A passive power factor correction technique for single-phase thyristor-based controlled rectifiers

R. Carbone

Abstract **—** An approach already introduced to correct in a very simple way the power factor (PF) of single-phase and three-phase diode rectifiers is extended to single-phase line-frequency phase-controlled rectifiers. Some recalls on the aforementioned PF correction technique and some fundamentals on the conventional controlled rectifier behaviour are stated in advance. Then, the conventional circuit of the single-phase thyristor-based rectifier is proposed to be modified in order to make possible the control of the DC-voltage mean value also in presence of a fully resistive behaviour of the DC-load, being this last condition an imperative constraint for the extension of the introduced passive power factor correction technique. Once modified the controlled rectifier circuit, the PF passive correction technique is theoretically extended to it and, then, it is practically operated on a circuit case-study, by using a lot of Pspice numerical simulations. For both uncontrolled and controlled rectifiers, the introduced PF passive correction technique is simply based on the use of a resistive-capacitive branch to be connected at the DC-terminals of the rectifier. By properly designing the parameter values of the correcting passive branch, the behaviour of the equivalent rectifier DC-load can be make fully resistive, so obtaining a rectifier AC-side absorbed current practically sinusoidal and in phase with the AC supplying voltage. The designing procedure of the introduced passive correcting branch is considered and investigated. Analyses of performances of the new controlled rectifier are developed with the help of several Pspice simulations on a DC-motor drive case-study of about 2.5 kW of active power and under different working conditions, obtained by varying the rectifier delay angle, α, in order to control the speed and the power of the motor. Some perspectives on the possibility to improve the conversion efficiency of the modified rectifier, sensibly worsen because of the introduction of the dissipative elements (the resistor) on the proposed correcting branch, are also developed together with some final considerations on the practical meaning of the currently defined rectifier PF index, that does not seems able to properly evaluate and compare performances of different rectifiers.

Keywords **—** Controlled rectifier, DC Motor Drives, Power Factor Correction, Total Harmonic Distortion Factor, Rectifier Conversion Efficiency.

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I. INTRODUCTION

As a consequence of the increasing use of power electronic converters, today one of the most lively research activity, in the specialized literature, is that devoted to the correction of the power factor (PF) of power electronic converters [1]-[32]. The main objectives of the researches are to minimize both the harmonic contents of the line currents absorbed by the converters from the supplying system and the displacement factor between the converter fundamental line current and the supply system fundamental phase voltage.

At present, a lot of correcting circuits are available for power factor correction when rectifiers are used as power supplies. They are simply called power factor correctors, PFCs.

These circuits can be essentially classified into two main categories: 1) active PFCs and 2) passive PFCs.

High frequency double-stage active PFCs [1]-[4] use an DC/DC boost-type converter operated as an input current shaper and a second DC/DC converter for output voltage regulation. The input DC/DC converter forces the current to follow the rectifier output voltage shape so making quasi-resistive the DC-load behavior. These active PFCs are known for their superior performances, even if some important penalties have to be also considered. First of all, its cost is high for a large volume of applications and the complexity of the resultant circuit causes some lake of reliability. On the other hand, double-stage active PFCs originate conducted and radiated interference and additional EMI filters could be necessary to comply with high-frequency emission limits.

High frequency single-stage active PFCs integrate the PFC function and the output voltage regulation in only one DC/DC converter [5]-[11]. Only one controller, but with a complex control strategy based on duty-cycle and/or switching-period modulation, is required. Furthermore, an additional large energy-storage capacitor between the PFC-cell and DC/DC-cell is needed in order to handle the differences between the instantaneously varying input and the constant output power and to guarantee good performances.

Single-stage active PFCs are characterized by lower cost but also by lower performances.

Line-frequency-commutated active PFCs are a good trade off between cost and performances [12]-[14]. All of them guarantee the compliance with standards by using L and C passive elements and a line-frequency commutated switch, so essentially increasing the AC absorbed current conduction angle.

The line-frequency-commutated PFC introduced and discussed in [14] results characterized by a high power factor, an inherent switch short-circuit protection and a lower needed inductor value to comply with IEC 1000-3-2 standard, as compared to the line-frequency-commutated boost-rectifier introduced in [12] and [13].

Passive PFCs, in spite of their lower global performances with respect to that of active PFCs, are normally robust, reliable, economical and do not generate EMI; so, today, passive PFCs are again profitably under investigation by a number of qualified researchers.

In fact, a number of passive PFCs circuit topologies have been proposed and discussed in the specialized literature [15]-[29].

Recently, a new and very easy circuit topology for passive power factor correction, characterized also by performances very close to those of active PFCs, was introduced [20]-[28]. It is essentially based on the use of a properly designed DC-side extra passive branch; DC-side current harmonics flowing on this extra correcting branch are added to the already present filter-load absorbed-current, so improving the rectifier AC-side absorbed current, without introducing additional nasty high frequency components typical of active PFCs.

Both low cost and high performances are expected for this circuit topology, as demonstrated by the results of several numerical experiments reported also in [20]-[28].

Unfortunately, the aforementioned passive PFC introduces additional circuit power losses on the needed resistor of the correcting additional passive branch. Even if only harmonic current components flow on this correcting resistor, they could significantly worsen the global power efficiency of the rectifier.

Additional power losses could be minimized by varying the PFC parameter values: starting from the nominal values obtained as above indicated, new values able to verify the IEC 1000-3-2 standard and to reduce the PFC current rms-value can be found out. Nevertheless, in minimizing the additional PFC power losses by this way, other important performance parameters of the rectifier, as the rectification efficiency, the power factor and the current crest factor, could result significantly worsen.

For this last reason, the most important think for improving the efficiency of the passive PFC under discussion is represented by the substitution of the correcting resistor of the PFC branch with a “resistance emulator”, that is to say, an electronic circuit able to reproduce the correcting resistor effects on the rectifier absorbed current, avoiding at the same time PFC extra power losses. This aspect is specifically investigated in [27], [28].

The aforementioned passive PF correction technique works only for single phase and poly-phase uncontrolled diode rectifiers, while it is not able to correct power factor of phase-controlled controlled rectifier, that are well known to be profitably utilized in a lot a practical applications (e.g. DC and AC power motor drives).

In this paper, after some recalls on the aforementioned passive PF correction technique and on the possibility to significantly improve the conversion efficiency of the corrected rectifiers, a new electrical scheme for thyristor based controlled single-phase rectifiers is firstly introduced, with the aim to make possible the extension to it of the already introduced passive PFC.

Some specific designing aspects are investigated and, then, the performances of the new controlled rectifier, modified with the above described passive PFC, are analyzed with the help of several PSPICE numerical simulations on a DC-motor drive case-study circuit of about 2.5 kW.

Finally, some considerations on the practical meaning of the PF index, currently utilized for evaluating and comparing performances of different kind of power electronic converters are also developed on the basis of the obtained results.

II. A Previously Introduced Passive Power Factor Correction Technique for Uncontrolled Rectifiers

A. Fundamentals

With specific reference to single-phase diode rectifiers, the introduced passive PFC is essentially based on the idea that the quasi-sinusoidal DC voltage waveform at the rectifier terminals, Vdc(t), can be utilized to supply an additional passive branch. The extra current harmonic components absorbed by this branch are added to the conventional filter-load current and, so, they are able to make quasi-sinusoidal the total rectifier DC-side current waveform, also making sinusoidal the rectifier AC-side absorbed current.

The invariance of the Vdc(t) voltage waveform is a not renouncing think; for this reason, the conduction angles of the rectifier diodes have not to be affected by the DC-filter behavior and, then, only rectifiers with inductive or inductive-capacitive DC-filters are explicitly considered.

The aforementioned idea can be better appreciated with the help of Fig.1.

In practice, the goal of the added passive branch, with R*, C* elements, in parallel with the filtered DC-load, is to absorb just those current harmonics that are filtered out by the DC-filter, avoiding the zero-frequency current-component in order to minimize additional power losses.

The designing procedure for the R* and C* parameters is strongly influenced by the topology of the utilized DC-filter and, as mentioned above, a solution is guaranteed only if the DC-filter does not affect the conduction period of the rectifier diodes, that is to say if the rectifier can be seen as an ideal voltage source with the quasi-sinusoidal DC-side voltage waveform depicted in Fig.1.

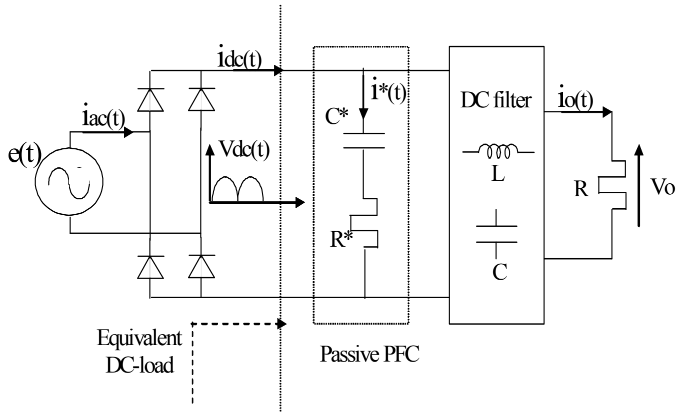

Fig. 1. Single-phase bridge diode rectifier scheme, with the introduced passive PF

In the following, the procedure for designing the correcting parameters, R* and C*, is formalized with specific reference to uncontrolled rectifier with inductive (L) and inductive-capacitive (L,C) DC-filters.

B. Designing the passive PFC for uncontrolled rectifiers with fully inductive DC-filter

In Fig.2 the topology of a diode rectifier in series with the proposed PFC and an L DC-side filter is depicted.

The goal of the proposed PFC circuit being that of making the equivalent DC-load resistive, it is formally enough to impose the following equation:

$$\overline{Z}eq = \left(R* + \frac{1}{j\omega C*} \right) // (R + j\omega L) = R \qquad (1)$$

where $\overline{Z}eq$ is the impedance of the equivalent DC-load (Fig.2) and L is the inductance value of the DC-filter inductor.

From (1), it immediately results:

$$R* = R, \quad C* = \frac{L}{R^2} \qquad (2)$$

C. Designing the passive PFC for uncontrolled rectifiers with inductive-capacitive DC-filter

In Fig.3 the topology of a diode rectifier in series with the proposed PFC and an L-C DC-side filter is depicted.

In order to avoid the capacitive behavior of the DC-load, not included in our objectives, for the circuit analysis it is assumed that the DC-filter inductance value, L, is high enough to guarantee that the conduction angles of the rectifier diodes are unaffected by the voltage at the terminals of the capacitor C, that is to say [19]:

$$L \geq \frac{R}{3\omega_{ac}}, \qquad (3)$$

where ω_{ac} is the AC-supply angular frequency.

Even if the resulting circuit is quite simple, the formalization of the problem of finding the R*, C* values able to make resistive the equivalent DC-load can result arduous. On the other hand, the problem can be suitably solved by taking advantage of some simple considerations, reported in the following.

Avoiding the too restrictive goal of making the behavior of the equivalent DC-load completely resistive, a significant improvement in the power factor can be obtained if the output rectifier-current, i_{dc}, is corrected in order to obtain the same 2-th harmonic component (the predominant harmonic component) of the current resulting in case of resistive DC-load, $\overline{I}^{2-th}_{dc,R}$. On the other hand, starting from the knowledge of the 2-th harmonic component of the output rectifier voltage and of the output rectifier-current resulting before the insertion of the proposed PFC, $\overline{V}^{2-th}_{dc}$ and $\overline{I}^{2-th}_{dc,RLC}$ respectively, it is possible to simply calculate the additional 2-th harmonic current components to be added by means of the PFC, $\overline{I}^{2-th}_{dc,R*C*}$, as shown in Fig.4.

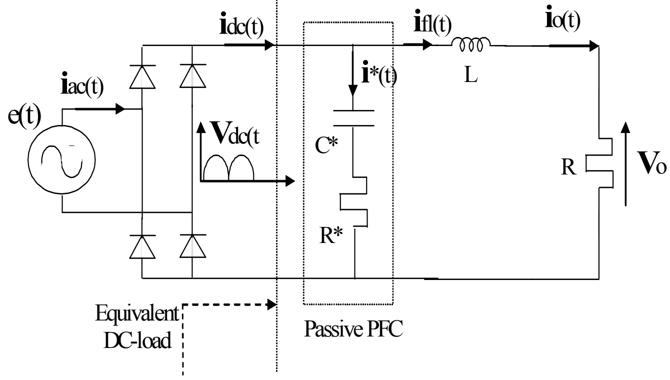

Fig. 2. Single-phase diode bridge rectifier scheme with L DC-filter and the proposed passive PFC

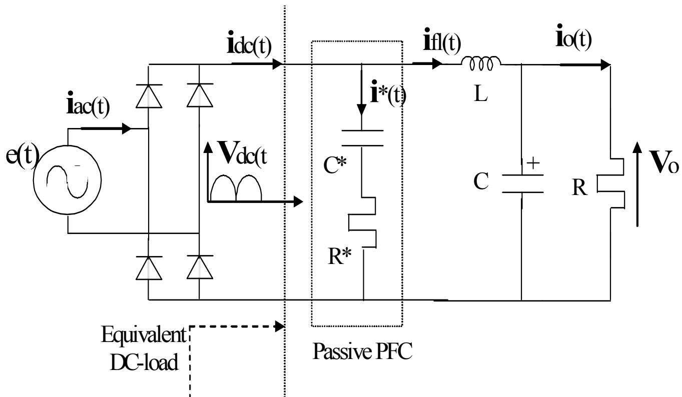

Fig. 3. Single-phase diode bridge rectifier scheme with L-C DC-filter and the proposed PFC

It is worthwhile underlining that, at frequencies higher than the AC supplying-system frequency, fac, the behavior of the filtered DC-load (without the PFC branch) can be considered essentially inductive, the filter being a low-pass filter with resonance frequency typically lower than 100 Hz.

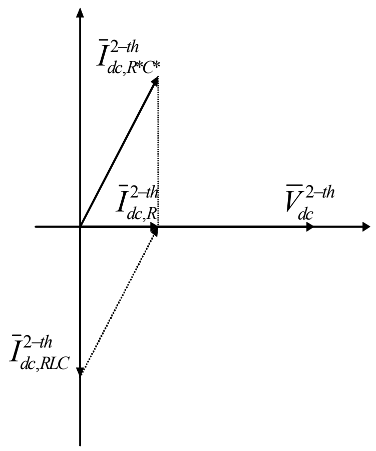

Fig. 4. Calculation of the PFC's 2-th harmonic current, $\bar{I}^{2-th}_{dc,R^*C^*}$, for passive PFC's parameters designing

Once calculated 2-th harmonic current component to be absorbed by the PFC, the values of R* and C* can be simply calculated and, by formalizing the problem, it results:

$$R^* = \frac{\cos\left[\tan^{-1}\left(\frac{R}{2\omega_{ac}L}\right)\right]}{\sqrt{\frac{1}{R^2}+\frac{1}{(2\omega_{ac}L)^2}}},$$

$$C^* = \frac{1}{2\omega_{ac}}\frac{\sqrt{\frac{1}{R^2}+\frac{1}{(2\omega_{ac}L)^2}}}{\sin\left[\tan^{-1}\left(\frac{R}{2\omega_{ac}L}\right)\right]} \qquad (4)$$

D. Some considerations on performances of the introduced passive PFC and on its applicability limits

In order to give evidence on the usefulness of the proposed passive PFC approach, in [20]-[22] several numerical experiments, operated with the help of Pspice and referring to different case-study circuits, have been considered.

By the aforementioned numerical experiments, it has been demonstrated that, in order to guarantee the proposed PFC effectiveness, it has to be utilized on circuits for which the continuous operation mode of the rectifier can be guaranteed, that is to say on circuits with L or proper L,C DC-filters. Taking into account also the IEC 1000-3-2 standard limits for harmonics in the AC-side absorbed current, the applicability of the proposed PFC seems to be strongly recommended in the case of a circuit with power higher than 1200 W, in the presence of L,C DC-filters. Furthermore, the introduced passive PFC shows high performances and low sensitivity on the variability of parameter values of the additional corrective branch.

An important aspect of the introduced passive PFC is that it introduces additional power losses on the additional resistor R*.

Even if only harmonic current components flow on R*, they could significantly worsen the power efficiency of the modified rectifier.

Additional power losses could be minimized by varying the passive PFC parameter values: starting from the nominal values obtained as discussed above, new values able to verify the IEC 1000-3-2 standard and to reduce the PFC current rms-value can be found out.

Nevertheless, in minimizing the additional PFC power losses, other important performance parameters of the rectifier, as the rectification efficiency, the power factor and the current crest factor, could result significantly worsen [20]. For this last reason, the most interesting way for improving the conversion efficiency of the proposed PFC is represented by the substitution of the resistor R* of the PFC branch with a "resistance emulator" able to reproduce the R* effects on the rectifier absorbed current, avoiding at the same time PFC extra power losses. Even if this aspect is fully and specifically investigated in [22], for the sake of readability, it is briefly synthesized in next section.

III. Introducing a "Resistance Emulator"

In order to improve the conversion efficiency of the introduced passive PFC, without worsening other circuit performances, additional power losses on R* are proposed to be minimized by introducing the idea of a "resistance emulator" (RE), that is to say an appropriate electronic circuit able to reproduce the behavior of the resistor R*.

In principle, the resistance emulator could be a diode single-phase bridge rectifier with a resistive load equal to R*, but this solution does not avoid additional power losses, again fully dissipated on the resistance emulator circuit.

Then, a very good idea to minimize additional power losses is that to give back to the load the active power absorbed at the terminals of the resistance emulator circuit.

In order to make possible this operation, firstly, the resistance emulator output voltage must have a DC component equal to that imposed at the terminal of the load by the main diode rectifier; then, a low power transformer can be utilized to supply the resistance emulator and to guarantee the right output voltage for the load; an inductor, L_e*, between the DC-side terminal of the resistance emulator and the load, is also utilized in order to uncoupling the resistance emulator circuit with the main diode rectifier, so avoiding interactions between them. The proposed circuit can be better appreciated with the help of Figg. 5 and 6.

Once connected the resistance emulator to the load, by means of L_e*, its behavior is not resistive and, to achieve it, a correction of the resistance emulator is also necessary. The correction technique is again passive and it again consists of a resistive-capacitive branch (R_e*, C_e*), to be put at the resistance emulator DC-side terminals, as indicated in Fig.7.

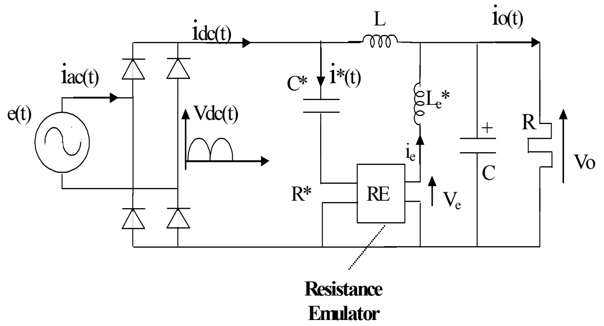

Fig. 5. Modifying the passive PFC, by means of a resistance emulator circuit

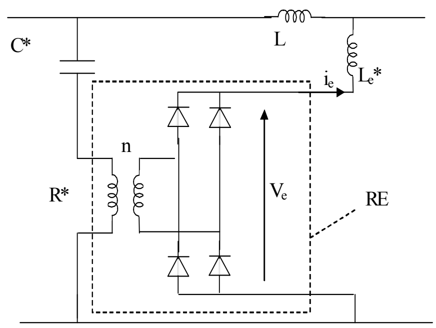

Fig. 6. The proposed resistance emulator circuit

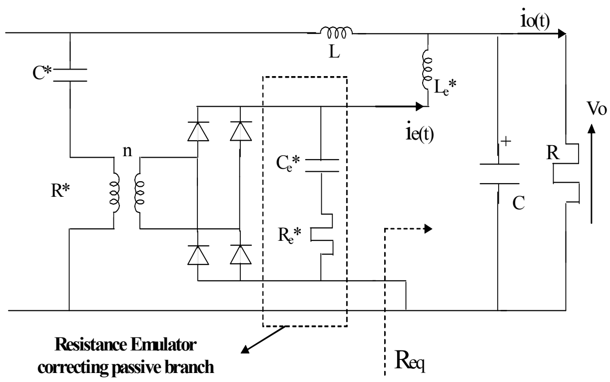

Fig. 7. The proposed resistance emulator, with its passive correction

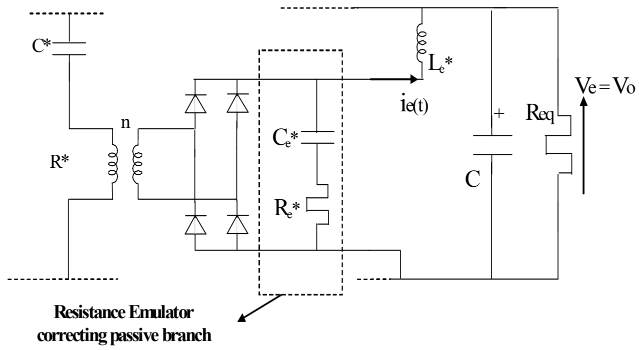

Fig. 8. Equivalent circuit of the Resistance Emulator, for its passive correction

The procedure for the calculation of the R_e* and C_e* values, needed for the passive correction of the resistance emulator circuit, has now to be properly carried out and this can be accomplished with the help of Fig.8.

In practice, once introduced an Req (Figg.7 and 8) able to absorb the same power that the resistance emulator circuit actually gives back to the load, the resistance emulator circuit with passive power factor correction has an identical topology of the corrected main rectifier of Fig.1, excepted than for the low power transformer. That is to say, the design procedure of the correcting branch elements, R_e* and C_e*, could be identical to that previously built for the correction of the main rectifier.

With this aim, now, the calculation of the Req value in Figg.7 and 8 has to be investigated.

The input power of the resistance emulator, P*, is smaller than that of the main rectifier and practically coincides with the power wasted on R* in Fig.1. A little percentage of this power is wasted on R_e*, while the remaining is given back to the load.

The input power of the resistance emulator, P*, can be also seen as a percentage of the load power, P_{LOAD}:

$$P^* = K\, P_{LOAD} \quad \Rightarrow \quad K = \frac{P^*}{P_{LOAD}}. \tag{5}$$

In a similar way, the power wasted on the resistor R_e*, P**, can be assumed to a percentage of the power wasted on R*, P*, with the same coefficient K:

$$P^{**} = K\, P^* \quad \Rightarrow \quad K = \frac{P^{**}}{P^*}. \tag{6}$$

Finally, the power, Pe, that the resistance emulator actually gives back to the load, results:

$$P_e = P^* - P^{**} = (1-K)KP_{LOAD} = (1-K)K\frac{V_o^2}{R}. \tag{7}$$

Being also the output voltage mean value of the resistance emulator, Ve, equal to that of the main rectifier, Vo, (because of the use of a proper transformer ratio, n), it is:

$$P_e = \frac{V_e^{\ 2}}{R_{eq}} = \frac{V_o^{\ 2}}{R_{eq}} = (1-K)K\frac{V_o^{\ 2}}{R}, \qquad (8)$$

then:

$$R_{eq} = \frac{R}{(1-K)K}. \qquad (9)$$

The value of the coefficient K can be simply calculated by simulating (e.g. by using Pspice) the whole circuit of Fig.1 with the passive correction branch and from equation (5).

Once calculated Req in Fig.8, in principle the R_e* and C_e* values for the passive correction of the resistance emulator can be calculated in the same way utilized for R* and C* in Fig.1; anyway, an other important difference occurs.
The DC-side voltage of the resistance emulator now also has a high 4-th harmonic component value, that has to be compensated in order to achieve the desired quasi-resistive behavior for the resistance emulator circuit.
Finally, starting from the aforementioned considerations, for the calculation of the R_e* and C_e* values the following formula are proposed:

$$R_e^* = \frac{\cos\left[\tan^{-1}\left(\frac{R_{eq}}{4\omega_{ac}L_e^*}\right)\right]}{\sqrt{\frac{1}{R_{eq}^{\ 2}} + \frac{1}{\left(4\omega_{ac}L_e^*\right)^2}}}, \quad C_e^* = \frac{1}{4\omega_{ac}}\frac{\sqrt{\frac{1}{R_{eq}^{\ 2}} + \frac{1}{\left(4\omega_{ac}L_e^*\right)^2}}}{\sin\left[\tan^{-1}\left(\frac{R_{eq}}{4\omega_{ac}L_e^*}\right)\right]} \qquad (10)$$

In [22], the same case-studies previously analyzed in [20] and [21] are considered too. The results have been given in terms of AC-side current waveform, its harmonic components, current THD, PF, current crest factor and rectifier efficiency. The resistance emulator circuit seems able to guarantee circuit performances practically identical to that previously obtained by using a resistor. Furthermore, extra power losses on the correcting resistor are now avoided and, then, the circuit efficiency results significantly improved and similar to that of the active PFCs.

IV. Introducing A Modified Circuit For Single-phase Thyristor Based Rectifiers And Extension To It of The Passive PFC

As underlined in previous sections, the passive PF correction technique, we are discussing, it is essentially based on the idea that, in order to make sinusoidal the AC-line current of a single-phase diode rectifier, the behavior of the equivalent load as seen from the DC-side terminals of the rectifier has to be made fully resistive; furthermore, it has been demonstrated that this is practically possible by introducing at the DC-side terminals of the conventional converter circuit an additional and correcting passive R*, C* branch.

On the other hand, as well known, in case of thyristor-based controlled rectifier, the mean value of the DC-side voltage can be controlled by delaying the ignition of thyristors; nevertheless, this control method is basically possible just thanks to the highly inductive behavior of the load, typically represented by DC-motors.

As a consequence, for the correction of PF of thyristor-based rectifiers, the aforementioned passive PFC circuit can not be immediately utilized, because the fully resistive load behavior requested for correction seems not compatible with the not renouncing rectifier output voltage controllability.

For this reason, firstly, the conventional single-phase thyristor-based rectifier circuit is proposed to be modified.

Because of their predominant importance, in the following, only DC-motor adjustable speed drives with only inductive effects on the DC-filter are explicitly referred.

The proposed electrical scheme for a new fully controlled rectifier is shown in Fig.9.

In practice, the circuit must be integrated by the addition of:
- two forced commutated electronic switches, S1 and S2 (GTO, Power BJT, …), in "anti-parallel" to the two thyristors on the top side of the rectifier,
- two diode, D1 and D2, in "anti-parallel" to the two thyristors of the bottom side of the rectifier.

The aforementioned additional switches, S1 and S2, have to be operated in a complementary way with respect to the operation of the thyristors T1 and T2. Specifically, S2 has to be switched-on when the supply voltage e(t) becomes positive and, in order to control the mean value of the load voltage, the ignition of the thyristors T1 and T4 is delayed of the α angle; obviously, S2 has to be forcedly switched-off when thyristors T1 and T4 are ignited. Complementarily, S1 has to be switched-on when the supply voltage e(t) becomes negative and the ignition of the thyristors T2 and T3 is delayed of the α angle; obviously, S1 has to be forcedly switched-off when thyristors T2 and T3 are ignited. For a graphical representation of the rectifier control logic, please refer to Fig.10.

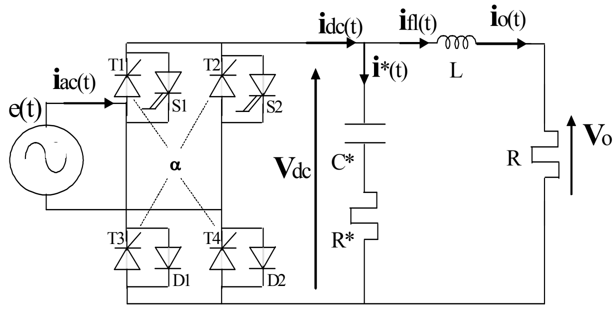

Fig. 9. Modified single-phase thyristor-based rectifier circuit, with passive PF correction

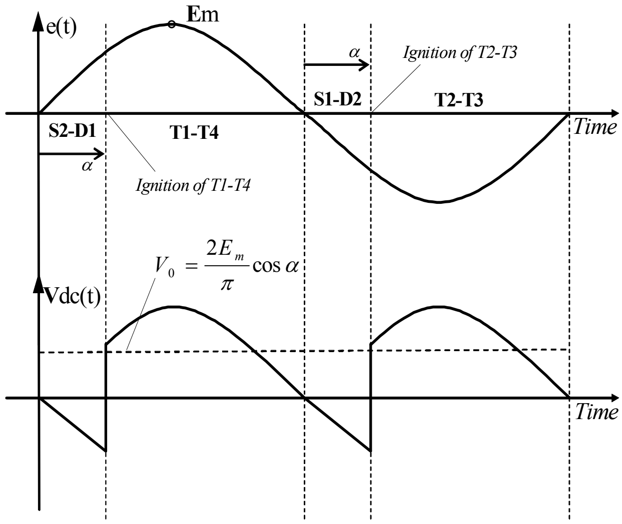

Fig. 10. Operation of the new phase-controlled rectifier switches and DC-side voltage (Vdc) waveform, in presence of a fully resistive load behavior

Once introduced the new circuit topology, together with a modified control logic for operation of rectifier electronic switches, the aforementioned passive PF correction technique can be immediately extended to it, by simply implementing the already introduced designing equation (2).

V.NUMERICAL VALIDATION OF THE MODIFIED CONTROLLED RECTIFIER

Some numerical experiments are performed on a line-frequency controlled single-phase rectifier case-study of about 2500 W of active power, in order to give evidence of the usefulness of both the proposed circuit correction and of the proposed passive PF correction technique.

A sensitivity analysis of the power factor correction to the variation of the delay angle α, for controlling the DC-side mean value of the rectifier output voltage, Vdc, is also performed, together with the analysis of the power conversion performances of the new rectifier.

The case-study scheme explicitly considered for numerical simulations is that depicted in the already mentioned Fig.9, while the simulation parameter values are reported in the following Table I.

Table I. Parameter values for numerical simulations of the case-study circuit of Fig. 9

E [V]	L [mH]	R [Ω]	C* [μF]	R* [Ω]
20	60	15	267	15

The conventional rectifier (that is to say the rectifier without circuit modifications and without PF correction) and the proposed controlled rectifiers are, both, numerically analyzed with the help of PSpice.

Simulations are performed for different values of the thyristor delay angle, α, in order to show as the PF of the conventional rectifier, already poor because of the AC current harmonic components, rapidly demotes by increasing the α value while the PF of the proposed rectifier has a unity value for all the examined conditions.

The simulation results are synthesized in terms of waveforms of the AC side absorbed currents and DC-side load voltages (see Figg. 11 and 12), together with the values of main AC current harmonic components, its THD value and the PF values, that are reported in the following Table II.

In order to show that, probably, a unity value for the rectifier PF, as currently defined, is not a sufficient index to indicate an ideal power electronic converter behavior, the ratio, PR, between the active power delivered to the DC-load and the apparent power absorbed from the supplying system is also considered and plotted in Fig.13 for each examined working condition.

The most evident things, that come out from the analysis of the simulations results, can be synthesized as in the following.

The waveforms of the DC-side rectifier voltages, reported in Fig.12, show that the new rectifier is able to control the mean value of the DC-load voltage by varying the thyristor delay angle α, in the same way than that of the conventional one.

From Fig.11, for the conventional rectifier, the AC-side current is not sinusoidal and it is reach in harmonic components, for any value of the thyristor delay angle, α; as a consequence, the rectifier PF has a value lower than unity also for α equal to zero degrees. Furthermore, by increasing the value of α, the rectifier PF rapidly demotes.

After the modification of the rectifier conventional circuit and with the use of the passive PF correction technique, the AC-side rectifier current practically becomes sinusoidal and in phase with the supply-voltage, for any value of the thyristor delay angle, α.

From the analysis of the current spectra, the current absorbed by the new rectifier has always the same rms and it is always greater than that of the conventional rectifier.

This means that, in order to compensate for current harmonics absorbed by the conventional rectifier, the modified rectifier absorbs from the supplying system an additional active power; in practice, this additional power, instead of being profitably delivered to the DC-load, it is dissipated on the introduced resistor, R*, that is a fundamental part of the passive PFC.

Unfortunately, the power dissipated on the resistor R* unprofitably increases when power delivered to the DC-load decreases, by increasing the value of the thyristor delay angle, α.

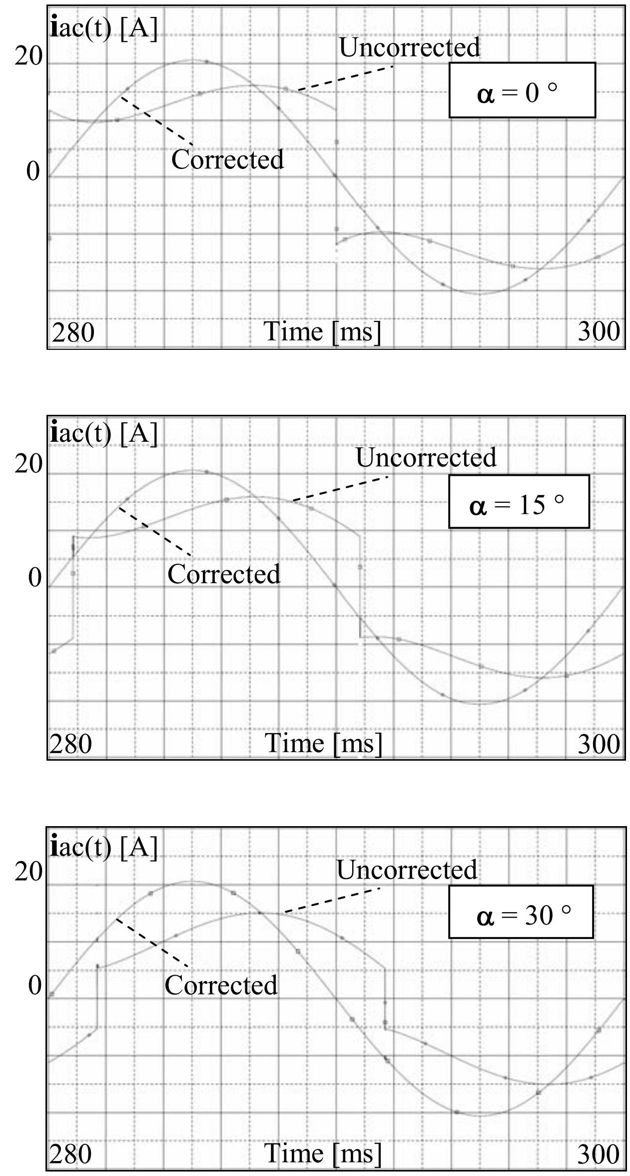

Fig. 11. AC-side rectifier current waveforms without and with the proposed PFC, for different values of α.

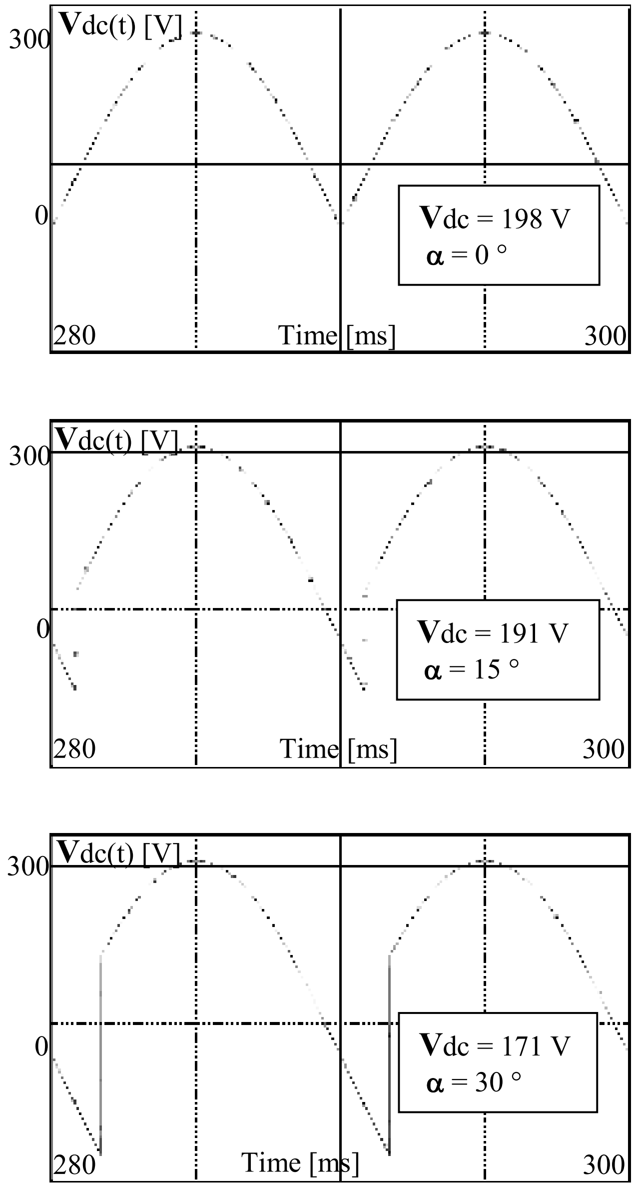

Fig. 12. DC-side rectifier voltage waveforms without and with the proposed PFC, for different values of α.

Table II. AC-side current harmonics [A_{rms}], THD and PF, for the conventional (conv) and the new rectifiers, for different values of α.

	α = 0 [degrees]		**α = 15** [degrees]		**α = 30** [degrees]	
f [Hz]	**Conv.**	**New**	**Conv.**	**New.**	**Conv.**	**New**
50	12.5	14.6	12.3	14.6	11.4	14.6
150	3.30	0.0	2.58	0.0	1.56	0.0
250	2.01	0.0	1.58	0.0	1.54	0.0
350	1.45	0.0	1.13	0.0	0.95	0.0
450	1.13	0.0	0.88	0.0	0.68	0.0
THD [%]	35.4	0.0	31.6	0.0	23.1	0.0
PF	0.94	1.0	0.92	1.0	0.84	1.0

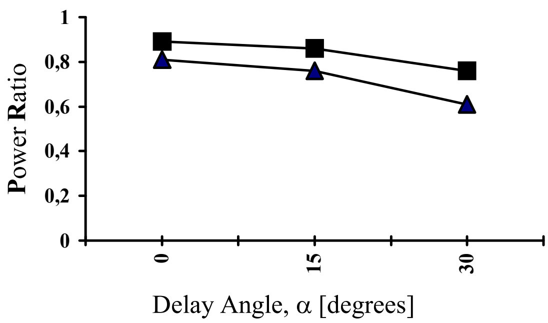

Fig. 13. Plotting the power ratio, PR, between the DC power delivered to the load and the absorbed AC apparent power, for the conventional (■) and the new (▲) rectifiers, for different values of α.

By plotting the ratio, PR, between the active power that the modified rectifier delivers to the DC-load and the apparent power that it absorbs from the supplying system, it is possible to underline that (see Fig.13) the PR of the modified rectifier is always lower that that of the conventional rectifier. Furthermore, the PR of the modified rectifier decreases more rapidly that that of the conventional rectifier, by increasing the thyristor delay angle, α.

From the aforementioned considerations it results evident that, in order to make practically attractive the introduced new controlled rectifier, the active power dissipated on the additional resistor R* has to be eliminated or significantly reduced. This is in theory possible, as aforementioned and as demonstrated in some previous papers that are specifically referred to uncontrolled rectifiers, by introducing a properly designed electronic “resistance emulator” able to reproduce the same resistive behavior of R*, without dissipating additional active power.

This topic will be explicitly analyzed in a future and specific paper.

In the next section, in order to better appreciate the practical meaning of the previously discussed simulation results, some additional considerations on “power conversion efficiency” and on Power Factor index definitions for power electronic converters are developed.

VI. Some Considerations on Practical Meaning of Power Factor of power electronic converters

On the basis of current definition of converter power factor index, PF, and from the analysis of previously presented simulation results, it comes out that the new introduced controlled rectifier has a unity PF, for any value of the thyristor delay angle, α, while the conventional rectifier always shows a worse PF value.

Nevertheless, it is well evident that, for a fixed active power profitably delivered to the DC-load, the new rectifier absorbs from the supplying system active (and apparent) power values significantly greater than that absorbed by the conventional rectifier.

From this considerations, it follows that, probably, the converter PF index as currently defined is not an index able to properly take into account by itself the converter performances in global terms [33], [34].

As an example, in case of a conventional single-phase fully controlled rectifier that supplies an ideally filtered DC-load (e.g. L $\rightarrow \infty$ in Fig.9), its PF, as currently defined, is unfavourably less than 1:

$$PF = \frac{P_{AC}}{S_{AC}} = \frac{EI_1 \cos\alpha}{EI_{AC}} = \frac{2\sqrt{2}}{\pi}\cos\alpha \,. \qquad (11)$$

Nevertheless, the rectifier clearly shows to be able to deliver to the DC-load an active power value, P_{DC}, equal to the whole active power absorbed from the supplying system, P_{AC}; this practically favourable rectifier property is not taken into account by the PF index as defined in (11), limiting itself to give evidence only of the negative impact on the supplying system caused by current harmonic components and displacement factor between the supplying voltage and the absorbed current.

Probably, all the aforementioned aspects of the rectifier behaviour could be taken into account by simply introducing a new definition for PF index, that is to say the PR index already introduced in the previous section of the paper:

$$PF \rightarrow PR = \frac{P_{DC}}{S_{AC}} = \frac{2\sqrt{2}}{\pi}\cos\alpha \frac{I_{DC-load}}{I_{AC}} \,. \qquad (12)$$

This index is already given in some book; nevertheless, it typically defines the so called Transformer Utilization Factor, TUF, of a converter [34].

One well evident advantage of the introduced PR index is that for the conventional fully controlled rectifier it coincides with the PF index as currently defined, so properly taking into account of the negative impact caused, on the supplying system, by absorbed current harmonic components and by the displacement factor between the supplying voltage and the absorbed current waveforms.

Furthermore, it seems to be able to better operate, from a more practical point of view, a performance comparison analysis among different converter circuits, as can be appreciated by simply analyzing the results already discussed in section V and synthesized in Fig.13.

VII. Conclusions and Perspectives

The circuit of the conventional thyristors-based line-frequency controlled single-phase rectifier has been rearranged in order to make possible the improvement of its power factor.

Once modified the circuit, the rectifier power factor is improved by extending to it an already introduced passive and economical correction technique.

The passive PFC technique is essentially based on the use of a passive R*, C* branch, to be added at the DC-side terminals of the rectifier, in order to make fully resistive the behavior of the DC equivalent load.

The analysis of the results, obtained by loading different PSPICE simulations on a case study of about 2.5 kW of active power and under different working conditions, have shown the effectiveness of the introduced PF correction technique, particularly showing that the circuit can have a unity PF for any load condition and for any value of the delay angle, α, at the same time being also able to control the mean value of the rectifier DC-side voltage, like a conventional controlled rectifier.

Nevertheless, simulation results have also shown that, a unity value for the PF, as currently defined in the specialized literature, does not necessary means that the circuit behavior corresponds to a perfect and an ideal behavior of the converter, because this conditions can be unpleasantly accompanied by a great level of active power that is requested to the supply network by the rectifier but is not usefully delivered to the DC-load.

Starting from this last consideration, two further research activities seem to be hoped for the future:

- introducing, discussing and analyzing new and more comprehensive performance indices for power electronic rectifiers;
- improving power conversion performances of the proposed fully controlled rectifier by introducing a resistance electronic emulator, able to minimize power losses on the resistor R* of the currently proposed passive correcting branch.

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