A Generic Model of a Gyrator Based APFC

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Abstract - **A generic model of a double bridge "AC inductor" based Gyrator-behaved APFC is presented, analyzed and verified by simulation and experiments. Based on the results of the study, a design procedure is developed for specifying the control law and the optimal parameters for ZVS and minimum conduction losses of the proposed APFC. The proposed APFC requires neither line voltage, nor input current sensing circuitry except for line synchronization. The theoretical predictions are well supported by simulation and experimental results that were obtained by a digitally controlled system.**

Index Terms — Gyrator, Rectifier, APFC, Double bridge, "AC Inductor", AC-DC converters, power conversion.

I. Introduction

The traditional approach of Active Power Factor Correction (APFC) is based on sensing both input voltage and input current waveforms in order to achieve a close to unity power factor. The sensed signals are processed by analog multiplier and divider to implement the programming law [1-6]. An alternative strategy is the border line control [7, 8], which can be implemented without a multiplier. This control method leads to a variable frequency operation in order to properly shape the current drawn from the grid. However, due to the relatively high RMS value of the borderline current waveform, this approach is limited to relatively low power levels.

More advanced APFC systems, that do not require voltage sensing and analog multiplier-divider blocks were introduced in [9-12]. These systems exploit the relationship between the voltage applied to an inductor and the current developed through it, in order to follow the grid waveform.

The APFC approach proposed in this work does not require the sensing of neither the input voltage nor the input current, except for grid synchronization signal. Hence, the proposed APFC does not require the circuitry associated with current and voltage sensors. Furthermore, since the input voltage does not serve as a reference to generated input current, input voltage distortion will not affect the shape of the input current. Another advantage of the proposed system is high power capability that stems from the fact that it is based on a double bridge topology [13]. This topology is highly versatile, allowing isolation by high frequency transformer between the load and the grid, if required. The Gyrator nature of the double bridge topology makes it possible to design a system with low output voltage as opposed to the Boost based APFC which produces a high output voltage.

Hardware realization of a Gyrator was proposed in [14] and further development and analog implementation of the element as an impedance inverter were demonstrated in [15]. The first demonstration of a power Gyrator (as opposed to signal Gyrator) using switch mode converters is given in [16]. In the latter, the Gyrator function was realized by applying classical buck, boost and buck-boost switch mode converters in closed loop. The double active bridge topology was later shown to behave as a Gyrator [13, 17]. Notwithstanding the popularity of the double bridge [18-20], the investigation of its Gyrator-behaved nature was carried out in previous works only for a specific range of numerical parameters, like in [21], and consequently, covering only part of the operation span of the topology, while missing the generalization.

The objective of this study was to develop a generic model of a double bridge "AC Inductor" Gyrator-behaved topology employed as an APFC. Having at a hand generic model, design process of a system is less demanding in the terms of time, money and some other resources. The novel APFC control idea, which does not require sensing the input voltage or current, presented here, is based on the Gyrator nature of the double bridge topology. Utilizing the stabilized DC output voltage, a sinusoidal current source is reflected to the grid. Being a "natural" current source, Gyrator topology eliminates the necessity in internal current loop, and digital control implementation takes it one step further, omitting the input voltage sensing requirement. The paper presents theoretical concept, simulation and experimental results. The experimental system was a digitally controlled Gyrator-based APFC system.

II. The Double bridge "AC Inductor" topology as an APFC with no input sensing

A Gyrator is a network element that transforms current into voltage and vice versa (Fig. 1a). The relationship between the input and output ports of a Gyrator (1) implies that a voltage source connected to either side of Gyrator will be reflected to the other side as a current source (Fig. 1b):

$$\begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} 0 & g \\ -g & 0 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \quad (1)$$

The proposed Gyrator-behaved double bridge (Fig. 2) is based on the "AC Inductor" concept defined as an inductor that operates with zero average current [22]. 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. This topology (Fig. 2) consists of two active full bridges connected by an inductor between each other. Each of the bridges is operated at 50% duty cycle and complementary between its diagonal switches. As derived in [23], the trans-conductance characteristics, or gyration ratio of this scheme is:

$$g = \frac{DT_s}{L}\left[1-2D\right] = \frac{\varphi}{2\pi \cdot f_s L}\left[1-\frac{\varphi}{\pi}\right] \tag{2}$$

where φ is the phase shift between the two bridges (φ=D·360º), f_s is the switching frequency, and L is the inductance of the choke. Gyration ratio as a function of phase shift between the bridges is presented in Fig. 3.

The unique features of the Gyrator-behaved double bridge topology allow the implementation of isolated APFC with no sensing of input waveforms, relying solely on an output voltage and a grid synchronization signal. In the proposed double bridge isolated APFC system (Fig. 4), the output voltage V_{out} assumed to be DC, and following (1)

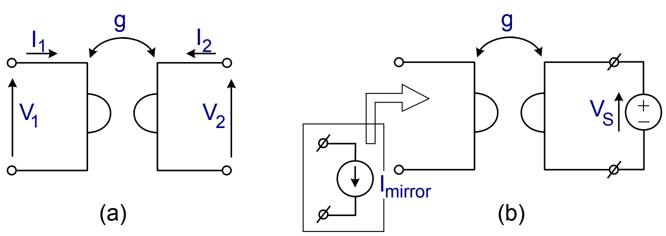

Figure 1: (a) Gyrator symbolic representation, (b) Voltage to current source transformation.

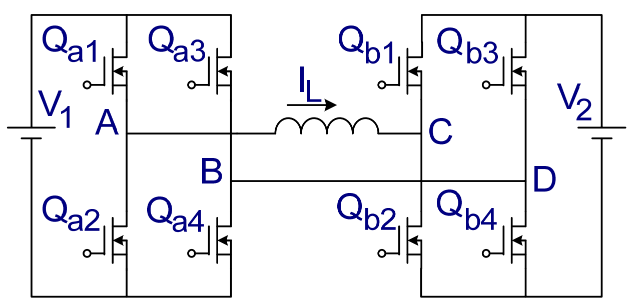

Figure 2: Double bridge Gyrator-behaved topology.

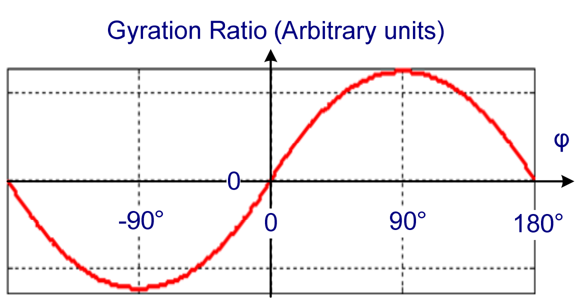

Figure 3: Theoretical behavior of gyration ratio.

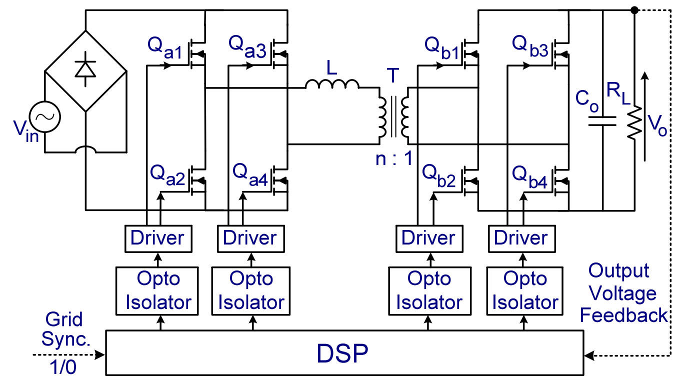

Figure 4: Proposed double bridge based APFC block diagram.

is reflected to the input terminal of the Gyrator-behaved double bridge topology as a current source. The required sinusoidal shape of the current source is achieved by applying an APFC programming law (which is discussed in the next section) to the gyration ratio, via phase shift control between the two bridges. Being a current source, the Gyrator consumes a sinusoidal current regardless the shape and phase of input voltage. However, to ensure in-phase operation between the voltage and the current, the zero crossing of the grid voltage is monitored, and the current is synchronized to the voltage, completing the PFC requirements.

III. Generic Model of a Double Bridge Topology, and APFC Programming Law

The purpose of the model is to provide a handy tool for choosing converter parameters, such that the APFC will run at the optimal efficiency, and will always operate under soft switching conditions. Soft switching region was derived by using the simplified double bridge scheme presented in Fig. 5. It was found that for the case of $V_1 > V_2$ (Fig. 5), left bridge will always operate under ZVS conditions, because at the time points of t = 0, $I_{L(AB)} > I_{L(CD)}$, and at t = T/2, $I_{L(AB)} < I_{L(CD)}$ (Fig. 6a), ensuring body diodes conduction prior to the MOSFET turn on. Right bridge will operate under ZVS conditions for the phase $\varphi > \varphi_{limit}$, which ensures that at the time points of t=φ, $I_{L(CD)} < I_{L(AB)}$, and at t = T/2 + φ, $I_{L(CD)} > I_{L(AB)}$ (Fig. 6b). Due to the bidirectional nature of the double bridge topology, it is obvious that in the case of $V_1 < V_2$, the roles of the left and the right bridges will change, and all the conclusions that were

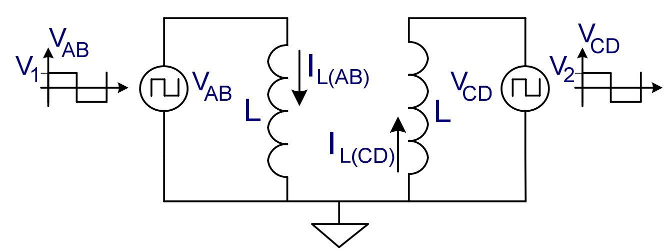

Figure 5: Simplified superposition inductor current analysis.

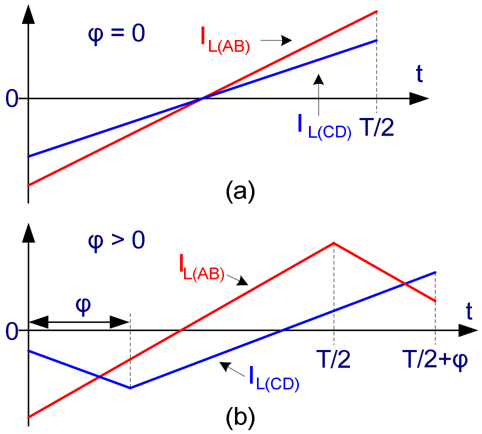

Fig. 6: Inductor current due to left ($I_{L(CD)}$) and right ($I_{L(AB)}$) bridges, (a) φ = 0º, (b) φ > 0º.

obtained for the right bridge will relate to the left bridge, and vice versa. Limiting phase φ_{limit} for ZVS operation was calculated, and found to be: (3) for the right bridge and (4) for the left bridge.

$$\varphi_{lim} = \frac{\pi}{2}\left(1 - \frac{V_2}{V_1}\right), \quad V_1 > V_2 \tag{3}$$

$$\varphi_{lim} = \frac{\pi}{2}\left(1 - \frac{V_1}{V_2}\right), \quad V_1 < V_2 \tag{4}$$

Similar ZVS limits were reported in [21].

Another parameter presented in the model is the index of conduction losses - α, which was derived as the ratio between the DC current transferred to the load - I_{avg}, and the total RMS current that flows through the inductor – $I_{L(RMS)}$:

$$\alpha = \frac{I_{avg}}{I_{L(RMS)}} = \frac{n \cdot (D - 2D^2)}{\sqrt{\frac{1}{48}(1-k)^2 + k \cdot (D^2 - \frac{4}{3}D^3)}} \tag{5}$$

where n is the transformer winding ratio, D is the duty cycle which is dual to φ, k is the voltage ratio and equals:

$$k = \frac{n \cdot V_{out}}{V_{in}} \tag{6}$$

A method for implementing APFC without sensing input voltage waveform was proposed earlier in [9-12]. The proposed APFC control of this study can operate not only without sensing the input voltage, but also without sensing the input current. The method is based on making the input terminals of the double bridge to be resistive, R_e:

$$R_e = \frac{V^2_{in(RMS)}}{P_{in}} \tag{7}$$

The programming law required to ensure this resistive behavior was derived from (2) to be:

$$D = \frac{1 \pm \sqrt{1 - \frac{8}{R_e k}\sin(\omega_{Grid} t)}}{4} \tag{8}$$

where ω_{Grid} is the radial frequency of the grid, and t is time. The generic model of the APFC is based on a normalized input resistance R_e^* defined as:

$$R_e^* = \frac{R_e}{f_s \cdot L} \tag{9}$$

where f_s is the switching frequency, L is the choke inductance. Using this normalized factor (9) and employing (8), duty cycle values were calculated for different equivalent resistances, while output and input voltage ratio – k was used as a parameter. Applying (5), indexes of conduction losses were derived for any given duty cycle and input output voltage ratio. And finally, (3) and (4) were used to mark soft switching borders. The design guide map of Fig. 7 was then created by summarizing all of these calculations. This generic representation can now be used to design the optimal Gyrator-based APFC system.

The procedure of the system design begins by selecting the equivalent normalized resistance which is within the maximum efficiency (largest α) and soft switching range. This determines the minimum k value, and hence the transformer turns ratio. Next step is to choose the inductor, which is set to operate at the desired frequency and to comply with the actual R_e value which represent the power requirements. Analyzing for instance the red curve of R_e^* = 20, in Fig. 7, one can see that for k > 1.2 the APFC will operate under hard switching conditions at the input bridge. The remedy to this becomes clear from the map of the generic model: soft switching can be obtained beyond the point k = 1.2 if the duty cycle will be set to ~0.45 instead of ~0.05, maintaining ZVS but paying for that by a lower α and hence larger conduction losses. This may be acceptable considering the fact that this range corresponds to the low input voltage range of the line and hence low input current.

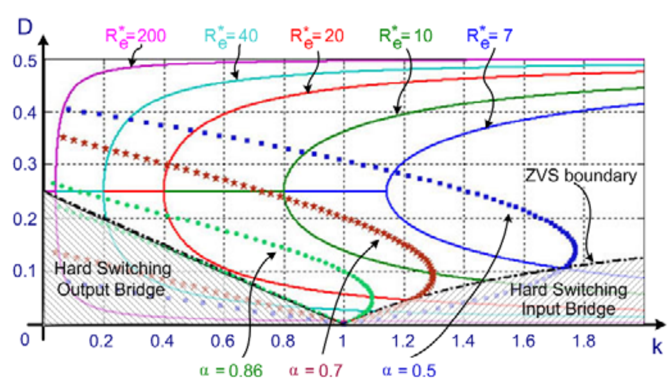

Figure 7: Map of the generic Gyrator-based APFC model.

IV. EXPERIMENTAL

A prototype of the proposed double bridge Gyrator-behaved APFC system that follows the block diagram of Fig. 4 was designed, built, and tested experimentally. The objective was to validate the viability of the derived generic model, and to verify the smooth operation of the novel input-sensorless APFC.

Following the generic model map (Fig. 7), $R_e^* = 20$ was chosen, and for higher efficiency the minimum value of k was set to 0.42. The target parameters of the experimental unit were: Input voltage: 110 VRMS; Output voltage: 70 VDC; Nominal output power: 100 W; Load resistor: 50 Ω; Inductor of 100 µH; Transformer ratio n = 1. Based on these parameters, the operating point was found to be at switching frequency of 60.5 kHz.

The experimental results (stars in Fig. 8) show a good agreement with the theoretical R_e^* curve. The discrepancy is due to the fact that the model assumes a lossless converter. The comparison between the simulated and experimental index of conduction losses – α, and the efficiency is summarized in Fig. 9. Typical waveforms of input voltage and current are given in Fig. 10. The APFC efficiency of the system over the full operating range is presented in Table I.

V. DISCUSSION AND CONCLUSIONS

A generic model of Gyrator-based APFC, and a novel input-sensorless APFC based on a double bridge converter are presented. Good agreement was found between the experimental results and the model's prediction. The differences are due to the losses in the practical components, which were not taken into account in the theoretical expression. The proposed input-sensorless APFC shows high performance in terms of current shaping and zero phase between the voltage and current waveforms. Unity power factor control could be achieved for the whole operation range enjoying ZVS of all switches.

This work introduces a new, input sensorless category of APFC systems. Soft switching operation regions are derived for the input and output bridges of double bridge Gyrator-behaved APFC. Control method based on navigation between different regions is proposed, ensuring soft switching of all switches over the entire period of the grid. The generic model proposed in this study deals with many system parameters, such as phase shift between the bridges (or duty cycle), output and input voltage ratio, transformer ratio (if exists), power level of the system that is expressed as the equivalent input resistance of the APFC, and conduction losses index. All these parameters are summarized in one map, which make it possible to choose optimal equivalent resistance and control strategy that ensures soft switching operation with minimum conduction losses and maximum efficiency.

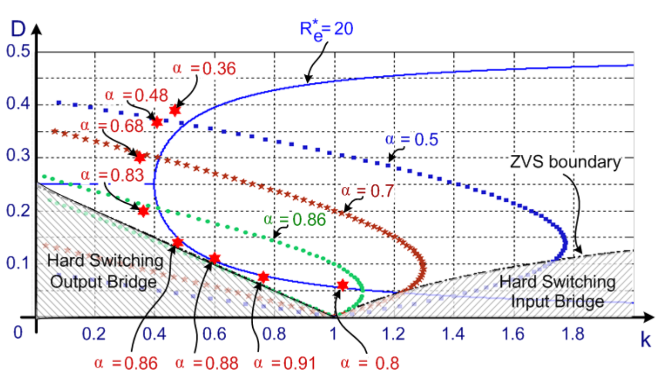

Figure 8: Generic model: Theoretical (line and dots) vs. experimental results (Red stars).

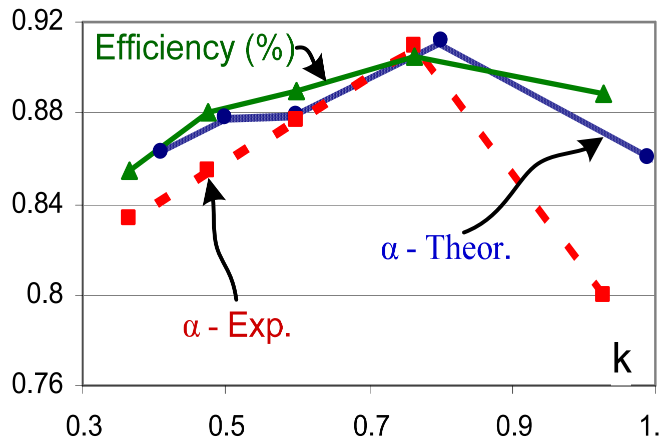

Figure 9: Theoretical and measured conduction losses index (α) and measured efficiency.

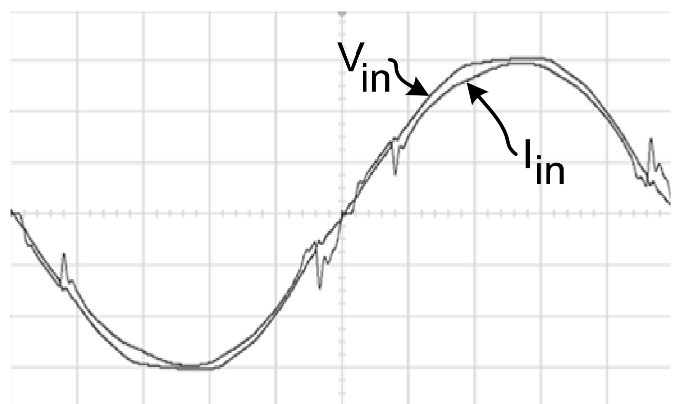

Figure 10: Typical waveforms.
Voltage: 50V/Div; Current: 500ma/Div; Time: 2ms/Div;

TABLE I
APFC EFFICIENCY OVER THE FULL WORKING RANGE

P_{out}	V_{in}	V_{out}	Efficiency
51W	110 VRMS	68 VDC	72 %
94W	110 VRMS	34 VDC	80 %
201W	162 VRMS	100 VDC	80.5%

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