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Energy saving by power electronics: towards a new concept of renewable source

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Abstract.

The use of fossil sources has been increasing the excess of carbon dioxide (CO_2) emission in the atmosphere since the last century with detrimental to the weather. Renewable Energy Sources (RESs) appear a valid solution to mitigate CO_2 emissions but their growth is still too small compared to fossil sources, for this reason they need to be sustained by available technologies. Among these, the use of More Power Electronics (MPE) for electrical energy conversion leads to increase efficiency conversion and the investment is compensated in few time both for new equipment and retrofitting. The saved energy meets the definition of renewable energy. The whole amount of the energy saving potential achievable by MPE is comparable to the electric energy generated by the installed renewable sources.

Key words

Power electronics, energy saving, negawatt, carbon dioxide emissions.

1. Introduction

Nowadays an increasing interest towards the prevision of what can happen to our planet in the next future is registered. This is mainly due to the effects of the global warming whose effects can be experienced by everybody.

It is possible to recognize the Earth as an energy storage system. Since life appeared, a part of energy coming from the Sun was stored by photosynthesis which allowed enormous biomass reserves to be constituted producing fossil fuels. The human activity has been utilizing on a massive scale this resources since the second half of the XIX century starting with fossil coal and then with oil and natural gas during the first half and the second half of the XX century respectively [1]. On the other hand, a small quantity of biomass has been produced during the last centuries and this energy is going to end. Once that this "battery" will be completely discharged, life will not possible never again.

Nature gives us a lot of stable cycles at the human scale. For example, in biological systems, during the day/night cycle, biological loads are supplied by sun energy, energy is produced by photosynthesis and the waste products are recycled.

Another example of stable cycle is the natural Carbon Cycle in which Carbon is exchanged, among Earth's oceans, atmosphere, ecosystem, and geosphere. It guarantees the fundamental building block of life and plays an important role in many chemical processes. All living organisms are built of carbon compounds. It is present in the atmosphere primarily as carbon dioxide (CO_2), and methane (CH_4). Life processes are supplied by carbon compounds in the form of CO_2, it is exhaled by all animals and plants and is assimilated by plants during photosynthesis to build new carbon compounds. The atmosphere exchanges CO_2 continuously with the oceans. The early presence of CO_2 in the atmosphere avoids to radiate heat away from the planet preserving life. Unfortunately, the human intervention by burning of fossil fuels has damaged this balance increasing the CO_2 in the atmosphere, with consequent global warming, causing positive feedback effects. For example, when air conditioners, whose energy is obtained by fossil fuels are used to mitigate the heat, it results in a further CO_2 production increasing global warming with consequent increasing of the use of air conditioners. Moreover, water vapour in the atmosphere contributes to life but global warming produces an excess of water vapour that increases the greenhouse effect and produces further water evaporation.

It can be remarked that the magnetic field of the Earth preventing the interaction with the atmosphere (avoiding that Earth becomes like Mars or Venus for the solar wind effect) makes not possible to get over vapor outside the atmosphere.

Despite to the need for carbon footprint reduction and the shortage of fossil fuels, the demand for energy is increasing and a great amount of energy consumption is still sustained by traditional fossil sources. As a matter of fact, it is noteworthy that the energy consumption per capita is practically stable since 1970 (about 300 GJ/year•person in USA) hence it is roughly proportional to the increase of population [1].

In addition, countries' economic efficiency are still based on oil consumption increasing; this consumption is the main driver behind the progress of industrialization and urbanization regardless of the country's development stage [2]. The Carbon Capture and Storage (CCS) [3] does not seem an effective solution due to its high cost and the recent accident at the Fukushima Daiichi nuclear plant together with the complexity to manage radioactive waste has probably changed the expectation towards nuclear energy [4].

Despite the advantages, the growth of renewable source market share appears relatively slow and comparable with the growth of other fossil sources in the

past. This is mainly due to the energy produced by RES that rarely fits the energy demand. These variations should be buffered by gas or coal-fired power plants or dedicated storage systems but, although many technologies have been recently set up, the spreading of big plants would require time and the problems related to energy transportation by existing grids remain [5].

From the above considerations it is clear that RESs cannot be considered a mere alternative to fossil fuels. The diffusion of RESs has to be accompanied by a rationale use of energy. This is dramatically crucial for the survival of our planet.

The aim of this paper is to show that the adoption of power electronics based solutions can contribute to the sustainability of electric systems. It is explained in the following by showing the role of power electronics in a conversion system (section II). Section III and IV are respectively devoted to the new power devices and to power circuit topologies allowing the efficiency to be increased. In section V the sustainability of a power electronics equipment is analysed by introducing the energy pay-back time as parameter. Finally, section VI shows that the energy saved by more power electronics can be considered a renewable source.

2. The role of power electronics

Actually, electricity supplies more than one third of the global energy request. The advantages in using electric energy consist on its relatively easy transport over long distances, on the possibility to adopt emission control strategies in centralized fossil fuel power stations and, more recently, in the use of renewable sources. [6-7].

These reasons are contributing to a faster growth of the demand for electricity compared to other energy forms over the next three decades. It is expected that the consumption, in comparison to other forms, will grow further. Roughly 70% of electrical energy in USA is now processed through power electronics which will eventually expand to 100% [6]

Unfortunately a big amount of electric energy before utilization is lost as heat along the supply chain. Indeed, conversion losses from mechanical to electric energy are about 60%, during the energy distribution, additional 15% is lost including AC/DC and DC/AC conversion over long lines. In AC/DC/AC conversion for motor drives, traction or home appliances losses are about 20% and a further 20% is lost in the last AC/DC conversion for power supplies and in DC/DC conversion for point of loads.

Power electronics plays a key role through the chain of transformation from generation to storage and distribution cycle of energy: as a matter of fact the conversion is performed by power converters in all ranges of power levels (from a few W to MW) [8].

The optimization of power converters, aimed to losses reduction, is one of the factor that boosted the market of photovoltaic in the last two decades. As a matter of fact the cost of PV electricity has been abated from about 1.2 €/kWh in 1991 to about 0.15 €/kWh in 2014. A relevant part of the difference equal to about 0.5 €/kWh is due to the innovation of PV inverters. They have been improved in terms of enhanced inverter functionality such as efficiency, reliability, maximum power point tracking, failure management, communication capability allowing a saving of about 0.3 €/kWh and losses reduction allowing a saving of about 0.2 €/kWh. In the same period the cumulated PV capacity worldwide has risen from about 200 MWp in 1990s to 135 GWp in 2013 (corresponding to an average market growth of 44% for year) and the prices for both PV modules and PV inverters for grid feeding have been reduced of about 90%.

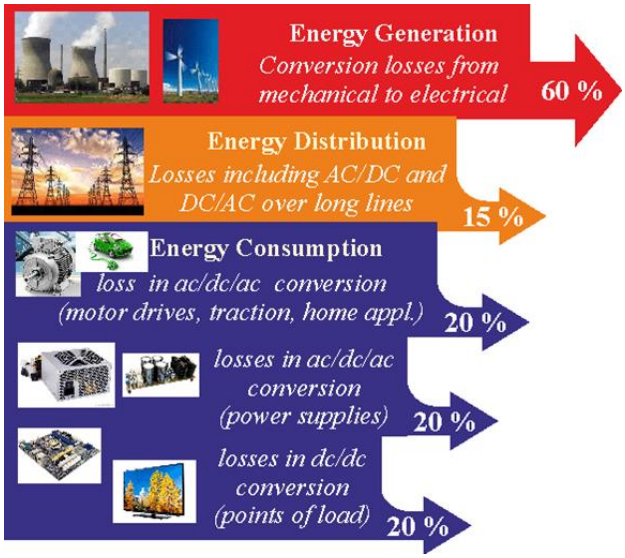

Fig.1: Schematics of losses through the path from energy generation to utilization.

Among the features of new designed inverters there are the increased rated power of inverter units, the presence of higher numbers of units leading to reduced component costs, a reduced assembly time due to design for batch production, a higher degree of automation and an improved functional integration due to several functions covered by a single inverter component.

Since a further cost reduction of electricity coming from RESs is necessary, new inverters functionality are expected, in terms of grid support and battery storage integration, requiring a further conversion stage and increasing the need for losses reduction to be competitive on the market [9].

It is possible to take on this new challenge by new devices and new topologies for power conversion circuits.

3. Wide Band Gap devices

The use of Silicon (Si) in the last decades as primary semiconductor choice for power electronic devices has been highly optimized obtaining low cost and high manufacturing capability. On the other hand, improved efficiency, reduced size and low overall system costs requirements have highlighted its limits. The study of new semiconductors has led research to the wide-band-gap (WBG) semiconductors in which the energy difference between the top of the valence band and the bottom of the conduction band is higher than the Silicon [10]. Among these, silicon carbide (SiC) and gallium nitride (GaN) are the most interesting with many devices available on the market.

The main features of these devices are the high temperature and high voltage capability for SiC devices

and the high frequency switching capability for GaN devices [11].

Both devices exhibit similar values of electron velocity and higher energy gap compared to Si devices. SiC devices are characterized by the highest thermal conductivity and melting point, on the contrary GaN devices show high frequency switching capability. All these features make the WBG semiconductor based devices candidate to replace Si. [12-13].

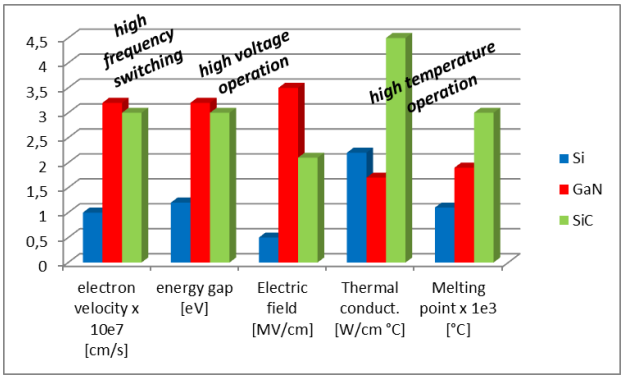

Fig.2: Comparison of WBG, SiC and Si performance

A. *Silicon Carbide devices*

SiC devices take advantage from the availability of high quality 100 mm wafers (150 mm available in the next future). Three main categories are recognizable: power rectifiers, unipolar power switches and bipolar power switches.

SiC power rectifiers show a blocking voltage higher of an order of magnitude compared to a Si device with the same drift layer thickness; moreover, the high thermal conductivity of SiC allows operating at high current density and/or minimizing the cooling system.

At the moment high-voltage SiC as Shottky Barrier Diodes (SBDs) and Junction Barrier Shottky (JBS) are really competitors of Si diodes and are available on the market.

SiC JFETs and MOSFETs are expected to be competitive with Si IGBT up to breakdown voltage of 5 kV.

Among the unipolar power switches, the SiC JFET is an interesting alternative in the voltage range up 1.5 kV to its counterpart Si power MOSFET and Si IGBT since the Si MOSFET is affected by large conduction losses and Si IGBT by large dynamic losses for fast switching operation. A 1.5 kV, 0.5 Ω on resistance hybrid switch for resonant converters and power supplies has been developed by Infineon and a 1.2 kV 70 mΩ SiC JFET-based switch (CoolSic) has been announced by the same manufacturer [14]. A 1.2 kV 33A SiC MOSFET is commercially available from Cree. Furthermore, structures with blocking voltage capability up to 10 kV have been recently demonstrated [10]

In the Bipolar power switches field the SiC IGBT shows the highest potential in terms of high voltage applications with several structures with voltage capability up to 10 kV. Higher values are expected in the next future [15].

SiC BJTs are also promising as well although in some devices degradation of gain and forward voltage drop in presence of forward stress is noticed. A 10 A BJT with a gain of 34 in the active region is proposed by Cree [16].

Finally is to be noticed the SiCGT (SiC Commutated Gate turn-off Thyristor) which is a 4.5 kV 120A having turn-on time of 0.2 μs, turn-off time of 1.7 μs and a structure coated with a new high resistive resin able to operate at 400 °C [17].

B. *Gallium Nitride devices*

Despite the high frequency and high voltage performance of GaN, some issues regarding the lack of good quality bulk substrates for vertical devices and lower thermal conductivity get slower the spread of the devices in the power electronic area whereas they are proposed in the field of photonics.

Most of the GaN Shottky power diodes reported up to now are either lateral or quasi-vertical structures [18]. Anyway, these lateral devices exhibit a breakdown voltage as high as 9.7 kV obtained on Sapphire substrates although the forward voltage drop is still high. Shottky diode are expected in the market in the next future in the 600V – 1.2 kV voltage range.

As for the power switches, several normally on devices as GaN HEMTs (High Electron Mobility Transistor) are attracting attention for high-power switching application in particular for switching power supplies in the MHz range and as microwave devices for base station of cellular phone. The voltage capability of GaN HEMTs is approaching 10 kV, as a result, high performance ALGaN/GaN HEMTs on Si substrates have been reported.

Some normally off devices are under study, at the moment there are devices available with a breakdown voltage in the range of 20-600V [19].

As for high-voltage power switching applications, normally off lateral GaN MOSFETs are an alternative to SiC MOSFETs and GaN HEMTs.

C. *Future perspectives of WBG devices*

The use of more efficient power devices is expected to be more relevant in that countries in which a great amount of electrical energy is processed.

The prospective application areas for WBG devices include transportation electrification, downhole drilling and renewable energy. Other fields as electric cars and more-electric aircrafts will benefit of the reduced size of converters and filters. Oil and Gas industry are particularly interested on high temperature devices able to operate in deep oil wells [20].

Photovoltaic inverters will achieve a greater efficiency reducing the overall system and life cycle costs.

Finally features as higher blocking voltages and higher efficiency will allow the adoption for HVDC, static compensator and solid state power transformers [11].

Power supplies and factory automation cover the low power area requiring a great number of rectifiers and power switches, on the other hand the high power area covered by HVDC and power transmission market requires fewer semiconductor devices but has a strong impact on grid reliability and performance.

4. More Power Electronics for losses reduction

The availability of low cost Silicon power switches has stimulated the study of circuital topologies aiming to face up to two challenges: to obtain the highest efficiency maximizing the power density and to have available such high efficiency under the whole range of the output power.

Usually the constraint on the efficiency optimization is more binding than the one on the power density as in the case of photovoltaic (PV) inverter systems and telecom rectifier modules whose efficiency has been considerably increased as shown in figure 3 [21].

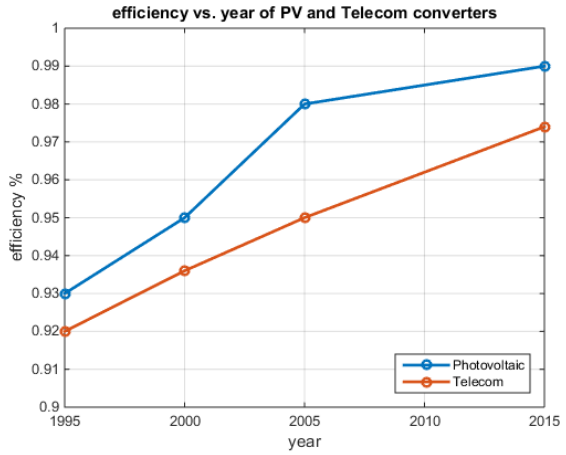

Fig.3: Increase of the efficiency of PV and telecommunication converters since 1995

Anyway, by MPE the efficiency optimization can be pursued with benefits for power density as well.

With reference to the boost converter sketched in figure 4 the efficiency is given by:

$$\eta = \frac{P_o}{P_i} = \frac{P_o}{P_o + P_{lst}} = \frac{1}{1 + \frac{P_{lst}}{P_o}} \approx 1 - \frac{P_{lst}}{P_o} \qquad (1)$$

Where P_i is the power delivered at the input port of the converter, P_o is the power achieved at the input port of the converter and $P_{lst} = P_i - P_o$ is the power due to the losses.

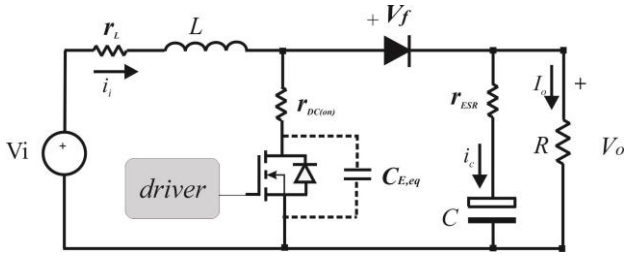

Fig.4: Scheme a DC/DC boost converter including parasitics lowering efficiency

It is clear that to obtain an efficiency near to one, the relative losses, in term of the ratio (P_{lst} / P_o) have to be minimized. For this reason it is interesting to investigate on how the relative losses depend on the output power.

Considering the continuous conduction mode (CCM) of the power converter of figure 4, the power due to losses is given by:

$$P_{lst} = \left(P_{aux} + \frac{1}{2} C_{E,eq} V_o^2 f_{sw} \right) + \\ + \left(V_f + k_{sw} f_{sw} \right) I_o + \\ + \frac{1}{(1-D)^2} \left(r_L + D r_{ds,on} + D(1-D) r_{ESR} \right) I_o^2 \qquad (2)$$

It can be noted that the first addend is constant since it contains losses due to the auxiliary systems (measure and control electronics, drive circuits, fans for forced power devices cooling) and the contribution of the charge/discharge operation of the equivalent capacitance of the MOSFET which depends on the square of the output voltage and on the switching frequency f_{sw}.

The second addend contains terms proportional to the output power. There are the contribution of the diode voltage drop V_f and the switching losses proportional to the output current and to the switching frequency.

Finally, the last addend groups the terms dependent in quadratic form on the output power. They are joule losses such as losses into the inductor parasitic resistance r_L caused by the input current $I_i = I_o(1\text{-}D)$, losses into the MOSFET conduction resistance $r_{ds,on}$ and losses in the output capacitor parasitic resistance r_{ESR}.

The lost power can be expressed by:

$$P_{lst} = k_c + k_l P_o + k_q P_o^2 \qquad (3)$$

Where k_c, k_l, and k_q are three proportionality constants. In order to maximize the efficiency (1), the ratio P_{lst} / P_o have to be minimized. It can be deduced that the best value of the efficiency is obtained when the constant losses equals quadratic losses.

$$\left. \frac{P_{lst}}{P_o} \right|_{\min} = \left(\frac{k_c}{P_o} + k_l + k_q P_o \right)_{\min} \Rightarrow \quad \frac{k_c}{P_o} = k_q P_o \qquad (4)$$

If the condition (4) is satisfied, the optimal efficiency is:

$$\eta_{opt} = 1 - k_l - 2\sqrt{k_c k_q} \qquad (5)$$

And the output power can be calculated

$$P_{o,opt} = \sqrt{\frac{k_c}{k_q}} \qquad (6)$$

It can be noted that the output power is far from the rated power and that in the optimal efficiency (5) the contribution of the terms linearly dependent on the output power is more relevant than the others.

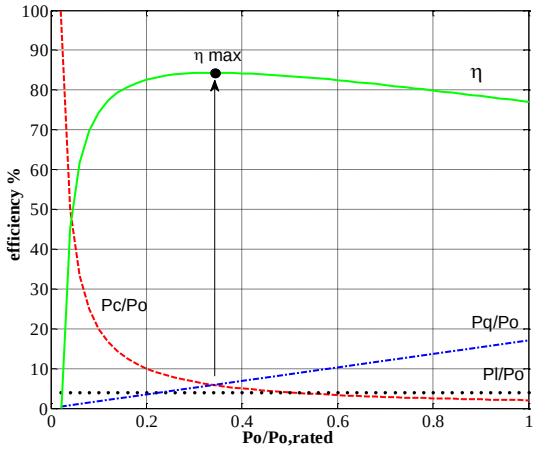

Fig.5: Maximum of efficiency obtained by hyperbolic, constant and linear losses

The above considerations are the basis to devise methods to improve the efficiency of power converters.

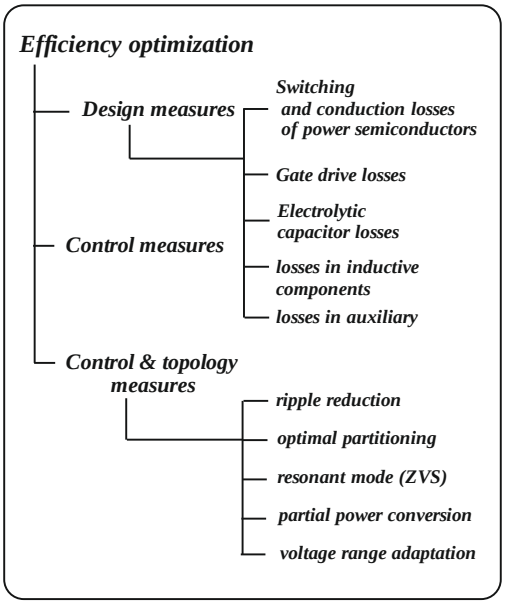

Fig.6: Outline of efficiency optimization techniques

The efficiency optimization can be obtained by design measures, control measure or by adopting both control and topology measures (figure 6).

The main target of the design measures is the reduction of the switching and conduction losses in power semiconductors. For a MOSFET device, losses depend on the conduction resistance r_{ON} and on the charge/discharge of its parasitic equivalent capacitance $C_{E,eq}$ occurring with frequency f_{SW} . Both these losses are tied to the chip area A_{Si}. The equivalent capacitance is proportional to the chip area whereas the conduction resistance is inversely proportional to A_{Si}, therefore the losses in power semiconductors can be written as:

$$P_{powersemic} = \gamma_{cond} \frac{1}{A_{Si}} + \gamma_{sw} A_{Si} f_{sw} \qquad (7)$$

Where γ_{cond} and γ_{sw} are constant. The optimal Silicon area is given by:

$$A_{Si,opt} = \sqrt{\frac{1}{f_{sw}} \frac{\gamma_{cond}}{\gamma_{sw}}} \qquad (8)$$

It can be noted that a high value of the switching frequency reduces the Silicon area but increases losses. On the other hand, the lowering of the switching frequency implies an increase of the volume occupied by the power device.

It is interesting to note that, considering only the power device losses, a Silicon area lower than the optimal one increases efficiency at light loads, on the contrary a higher Silicon area worsens efficiency in the whole range as sketched in figure 7.

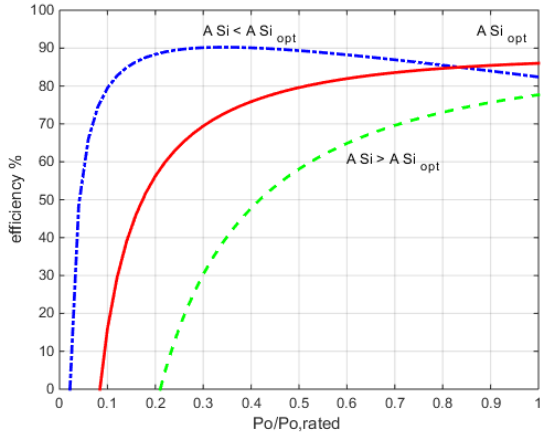

Fig.7: Efficiency versus different MOSFET chip area

The parasitic capacitance of the freewheeling diode (or of the power transistor in case of synchronous rectification) gives a further contribution proportional to the equivalent capacitance, to the square of the voltage and to the frequency.

The *gate drive losses*, in case of unipolar gate drive circuit are related to the gate charge and to the gate voltage after turn-on. The gate charge depends on the gate voltage and is proportional to the Silicon area.

$$P_{gate_driver} = V_{gg} Q^{*}_{gg}(V_{gg}) A_{Si} f_{sw} \qquad (9)$$

Where Q_{gg}^{*} is the gate charge per unit area. The gate drive losses behave like the capacitive switching losses of the transistor. Anyway, by the zero voltage switch (ZVS) exploiting resonance, the capacitive switching losses of the transistor can be drastically reduced and the value of the A_{Si} can be optimized on the basis of the P_{gate_driver}.

The electrolytic and *capacitors losses* are joule losses on the equivalent series resistance r_{ESR}, The r_{ESR} is usually variable with frequency, it can be reduced by adopting a parallel connection of multiple capacitors but at the expenses of an increase of the total volume.

The winding *inductors losses* are ohmic losses as well as the capacitor losses but in this case the current flowing through the inductor is much higher. These losses can be reduced by interleaved topologies in which the current is partitioned (see figure 8). The reduction of the current reduces ohmic losses but also in this case at the expenses of an increase of the total volume.

Finally, *auxiliary circuits losses* influence the efficiency especially at light load. The reduction of the clock frequency or the temporary deactivation of cooling fans can minimize this contribution.

The whole conversion circuit can be optimally exploited by *control measures* if it is always operated at its maximum efficiency. This suggests to deliver power to the load not continuously but, maintaining the required average value, operating the converter periodically. During the operation time interval it is operated at the optimal efficiency point, it remains in stand-by in the remaining time. It is possible, for example in a power factor correction (PFC) rectifier with a sufficiently high storage capacitance operated around the maximum of the mains voltage resulting, on the other hand, in a higher input current distortion [21].

Further improvement can be achieved *by topology and control measures*. As above explained, efficiency can be improved at light load by reducing the chip area (see figure 7), it suggests the use of multiple parallel systems so that each system is operated at its optimal efficiency. The phase shifted operation is advantageous for the reduction of the ripple of the input and output current and reduces the electromagnetic emissions with benefits to the EMI filter design [22].

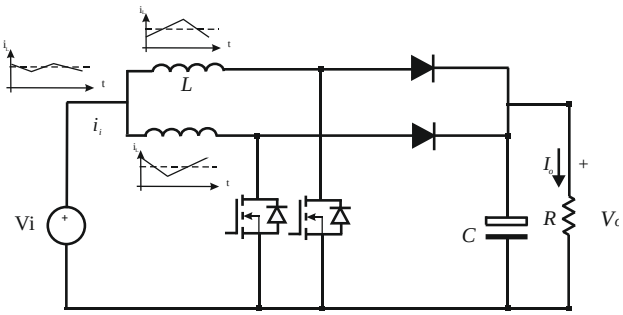

Fig.8: Interleaved converter

In case of a boost converters in a single-phase PFC rectifier, operated with 180° phase shift, with duty cycle *d*, the amplitude of the voltage ripple is given by:

$$\Delta i = \frac{V_o}{L f_{sw}} d(1-d) \tag{10}$$

It is maximum for *d*=0.5 and it is given by:

$$\Delta i\big|_{\max,n=1} = \frac{V_o}{4 L f_{sw}} \tag{11}$$

For two converters operated with 180° phase shift (maintaining the same inductor value) the odd multiples of the switching frequency cancel each other, the maximum ripple occurs at *d*=0.25 and *d*=0.75 and is equal to

$$\Delta i\big|_{\max,n=2} = \frac{V_o}{16 L f_{sw}} \tag{12}$$

This reduction is caused both by the facts that the frequency that causes the ripple is doubled and that the voltage amplitude that causes the ripple is halved.

Finally, since the reduction of the ripple is obtained with the same switching frequency, the switching losses remain unchanged but the joule losses on inductors are reduced. The reduction of the total output ripple allows the input capacitance to be lessened by a factor eight compared to a single stage or to an inductance value reduced to a quarter to be used for each stage. Moreover, for low power level, a reduced number of stages can be activated. If the total number of operated stage is greater than 1, the optimal power sharing is obtained when the same amount of power is managed from each stage. This can be explained since in this way the contribution of joule losses can be minimized contrarily to constant and linear losses whose contribution remain the same dividing the current. The switchover among *n* and *n+1* operated stages can be performed at the intersection of the respectively efficiency curves so that the converter runs always near to the maximum efficiency. The whole efficiency curve for n = 3 parallel subsystems is sketched in figure 9 together with the efficiency of a single and double stage converters.

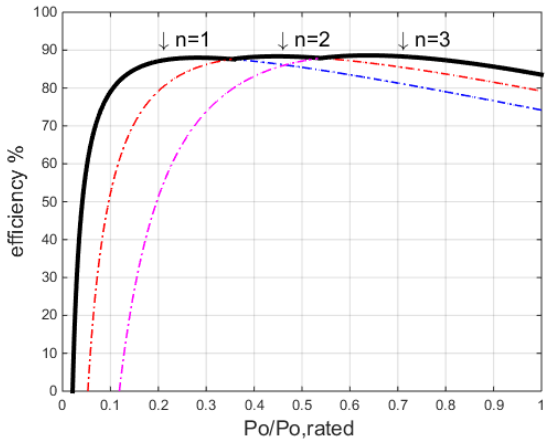

Fig.9: Maximum power conversion efficiency obtained by switchover of n=3 parallel subsystems.

By adopting Zero Voltage Switching (ZVS) techniques, instead of continuous conduction mode (CCM), switching and diodes drop losses can be abated.

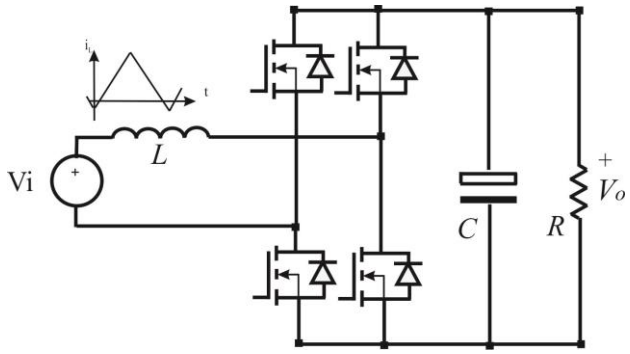

Fig.10: Resonant converter with zero voltage switching

As a matter of fact, with reference to figure 10, where the freewheeling diodes of figure 8 are changed with power MOSFETs, during the freewheeling period the upper MOSFET is maintained in on-state, providing a synchronous rectification, until a sufficient negative current is obtained. This current is impressed by the inductor and assures a fully resonant transition of the

voltage corresponding to the ZVS of the opposite MOSFET. In this way a significant losses reduction is achieved especially at light loads.

As example of high extreme efficiency converters, two PFCs have been recently presented in [21], [23]. The first one has a rated power of 3.3 kW, it is suitable for IT power supply or battery charger for electric vehicles. It is a bridgeless structure consisting of two phase-shifted subsystems equipped with Si-superjunction MOSFETs (CoolMOS C6) and SiC free-wheel diode and operated in CCM. The rated load efficiency is 99.1 % including auxiliary supplies. The second circuits is based on synchronous rectification by MOSFETs instead diodes and uses resonant transition mode to lessen losses. In this way a flat efficiency curve is obtained in the power range from 1kW to the rated power with efficiency equal to 99.3%.

At system level, the efficiency can be increased by topologies allowing the partial power conversion and the management of the operation voltage range.

The first approach can be explained with reference to figure 11. The output voltage $V_2<V_1$ is obtained by means of the buck converter, it subtracts the voltage V_c so that $V_2=V_1- V_c$. In this way only a part of the input power is processed by the converter and the power is delivered directly from the input. The whole efficiency is given by:

$$\eta=\frac{P_o}{P_i}=\frac{(I_i+I_c)V_2}{I_i(V_c+V_2)}=\frac{I_iV_2+I_iV_c\eta_c}{I_i(V_c+V_2)}=\frac{1+\eta_c(V_c/V_2)}{1+(V_c/V_2)} \quad (13)$$

Where η_c is the efficiency of the converter. It can be noted that for low values of the ratio V_c/V_2 the efficiency of the converter guarantees high values of the total efficiency as shown in figure 12.

Two examples of optimal managing of operation voltage range are sketched in figure 13a and 13b. In the former an additional converter that can be activated for out of the range input voltage is present; in the latter, the duty cycle variations are limited by the series-parallel connection of the secondary circuits [19].

As far as electric drive converters are concerned, different PWM techniques (including discontinuous PWM) allow the converter losses to be reduced [24-25]

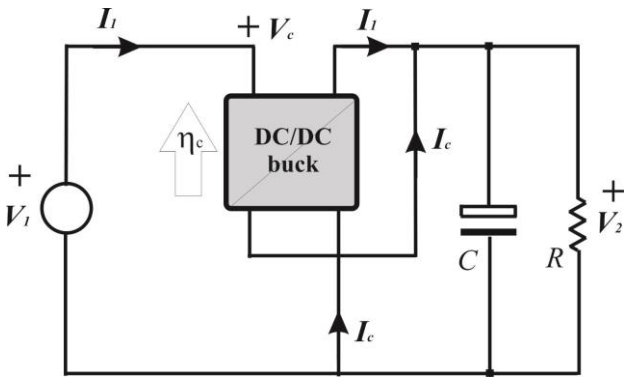

Fig.11: Example of partial power conversion based on a DC/DC buck converter.

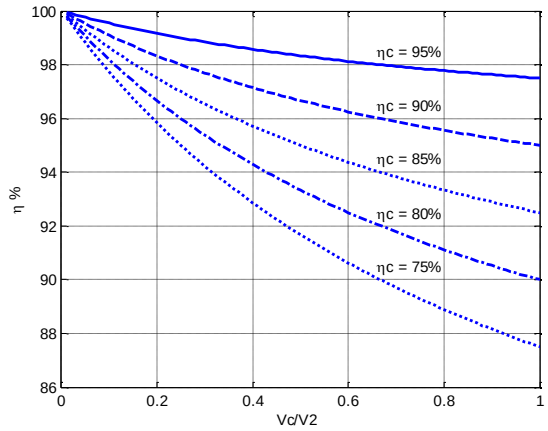

Fig.12: Efficiency curve for Partial Power converter based on DC/DC buck

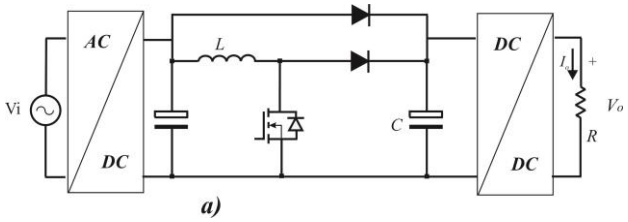

Fig.13a: Boosting with bypass diode

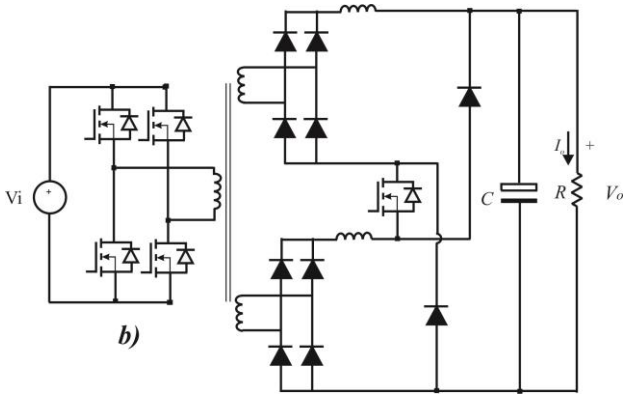

Fig.13b: Series-parallel connection of secondary circuits

5. Sustainability of PE equipment

As claimed into the introduction, it is clear that the way to drastically reduce greenhouse gas emissions leads to the massive use of renewable energy sources. On the other hand, the optimal exploitation of these sources requires sophisticated solutions based on power electronics converters in which the improvement of their performance implies the increase of the number of components.

These technical solutions have to be promoted at economy, public acceptance and policy levels demonstrating their sustainability. This can be supported by considering the energy cycle of a system in comparison with biological cycle considering that an electric system is supplied by electricity and that the loads are electrical. It is necessary to consider the full life cycle of the system rather that the day/night cycle. The sustainability of such a system is achieved when it is able to give back an energy greater than the sum of the whole

daily operational energy of the energy for manufacturing and of energy for recycling it. In particular, to quantify the contribution of power electronics based solutions to the sustainability, it is useful to calculate the energy payback time [26]. This parameter is defined as the time required for an energy producing system or device to generate as much energy as it was required for its manufacturing. It is similar to the concept of "pay-back time" but it takes into consideration the energy. For a power electronic converter the energy pay-back time is given by:

$$Energy\ pay_back\ time = \frac{(E_{embodied})_{system}}{(\Delta E_{operat})_{system}/year} \quad (14)$$

Where $(E_{embodied})_{system}$ is the required energy for manufacturing and recycling the converter (or the difference in case of retrofitting), $(\Delta E_{operat})_{system}$ is the difference, during one year of operation, between the energy before and after the retrofitting representing the yearly saved energy. An example of energy pay-back time evaluation is shown in table I. It considers two inverters for electric drives with rated power of 2.2 kW and 11 kW and efficiency ranging from 97% to 99%. The values of the embodied, saved and processed energy are taken from [26] where the lifetime is set equal to ten years. The embodied energy does not take into account the end-of-life management (disposal, recycling) that results much lower than cradle-to-gate cost. It can be noted that, also in the pessimistic case of constant embodied energy, the pay-back time is lower than one month and decreases as far as the efficiency is increased. Actually, the improved efficiency leads to lessen the embodied energy since the heatsink and cooling system are reduced.

The ratio embodied energy/dissipated energy increases with efficiency, increasing the lifetime implies a reduction of the ratio embodied energy/saved energy and of the ratio embodied energy/dissipated energy.

It can be deduced that the sustainability of a power electronic system is tied to the reduction of the embodied energy, of the increase of the efficiency and of its reliability in terms of lifetime. Finally, the obtained values of the pay-back time are lower than those of photovoltaic plant (1-3 years depending on technology) and of a wind plant (6-8 months).

TABLE I

	Embodied Energy [kWh]	Saved energy annually [kWh]	Processed energy annually [kWh]	Dissipated energy annually [kWh]	Embodied Energy/ Saved energy [%]	Embodied Energy/ Dissipated energy [%]	Energy payback time [months]
η=97%							
2.2 kW	129.3	3851.0	6097	182.91	0.336	7.1	0.403
11 kW	801.1	19853.0	32331	969.93	0.404	8.3	0.484
η=98%							
2.2 kW	129.3	3912.0	6097	121.94	0.331	10.6	0.397
11 kW	801.1	20176.3	32331	646.62	0.397	12.4	0.476
η=99%							
2.2 kW	129.3	3972.9	6097	60.97	0.325	21.2	0.391
11 kW	801.1	20499.6	32331	323.31	0.391	24.8	0.469

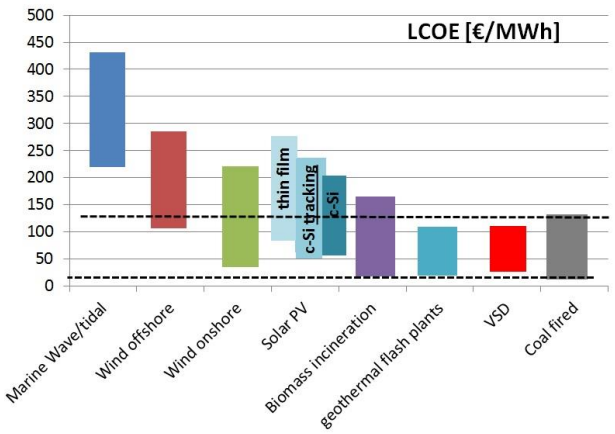

Fig. 14: LCOE index for different RES and coal fired plants

The convenience of MPE in electric energy conversion can be deduced comparing its Levelized Cost of Electricity (LCOE) for common renewable sources. The LCOE parameter is defined as:

$$LCOE = \frac{C_{dev} + C_{cap} + C_{O\&M}}{E_{annual}} \quad (15)$$

Where C_{dev} is the initial development cost, C_{cap} is the capital cost, $C_{O\&M}$ is the operation and maintenance cost and E_{annual} is the average annual energy production in the whole lifetime [27]. The LCOE index is adopted to quantify and compare the cost for different RES (excluding all subsidies and support mechanism), it represents the total lifecycle costs of producing a MWh of power using a specific technology. Usually the available data cover projects greater than 1 MW in capacity as the economics of smaller distributed generation can differ from those of larger projects and the data collection is cumbersome. Moreover, since the obtained values of LCOE vary with regions and data availability, a variation range is given [28]. The LCOE can be evaluated for Variable Speed Drives by using (15) as well. In this case E_{annual} corresponds to the saved energy. On the basis of commercial equipment it is easy to calculate that LCOE ranges from about 55 €/MWh to 82 €/MWh, it is always inside the interval defined by the coal fired plants, it

decreases as the rated power increases and the energy pay-back time is always lower than one month. In addition, some further advantages as reduced maintenance costs, reduced reactive power and reduced peak start-up current are recognizable [29].

6. Quantifying the value of PE

The contribution of power electronics can be evaluated on the basis of the fuel share of electricity generation [30]. It can be noted that in 2013 the produced electrical power has been equal to 23322 TWh of which 5.7% has been obtained by renewable as geothermal, solar, wind etc, 16.3 % by hydro plants, 10.6 % by nuclear energy, 21.7% by natural gas, 4.4% by oil and finally 41.3% by coal. Hence the amount due to renewable sources is 1329.3 TWh (5131 TWh considering also hydro). Roughly the consumption is due to electrical motor drives (60%), lighting (20%), power supply for consumers (10%) and power supply for computing (10%). About 75% of the electrical motor drives are pumps, fans and compressors. By adopting a variable speed drive instead of a throttle the saving is about 20%. Lighting can achieve a saving up to 50% with LED lamps and a further 10% of saving can be reached by improving the power supply [31]. By summing all potential saving for each categories a value of 4900 TWh is obtained. This is comparable, despite to the rough calculation, to the whole power achieved by renewables installed in the world.

This saved energy can be considered as a renewable one since it meets the renewable definition "as energy that is collected from resources which are naturally replenished on a human timescale".

The unit of power representing the amount of energy (measured in watts) saved is known as "negawatt". The term was coined by the chief scientist of the Rocky Mountain Institute and environmentalist Amory Lovins in 1989 [32]. The concept of a negawatt aimed to influence a behavioural change in consumers by encouraging them to think about the energy that they spend. In our case the negawatt production can be obtained by Power electronics as "the" key enabling technology.

Finally, considering that in 2013, the use of coal to produce 9631 TWh of electricity has caused the emission of 14807 Mt of CO_2, a saving of 4900 TWh by More Power Electronics would have avoided the dispersion of 7274 Mt of CO_2 (corresponding to a reduction of 22.6% of the total emission) in the atmosphere [30].

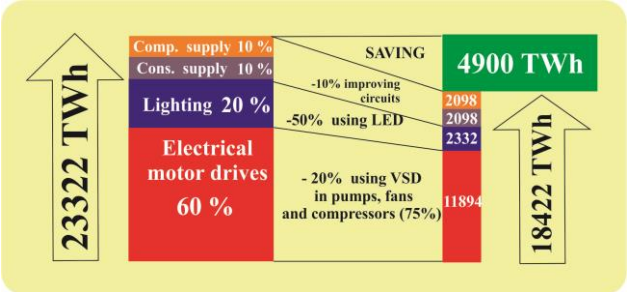

Fig. 15: summary showing energy saving potential

7. Conclusions

In this paper the contribution of power electronics as key technology to reduce the carbon dioxide emission has been discussed.

The growth of the use of Renewable Energy Sources is still slow and comparable to fossil resources; for this reason they need to be sustained by available technologies. Among these, the use of More Power Electronics for electrical energy conversion leads to increase efficiency conversion with a reduced energy pay-back time both in case of new equipment and retrofitting.

The sustainability of power electronics based solutions for energy conversion is shown, anyway these technical solutions need to be promoted at economy, public acceptance and policy levels.

Energy coming from renewables cannot be considered a mere substitute of the one obtained by fossil sources, a responsible use of this energy avoiding wastage is required to give a quick and effective answer to the increase of carbon dioxide emission in the atmosphere.

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