Recent advances on reducing harmonics in low-power adjustable speed drives

R. Carbone

Abstract**—** Problems and perspectives of single-phase PWM adjustable speed drives (ASDs) for low-power three-phase induction motors are investigated. Their positive impact on energy saving in large-scale residential house appliances and in small industrial settings is underlined. The problem of the generation of current harmonic components, both on the supply-side and on the motor-side, is analyzed and different practical possibilities for bringing back the problem within acceptable limits are focused. After briefly recalling the state of art for passive and active power factor correctors (PFCs) for single-phase power electronic converters, firstly, an innovative passive approach recently introduced in the specialized literature to correct the power factor (PF) of single-phase low-power PWM ASDs is recalled. Then, a different passive approach, already introduced by the Author for correcting the PF of conventional high-power three-phase PWM ASDs, is specifically extended to low-power single-phase PWM ASDs. Criteria for designing aforementioned passive PFCs are presented and a lot of numerical simulations performed by using Pspice, under different working conditions of the motor, are utilized for underlining strengths and weaknesses of considered PFCs.

Keywords**—** Adjustable speed drives, single-phase to three-phase converters, power factor correctors, harmonics, interharmonics.

I. INTRODUCTION

THE paper focuses the importance of using three-phase induction motors also for low-power residential appliances and small industrial settings [1]-[3]. In fact, in this kind of applications, currently utilized single-phase motors show an efficiency that is no more than 40%-50%. Furthermore, single-phase induction motors offer no method for continuous speed control, which means that valves, gears and other low efficiency mechanisms must be used to accommodate the load and at light loads, which is common, their efficiency is dramatically low.

By introducing three-phase induction motors with power electronic circuits for speed and torque control, the goal of reaching an efficiency over than 70% seems to be achievable together with a significant improvement of versatility and performances of these apparatus [4]-[7].

However, currently utilized single-phase motors are - positively - characterized by very low costs and high reliability; therefore, in order to be competitive, the designing of new drives based on three-phase induction motors can not ignore these important aspects. A good goal could be that of obtaining a reliable drive whose superior cost can be recovered in one-two years of operation thanks to their energy saving capability.

Basically, a standard drive for three-phase induction motors with a power electronic circuit for control (adjustable speed drives, ASD), to be used starting from a single-phase supply, consists of: a single-phase rectification stage, a DC link, a three-phase power electronic inverter and a three-phase induction motor.

In the last years, due to the great availability of power electronic devices (BJT, MOSFET, GTO, ...) with improved performances, improved reliability and also with reduced costs, the inverter stage has reached massive progress and, today, the most diffused ones are on the category of the well known three-phase bridge, with PWM control system. In an attempt to reduce their costs, several unconventional inverter alternatives have been introduced; they have lower parts count but they either sacrifice efficiency in the motor or require parts with higher ratings, generally negating an effective cost saving by using fewer parts.

Regarding the single-phase rectification stage, an uncontrolled diode bridge rectifier is widely utilized; undoubtedly, it is reliable and with low costs; however, it also generates an important amount of harmonic components on the current drown from the supply. The current harmonic injection process is responsible of additional losses in distribution lines and causes a very poor input power factor (less than 70%); some power quality standards, such as for instance the EN 61000-3-2, suggest to limit the injection on the supply of current harmonic components. In order to comply with standards, in the single-phase rectification stage a power factor correction (PFC) circuit must be introduced; they can be, essentially, divided into two categories: active PFCs and passive PFCs.

Active PFCs are undoubtedly characterized by superior performances with respect to the passive ones.

The double-stage category of active PFCs uses, firstly, an input DC/DC boost-type converter operated as a "*current shaper*", then a second DC/DC converter is utilized 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. However, these PFCs have some important penalties. First of all the increased cost is

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sometimes prohibitive for a large volume of low-power applications. On the other hand the complexity of the resultant circuit causes worse reliability. Finally, double-stage active PFCs originate conducted and radiated interference and additional EMI filters could be necessary to comply with high-frequency emission limits.

The single-stage category of active PFCs integrates the PFC function and the output voltage regulation in one DC/DC converter. The latter can be seen as a two-cell DC-circuit: the PFC-cell and the DC/DC-cell. Only one controller is required but a complex control strategy, based on duty-cycle and/or switching-period modulation, is needed. 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. A lot of solutions have been proposed in the literature discussing different circuit topologies and different control-strategies; it can be summarized that, with respect to double-stage active PFCs, single-stage active PFCs are characterized by lower cost but also by lower performances.

In order to reduce costs and high frequency EMI generation, a low frequency active PFC has been introduced and discussed in [8]; it is based on a modified conventional rectifier with passive L-C filter also including additional elements consisting in an AC low-frequency commutated switch (the switch operates at twice the line frequency) and two capacitors, C1 and C2. This approach improves both the AC absorbed current harmonic content and the PF; furthermore, it allows compliance with the standards by means of a much smaller inductor as compared to conventional passive PFCs.

Undoubtedly, the most easy and low cost way to physically implement a PFC is to use passive PFC essentially based on inductors (L) and capacitors (C) [9]-[13].

Conventional passive PFCs are characterized by low performances and PF values greater than 0.8 are very difficult to be obtained. For this reason, several unconventional circuit topologies realizing passive PFCs by means the use of additional passive elements (L, C and/or diodes) have been proposed in the specialized literature and most common circuits have been well recalled and discussed in [10]-[11]. However, in the aforementioned papers, it was shown that, also considering the circuit topology with superior performances, some disadvantages as the generation of DC and even harmonic components on the current drown from the supply, remain for these unconventional passive circuits.

In the following, a recently introduced [14] passive PFC for single-phase low-power ASDs is recalled.

Then, on the basis of a passive PFC already introduced by the Authors with reference to single-phase diode rectifier [12],[13] and three-phase high-power ASDs [15], a new passive PFC is presented and widely discussed.

The well known Pspice simulation tool is utilized, under different working conditions of considered ASDs, for underlining their strengths and weaknesses.

II. SINGLE PHASE ASDS FOR THREE-PHASE MOTORS

After recalling the well known conventional scheme, an innovative scheme, based on a passive PFC approach, introduced on 2005 by M. Cacciato et Alii [14], is also considered and briefly discussed.

Then, in next sections, an additional unconventional scheme with passive PFC is introduced by the Author and it is fully discussed.

A. The Conventional Scheme

On the basis of a single-phase mains availability, a conventional way to build an ASD for a low-power three-phase induction motor is that depicted in Fig.1. In practice, a single-phase diode bridge rectifier is connected in cascade, firstly, with an L-C passive filter and, then, with a three-phase voltage source PWM inverter.

When the voltage, Vdc(t), of the DC-filter capacitor, C, exceeds the supplying voltage, Vac(t), all diodes of the rectifier are reverse biased and current from the mains, iac(t), cannot flow; this circuit behavior is known as "dead zone" of the rectifier. As a consequence, the current drawn from the mains results highly impulsive, with an enormous amount of odd harmonic components (especially at very low frequencies) and leading to a very poor input power factor, PF.

In order to improve the PF (by reducing harmonics in the current drawn from the mains) the duration of the aforementioned "dead zone" phenomenon must be reduced, without compromising the stability of the DC-side voltage; this, is normally achieved by increasing the inductance value of the inductor, L, of the resonant L-C DC-filter, so tuning it to a very low frequency.

However, especially in household appliances, this way can result often impractical because of the high value of the DC-filter inductance greatly affects its volume and cost of the circuit.

As an alternative, passive PF correctors can be also utilized.

One of this [14] is essentially based on the use of a high-frequency three-windings transformer, able of inducing on the diode-rectifier the so called "dither effect" [16]; this circuit is one the subject of this paper and, then, it will be briefly recalled in the next section.

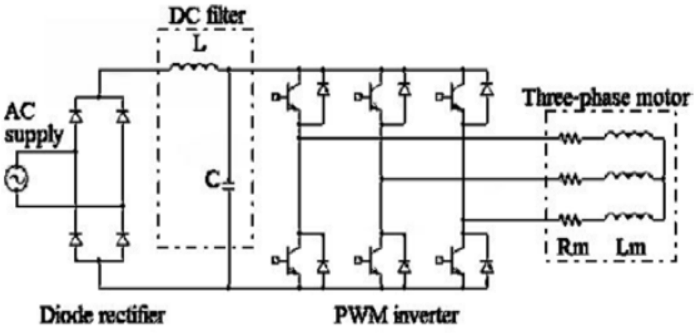

Fig.1. Conventional single-phase ASD for three-phase motors

A. Innovative Scheme with Passive PFC

On 2005, M. Cacciato et Alii have introduced a new ASD scheme, for equipping low-power three-phase motors for household appliances [14]. In the following, its behavior is briefly recalled, also with the help of Fig.2.

Basically, it modifies the DC-link of the conventional scheme, by substituting the series inductor, L, with an high-frequency (HF) three-windings transformer.

As depicted in Fig.2, the primary winding of the HF transformer is connected in series with the DC-link capacitor, C, while the two secondary windings are interposed between the diode rectifier and the DC-link. Two additional diodes (one for each secondary winding) are also utilized; they are connected in series to the two secondary windings, in order to avoid any freewheeling current circulation between them.

Due to this circuit configuration, the primary winding of the HF transformer catches the high-frequency bipolar current that flows through the DC-link capacitor because of the PWM modulation operated by the inverter. Then, this current is, alternatively, transferred on the secondary windings of the HF transformer so forcing the diode-rectifier to conduct also during the inherent "dead zone" time. The two secondary windings of the HF transformer have an inverse magnetic coupling with the primary winding so that:

- if the inverter is switched to a state such that a positive current pulse flows on the primary winding (that is to say, the capacitor is in a discharging state), then a positive current pulse is induced only in one of the two secondary windings;
- if the inverter is switched to a state such that a negative current pulse flows on the primary winding (that is to say, the capacitor is in a charging state), then a positive current pulse is induced only in the other of the two secondary windings.

In that way, the HF three-windings transformer works as a dither source, without using any active switch working at high frequency as in [16]. As a result, PF of the diode-rectifier can be improved with a quite simple and low-cost circuit. In order to obtain an adequate dithering effect, without causing a too large peak over-voltage at the DC-side inverter terminals (that could result dangerous for the inverter power devices), a first concern is the selection of proper and different values for the two transformer turns ratio. The best solution seems that of selecting two turns ratio that are able to guarantee an acceptable PF correction at the rated motor power.

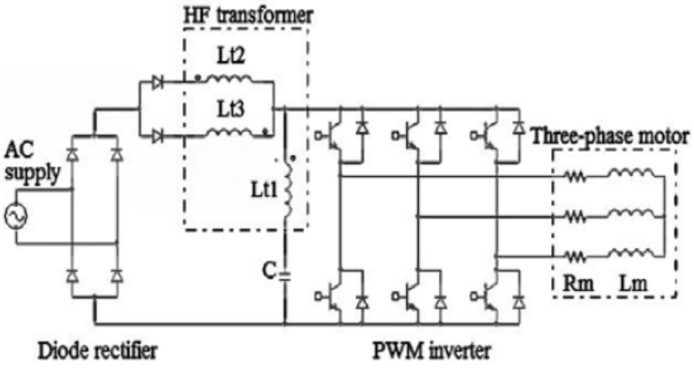

Fig.2. A recently introduced innovative single-phase ASD [14]

III. Introducing a New Passive PFC

In [12] a simple passive PFC has been introduced and discussed with reference to single phase diode rectifiers with a DC-load; Fig. 3 shows the proposed electrical scheme, in the case of a simple DC resistive load with a L-C filter.

From Fig. 3, it is evident that the passive correction technique is essentially based on the idea that the quasi sinusoidal DC voltage waveform at the rectifier terminals, **V**dc(t), can be utilized to supply an additional passive branch (R*, C*); the extra current absorbed by this branch, **i***(t), is added to the filter-load current and it is able to make the total DC-side current waveform, **i**dc(t), quasi sinusoidal so making sinusoidal the AC-side absorbed current, **i**ac(t). To achieve this goal, the R* and C* parameter values have to be selected so that the equivalent impedance as seen from the DC-side terminals of the single-phase rectifier results resistive and equal to the DC load resistance, R.

In order to make the extension of the aforementioned passive power factor correction technique possible also to ASD for low-power three-phase induction motors, some modifications are now needed. In fact, in [12] it was also demonstrated that the choice of the R* and C* values is strongly influenced by the DC-load behavior and specific equations have been derived and successfully tested only for a resistive DC-load with L or L-C filter.

The ASD circuit that is now under study, evidently, is more complex because of the presence of the PWM inverter that supplies the induction motor. Then, in order to made up a procedure for selecting the R*, C* values in this new contest, firstly, the inverter motor group is proposed to be substituted by means of an equivalent resistor, R, that, with the same voltage at the inverter DC-terminals, is able to absorb, at the rated power, the same active power actually absorbed by the inverter motor group. Once calculated this equivalent resistance, R, it results:

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

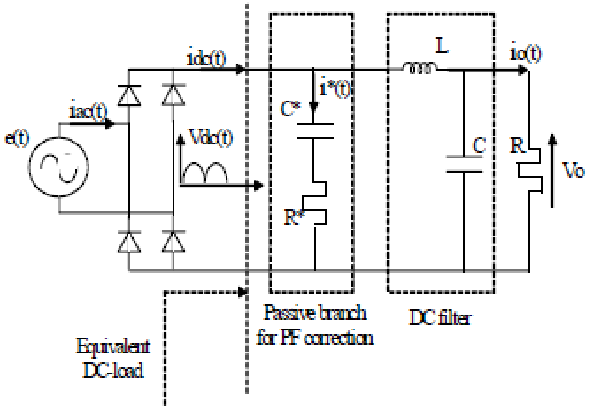

Fig.3. Simplified scheme of the new PFC introduced by the Author

IV. IMPROVING THE EFFICIENCY OF THE NEW PFC

From Fig.3, it is simple to underline that only harmonic current components flow on R*, due to the presence of the capacitor C* that stops the flow on the (R*, C*) branch of the DC current component; however, the flow of current harmonic components on R* could cause significant Joule power losses, so worsening the power efficiency of the PFC circuit.

In order to obtain a high efficiency passive PFC, without worsening other performances, additional power losses on R* can be minimized by introducing a "*resistance emulator*" (RE), that is to say an appropriate electronic circuit able to reproduce the behavior of the resistor R*. In principle, this RE circuit could be a diode single-phase bridge rectifier with a resistive load connected at the R* terminals; however, this solution does not directly avoid the problem because of power losses on R* which are simply moved on the additional rectifier resistive load.

Then, it is introduced the additional idea that the active power absorbed by the RE circuit has to be given back to the main load (that is to say, the inverter-motor group).

In order to make this operation possible, firstly, the RE output voltage must have a DC component equal to that imposed at the terminal of the inverter by the main diode rectifier with L-C filter; therefore, a low power transformer is needed for supplying the RE circuit and to guarantee the right output voltage for the inverter.

Furthermore, an inductor, L_e*, between the DC-side terminal of the RE circuit and the inverter, is also utilized in order to uncoupling it from the main diode rectifier, so avoiding direct interactions between them. Once connected the resistance emulator to the inverter, its behavior is not directly resistive and, to achieve it, a correction of the RE circuit (second order correction) is also necessary. The correction technique is again passive and it consists of a resistive-capacitive branch (R_e*, C_e*), to be put at the resistance emulator DC-side terminals.

The procedure for the calculation of the R_e* and C_e* values, has now to be properly carried out. In [12] it has been shown that, by introducing an equivalent resistance, Req, 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.3, 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 very similar to that previously built for the correction of the main rectifier. 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.3. Only 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}:

$$P^* = K\,P_{LOAD} \quad \Rightarrow \quad K = \frac{P^*}{P_{LOAD}}. \tag{2}$$

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

$$P^{**} = K\,P^* \quad \Rightarrow \quad K = \frac{P^{**}}{P^*} \tag{3}$$

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

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

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:

$$P_e = \frac{V_e^{\,2}}{R_{eq}} = \frac{V_o^{\,2}}{R_{eq}} = (1-K)K\frac{V_o^{\,2}}{R}, \tag{4}$$

then:

$$R_{eq} = \frac{R}{(1-K)K}. \tag{5}$$

The value of the coefficient K can be simply calculated by numerically simulating the whole circuit of Fig.1 with the passive correction branch (R*, C*) and from equation (2). Once calculated the aforementioned Req, 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.3; anyway, an other important difference occurs. The DC-side voltage of the resistance emulator now also has a high 4-th harmonic component value (instead of a 2-th harmonic component as in the case of the main rectifier), 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 expressions are proposed to be used [12]:

$$R_e^* = \frac{\cos\left[\tan^{-1}\left(\dfrac{R_{eq}}{4\omega_{ac}L_e^*}\right)\right]}{\sqrt{\dfrac{1}{R_{eq}^{\,2}} + \dfrac{1}{\left(4\omega_{ac}L_e^*\right)^2}}}, \quad C_e^* = \frac{1}{4\omega_{ac}}\,\frac{\sqrt{\dfrac{1}{R_{eq}^{\,2}} + \dfrac{1}{\left(4\omega_{ac}L_e^*\right)^2}}}{\sin\left[\tan^{-1}\left(\dfrac{R_{eq}}{4\omega_{ac}L_e^*}\right)\right]} \tag{6}$$

The idea of the proposed RE circuit can be better appreciated with the help of Figg. 4 and 5.

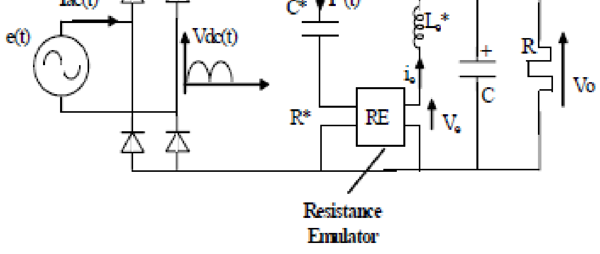

Fig.4. Scheme of the new passive PFC, with the RE circuit

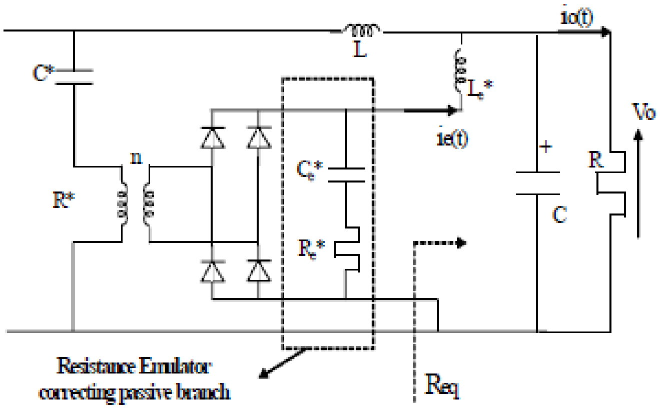

Fig.5. The RE circuit in detail

V. NUMERICAL EXPERIMENTS

In the following, several numerical experiments are performed in order to compare performances of the introduced passive PFCs for the the single-phase ASD under consideration; the well known PSPICE package is utilized. The results are analyzed and discussed by separately referring to the supply-side and the motor-side. Most of the results referred to the supply-side are extracted from [18].

With reference to the conventional scheme and the new scheme introduced by the Author, simulations are performed on a case study of about 2.5 kW of rated power, P_N, under different working conditions of the motor.

It consists of a three-phase PWM ASD for an asynchronous motor of about 2.5 kW of active rated power, P_N.

The diode rectifier operates with a supplying line to neutral voltage amplitude of $Vrms$ = 220 V, at the line frequency of fac = 50 Hz.

With reference to Fig.1, the parameter values of the DC-filter inductor, Lf, the DC-filter capacitor, Cf, and the maximum switching frequency of the PWM inverter devices, fsw_max, are reported in Table I. With reference to Fig.3, the R* and C* parameter values are calculated as indicated in section II and are reported in Table II. With reference to Figg.4 and 5, by performing the designing procedure proposed in section III, the additional parameter values to be used for implementing the emulator circuit, RE, are calculated and are reported in Table III.

It is important to underline that equations from (1) to (6) are used for calculating the theoretical values of the aforementioned circuit parameters. However, because in case of an ASD - typically - variable motor working conditions are welcome, in order to avoid a strong worsening of the circuit PF at light loads, the aforementioned parameter values are "lightly adjusted" by settling them around a motor working condition lower than the rated one (in our case, at about 80% of the rated one).

Table I. Values of the circuit main parameters

Lf [mH]	**Cf** [μF]	**fsw** [Hz]
31	940	10000

Table II. Main PFC parameter values, utilized for the case-study analysis

C* [μF]	140
R* [Ω]	10

Table III. Additional circuit parameter values, in presence of the RE

n	**Le*** [mH]	**C**** [μF]	**R**** [Ω]
3.8	210	20.0	105

With reference to the innovative passive PFC introduced on 2005 by M. Cacciato et Alii [14], as it is essentially conceived for very low-power residential house appliances, numerical experiments have been already performed by the Authors on a case-study of about 250 W of rated power and under different working conditions of the motor; data and simulation results are fully reported in [17]. The aforementioned results will be partially reported on next sections, in [p.u.] units, in order to make possible some interesting comparative considerations that can regardless from the motor power entity.

B. Numerical Results, Referred to the Supply-Side

Fig. 6 shows the waveforms of the AC line currents drown from the supply by the PWM ASD circuit with the conventional ASD (without the PFC), for different values of the motor power, Pm; the resulting current THD are also reported, as a percentage of respective current fundamental components.

Fig. 7 shows the waveforms of the AC line currents drown from the supply by the PWM ASD circuit when the proposed PFC, with the resistance emulator circuit, is introduced**,** for different values of the motor power, Pm; the resulting current THD are also reported, as a percentage of respective current fundamental components.

From Fig.6, it is evident that waveforms of currents drown from the AC supply by the conventional ASD are characterized by a poor quality (very high harmonic content and THD) at all the motor working conditions. However, the conventional single-phase to three-phase power electronic converter is characterized by a high conversion efficiency of about 94%.

From Fig.7 it is evident that the proposed passive PFC is able to significantly improve the circuit PFC, at all the considered motor working conditions. However, from the analysis of the full passive PFC circuit of Fig.3 a conversion efficiency significantly lower than that of the conventional ASD (of about 82%) has been calculated for it. The introduction of the RE circuit has significantly improved the efficiency of the new ASD (to about 93%) without affecting the circuit PF.

In [14] and [17] the innovative circuit introduced by Cacciato et Alii has been widely investigated by numerical experiments. In the papers, it has been demonstrated that the innovative circuit absorbs from the AC supply a current with an improved THD of about 40% both at the rated and at reduced motor powers.

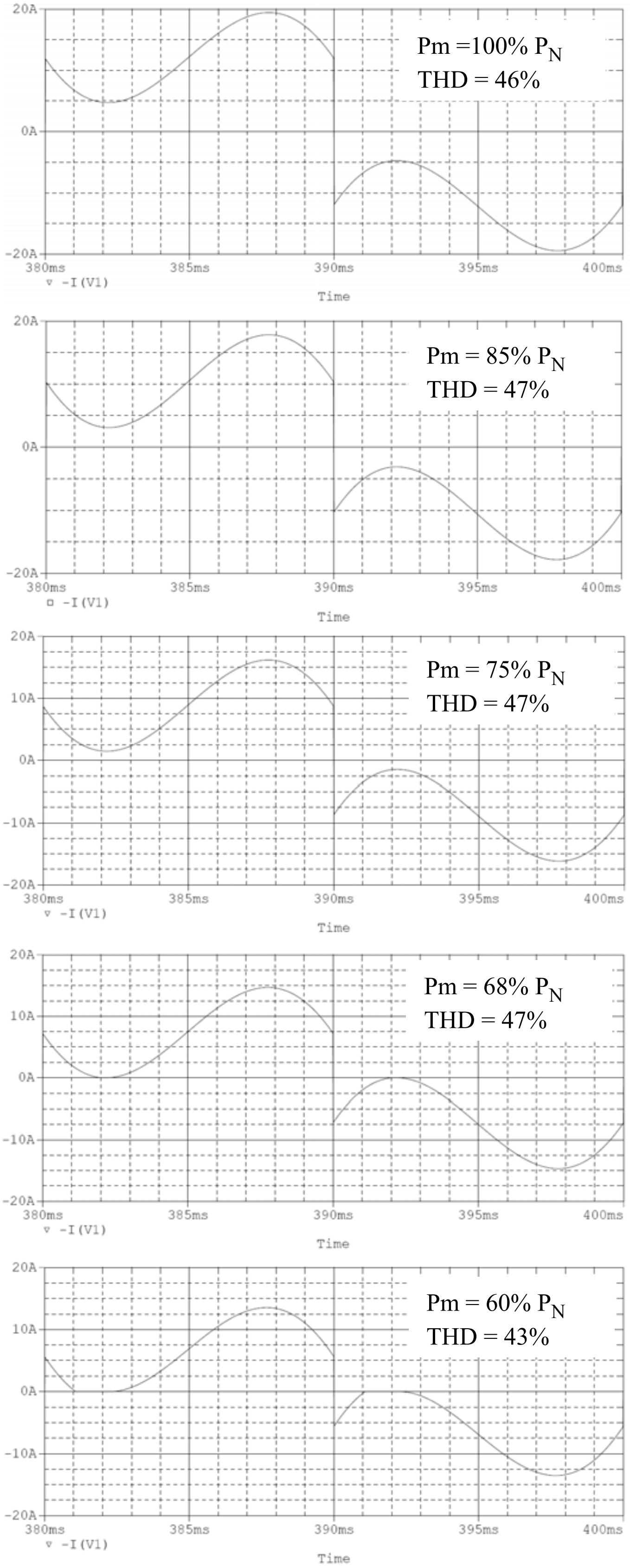

Fig.6. Currents drown from the supply by the conventional ASD, at different motor powers, Pm

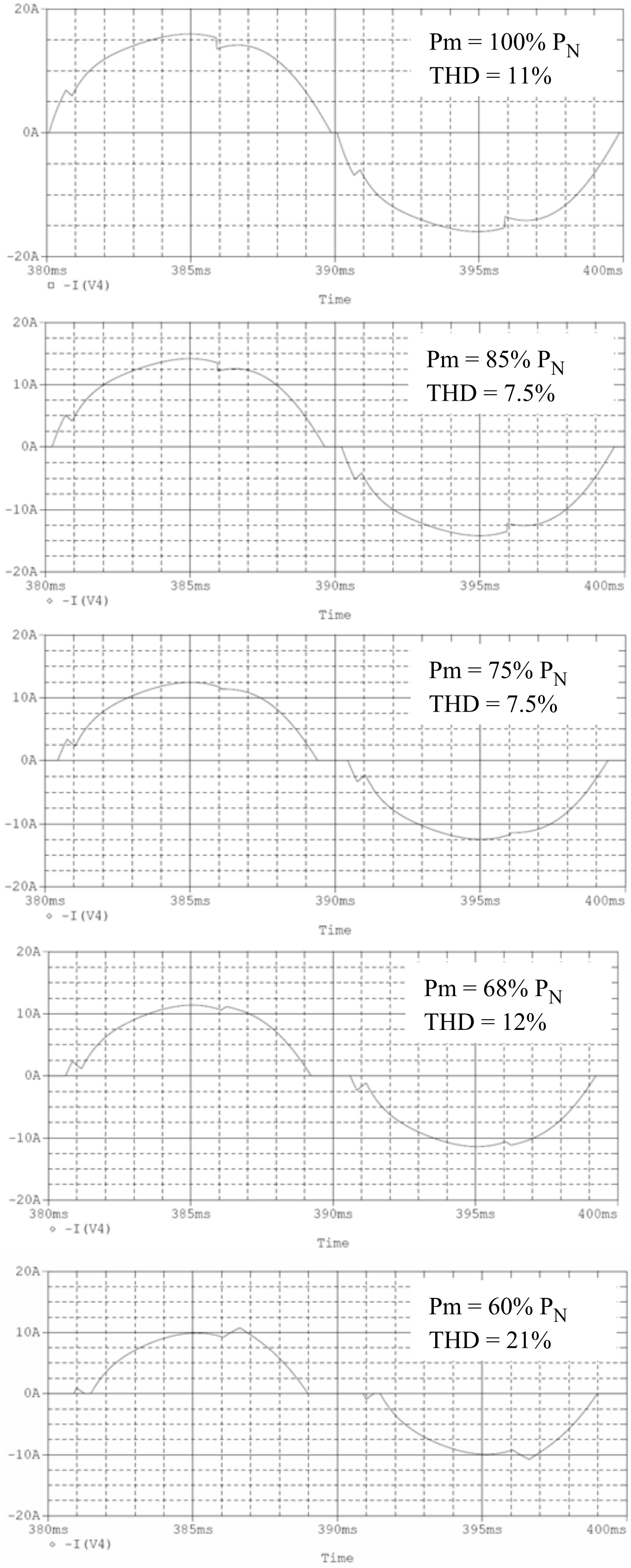

Fig.7. Currents drown from the supply by the new ASD with passive PFC, at different motor powers, Pm

C. Numerical Results, Referred to the Motor-Side

Figg. 8 and 9 show the waveforms and the spectrum (in [p.u.]) of the currents on motor windings, generated by the new ASD scheme introduced in section III, at – respectively - motor frequencies, fm, equal to 40 Hz (motor power is reduced at about 70% of P_N) and 30 Hz (motor power is reduced at about 50% of P_N). Interharmonic current components, at low-frequencies, are underlined in both cases.

Figg. 10-13 are directly extracted from [17]; they refer to waveforms and spectra of currents on motor windings, at motor frequencies equal to 40 Hz and 30 Hz, in case of the conventional ASD scheme recalled in section II.A (Figg. 10 and 11) and in case of the innovative PFC recalled in section II.B (Figg. 12 and 13). Also in these cases, interharmonic current components at very low-frequencies are underlined.

From the analysis of the results reported in the aforementioned Figg., it is well evident that:

- even if the conventional ASD absorbs from the AC-supply a current characterized by a poor quality because of a very high harmonic content, both at the rated and at reduced motor powers, it generates currents on motor windings practically unaffected by unbalances and/or low-frequencies interharmonic components;
- even if the innovative ASD of Cacciato et Alii absorbs from the AC-supply a current characterized by a reduced harmonic content, both at the rated and at reduced motor powers, it generates currents on motor windings significantly affected by insidious unbalances and/or low-frequencies interharmonic components;
- in addition to the fact that the new introduced ASD absorbs from the AC-supply a current with a very low harmonic content, both at the rated and at reduced motor powers, it generates currents on motor windings practically unaffected by unbalances and/or low-frequencies interharmonic components.

VI. CONCLUSIONS

Recent advances on single-phase ASD for low-power three-phase induction motors have been presented.

An innovative scheme with passive PFC, introduced on 2005 by Cacciato et. Alii [14] has shown the ability to significantly reduce, with respect to the conventional scheme, harmonics on the current absorbed from the AC-supply; however, it seems to negatively amplify the inherent inclination of this kind of ASD of generating currents on motor windings rich of insidious unbalances and/or interharmonic components at very low-frequencies.

A new scheme introduced by the Author, with a different passive PFC, has shown, especially in the range of few kW of the motor power, the ability to absorb from the AC-supply a current with very low harmonic content; at the same time, it seems able to generate currents on motor windings unaffected by sensible unbalances or interharmonic components, both at the rated and at reduced powers of the motor. The introduced passive PFC can be considered attractive also for its high energy efficiency.

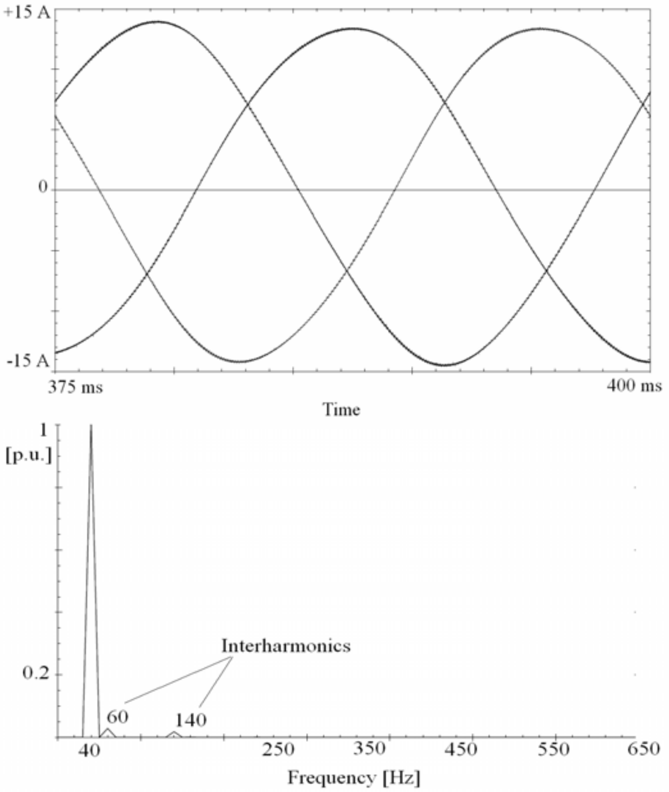

Fig.8. Currents (waveforms and spectrum) on motor windings of the new PFC scheme, at motor frequency fm=40Hz

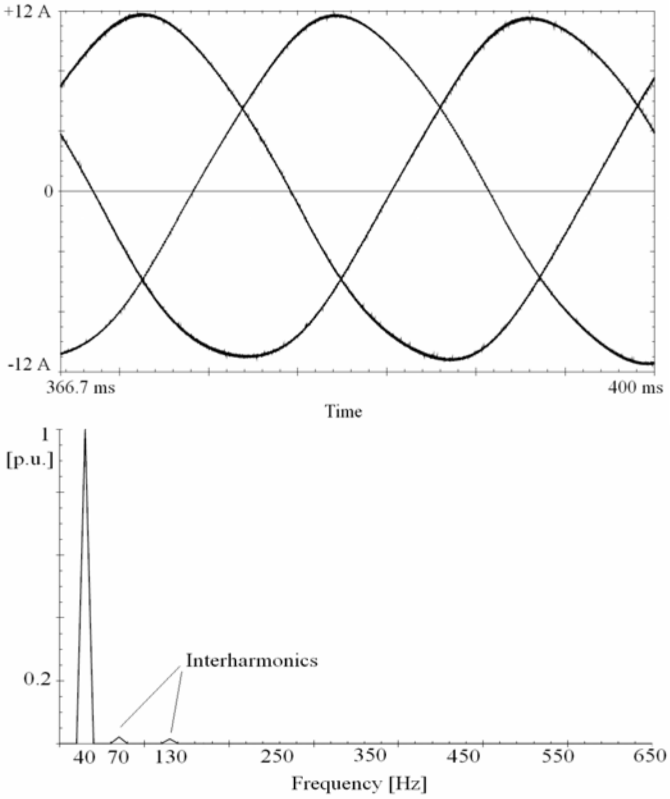

Fig.9. Currents (waveforms and spectrum) on motor windings of the new PFC scheme, at motor frequency fm=30Hz

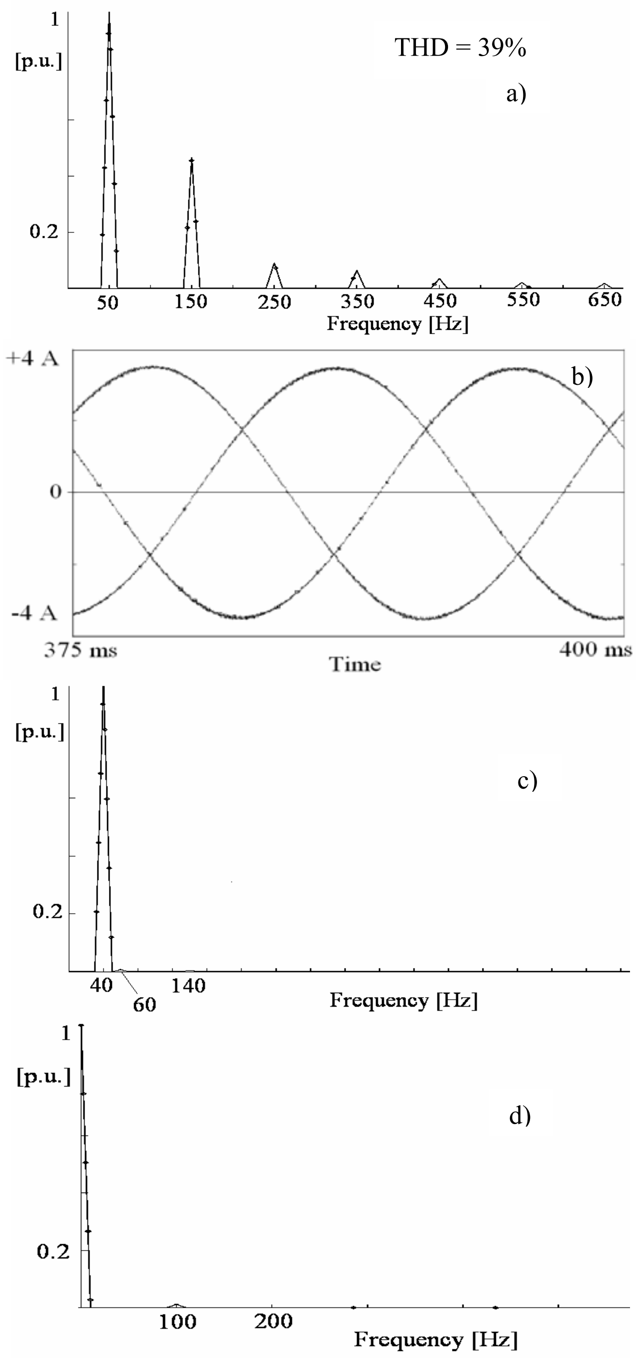

Fig.10. Currents (spectra and waveforms) of the conventional ASD, at fm = 40 Hz. a) AC-supply current; b) and c) motor currents; d) DC-side inverter current

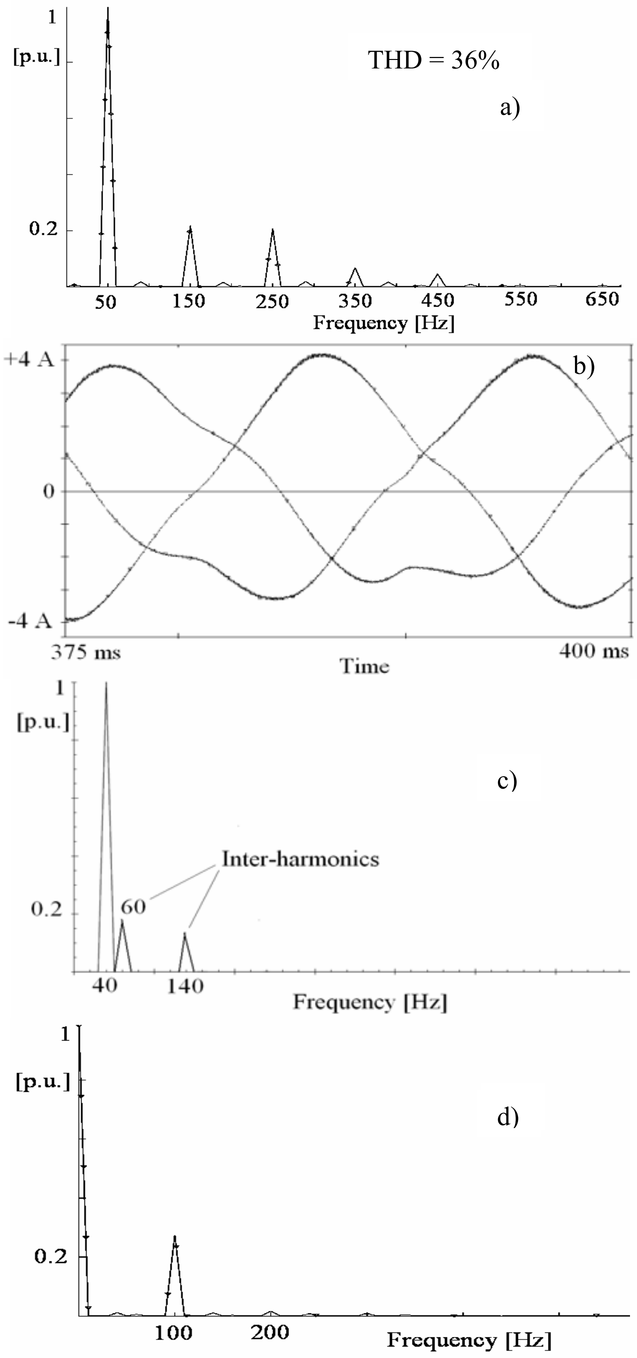

Fig.12. Currents (spectra and waveforms) of the innovative ASD [6], at fm = 40 Hz. a) AC-supply current; b) and c) motor currents; d) DC-side inverter current

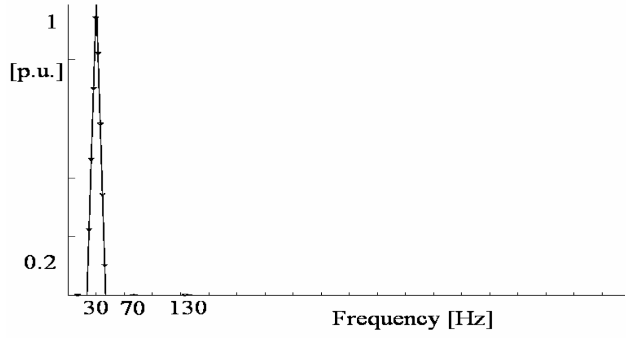

Fig.11. Motor current of the conventional ASD, at fm=30 Hz

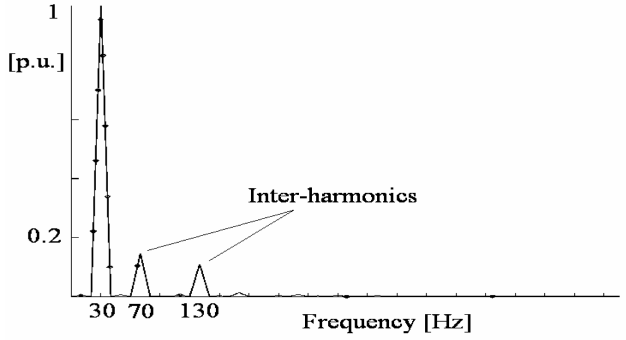

Fig.13. Motor current of the innovative ASD [6], at fm=30Hz

REFERENCES

[1] Haile S. Rajamani, R. A. McMahon: "*Induction Motor Drives for Domestic Appliances*". IEEE Industry Application Magazine, May/June 1997, pp. 21–26.

[2] J.R. Wells, B.M. Nee, M. Amrhein, P.T. Krein, P.L. Chapman: "*Low-Cost Single-Phase Powered Induction Machine Drive for Residential Applications*". Proceedings of Applied Power Electronics Conference and Exposition. IEEE "APEC'04". 2004, pp. 1579–1583.

[3] J.R. Wells, B.M. Nee, M. Amrhein, P.T. Krein, P.L. Chapman: "*Low-Cost Single-Phase Powered Induction Machine Drive for Residential applications*". Proceedings of Nineteenth Annual IEEE, pp. 1579 – 1583, Vol.3. ISBN: 0-7803-8269-2.

[4] O. Muravlev et al.: "*Energetic parameters of induction Motors as the basis of energy saving in a variable speed drive*". Electrical Power Quality and Utilization, Vol. IX, No. 2, 2005.

[5] Moghani, J.S.; Heidari, M.: "*High efficient low cost induction motor drive for residential applications*". IEEE Int. Conference "SPEEDAM 2006". 23-26 May 2006, pp. 1399-1402.

[6] C. Thanga Raj, S. P. Srivastava, and Pramod Agarwal: "*Energy Efficient control of Three-Phase Induction Motor – A Review*". International Journal of Computer and Electrical Engineering, Vol. 1, No. 1, April 2009, pp.1793-8198.

[7] P. Enjeti, A. Rahman: "*A new single-phase to three-phase converter with active input current sharing for low cost motor drives*". IEEE Transactions on Industry Applications, vol. 29, no. 4, pp. 806-813, 1993.

[8] G. Spiazzi, E. da Silva Martins, J. A. Pomilio: "*A Simple Line-Frequency Commutation Cell Improving Power Factor and Voltage Regulation of Rectifiers with Passive L-C Filters*". Proc of IEEE Power Electronics Specialist Conf. (PESC), Vancouver, June 20001.

[9] R. Redl: "*An Economical Single-Phase Passive Power-Factor-Corrected Rectifier: Topology, Operation, Extensions, and Design for Compliance*". IEEE Applied Power Electronics Conf. (APEC), Feb. 98, pp. 454-460.

[10] R. Redl, L. Balogh: "*Power-Factor Correction in Bridge and Voltage-Doubler Rectifier Circuits with Inductors and Capacitors*". IEEE Applied Power Electronics Conf. Proc. (APEC), March 1995, pp. 466-472.

[11] Jovanovic, D. E. Crow: "*Merits and Limitations of Full-Bridge Rectifier with LC Filter in Meeting IEC 1000-3-2 Harmonic-Limit Specifications*". IEEE Applied Power Electronics Conf. (APEC), March 1996, pp. 354-360.

[12] R. Carbone, A. Scappatura: "*A high efficiency power factor corrector for single phase bridge diode rectifier*". IEEE Conf. "PESC '04", June 20-25, 2004, Aachen, Germany.

[13] R. Carbone, P. Corsonello, M. Fantauzzi, A. Scappatura: "*Power Factor correction in Single-Phase Rectifiers: a Performance analysis of Passive and Line-Frequency-Commutated Active Techniques*". Third IASTED International Conference on Power and Energy Systems "*EUROPES 2003"*, September 3-5, 2003 Marbella, Spain.

[14] M. Cacciato, A. Consoli, S. De Caro, A. Testa: *"Using the DC-bus Current to improve the Power Factor in Low-Cost Electric Drives"*. IEEE Transactions on Industry Applications, Vol.41, N.4, July/August 2005, pp. 1084-1090.

[15] R. Carbone, A. Scappatura: "*An improved three-phase rectifier for PWM adjustable speed drives with passive power factor correction and resistance emulation*." WSEAS TRANSACTIONS ON CIRCUITS AND SYSTEMS, vol. 4, 2005. ISSN: 1109-2734.

[16] I. Takahashi: "*Power factor improvement of a diode rectifier circuit by dither signals*". In Conf. Rec. IEEE IAS Annual Meeting, Seattle, WA, Oct. 1990, pp. 1289-1294.

[17] Carbone R., A. Tomaselli: "*Passive Harmonic Filtering Systems for Low Power PWM ASDs: A Comparative Analysis and Perspectives"*. Proceedings of IEEE "Speedam 2010", June 14-16, 2010, Pisa (Italy).

[18] R. Carbone, R. Morello: "*A single-phase to three-phase low-power adjustable speed drive with low current harmonics*". IEEEAM-WSEAS International Conference on Circuits, Systems and Signals "CSS 2010", September 15-17, 2010, Valletta, Malta

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