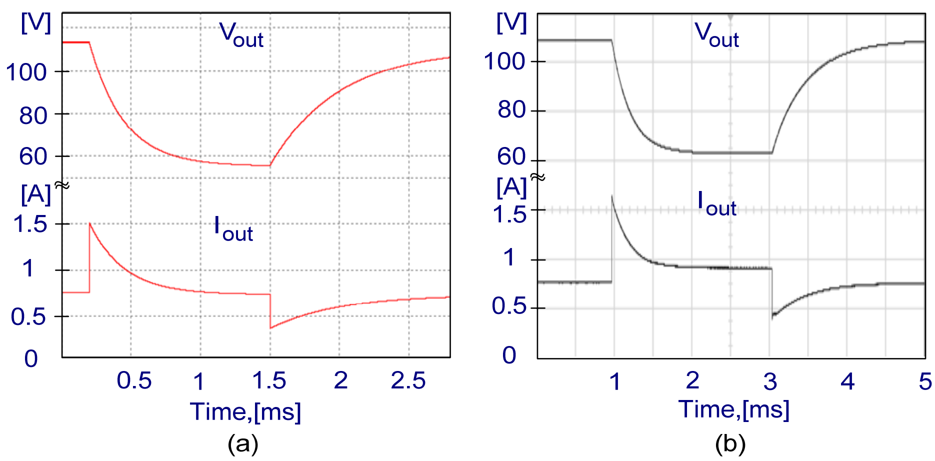


Figure 11: Load step up and step down between 150Ω and 75Ω: (a) Simulation, (b) Experimental.

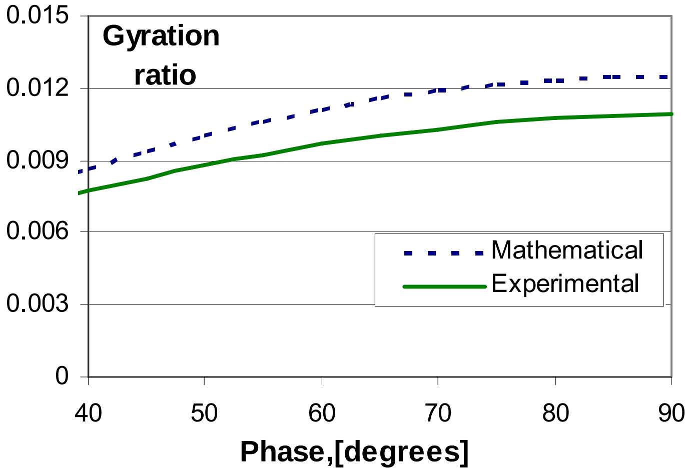


Figure 12: Gyration ratio: Dashed line – Mathematical computations, Solid line – Experimental results.

6. Discussion and Conclusions

The double bridge Gyrator-behaved switch mode converter was investigated applying the TI's TMS320F2808 DSP.

The innovative control development method, employing PSIM simulation software, was found to be easy to implement and accurate. This proposed method can easily be adopted in the control algorithm development of other switch mode systems.

Simulation and experimental results verify the Gyrator behavior of the investigated topology. Good agreement was found between the theoretical predictions and the experimental results. The deviation between the theoretical and experimental is attributed to the losses in the practical circuit components which were not taken into account in the mathematical expressions.

The results of this study support the assertion that DSP control can significantly simplify and reduce the cost of the implementation of complex and intricate control methods of power conversion systems, and open the door to commercial applications of new, hitherto untapped, topologies.

7. References

[1] B. D. H. Tellegen, "The Gyrator, a New Electric Network Element" Philips Res. Rept. Vol 3, pp. 81-101, April 1948.

[2] B. G. Bogert, "Some Gyrator and Impedance Inverter Circuits", Proc. IRE, vol. 43, pp. 793-796, July 1955.

[3] S. Singer, "Gyrator Application in Power Processing Circuits", IEEE Trans. On Industrial Electronics, Vol. IE-34 No.\2573, pp. 313-318, August 1987.

[4] M. Ehsani, I Husain, M. O. Bilgic, "Inverse Dual Converter (IDC) for High-Power DC-DC Applications" IEEE Trans. On Power Electronics vol. 8, no:2, pp.216-223, October 1993.

[5] Mustansir H. Kheraluwala, Randal W. Gascoigne, Deepakraj M. Divan and Eric D. Baumann, "Performance Characterization of a High-Power Dual Active Bridge dc-to-dc Converter", IEEE Trans. On Industry Applications, vol. 28, no: 6, pp. 1294-1301, November / December 1992.

[6] F. Krismer, S. Round, J. W. Kolar, "Performance Optimization of a High Current Dual Active Bridge with a Wide Operating Voltage Range", IEEE Power Electronics Specialists Conference, pp1-7, June PESC-2006.

[7] Zeltser I., and Ben-Yaakov S., Modeling, analysis and simulation of "AC inductor" based converters. IEEE Power Electronics Specialists Conference, PESC-2007, 2128-2134, Orlando, Florida, 2007.