It is now well known that the quality of electric power is a key factor for the electricity service. It defines how good the characteristics (amplitude and frequency) of the supplied power meet the rated ones. Voltage dip (or sag) and swell, short and long interruptions, voltage spike, under and over voltage, harmonic distortion, voltage unbalance are the common power quality problems. Among these last, the harmonics issue is getting more and more important over the last decades and this trend will surely continue its race. This is essentially due to the widespread use of electronic components in electric equipment: it changes the nature of the electric loads from linear to non-linear and makes them, on the one hand, responsible for the harmonics generation in the power grid but very sensitive to the power quality problems on the other hand.

UNIVERSITÉ DU LUXEMBOURG

DISTRIBUTED HARMONIC COMPENSATION FOR POWER QUALITY IN SMART GRIDS_

Patrick Kobou Ngani, Prof. Dr.-Ing. Jean-Régis Hadji-Minaglou, Prof. Dr.-Ing. Emmanuel De Jaeger, Prof. Dr.-Ing. Michel Marso

What are harmonics?

Harmonics are voltages or currents waves of which the frequencies are integer multiples of the fundamental frequency; this means, for a grid with the fundamental frequency of 50 Hz, the fifth and seventh harmonic frequencies would be 250Hz and 350Hz respectively. A harmonic distorted waveform will no longer be a pure sine wave. It is important to mention that harmonics are generally considered as a steady state phenomenon and therefore not to be confused with spikes, dips and other forms of transient events.

Causes and effects of harmonics

As mentioned before, harmonics are produced by non-linear loads that draw non-sinusoidal currents. Their main characteristic is actually that the waveforms of the drawn current is not purely sinusoidal, even if they are fed by a perfect sinusoidal voltage. A distinction can be made between two groups of non-linear loads: The "modern" non-linear loads including energy converters based on power electronic components and the "classical" non-linear loads not related to the power electronics but, for instance, to:

_Transformers
_Rotating machines
_Fluorescent lamps with magnetic ballasts
_Arc furnaces
_Welding machines

Already in use for many decades, these loads rely on the magnetization effect where they operate near the knee of the saturation curve of the material (of which the magnetic characteristic is not linear). There are also arcing devices; their operating voltage-current characteristics are extremely non-linear.

"Modern" non-linear load are for example:

_Inverter fed AC voltage sources
_Adjustable speed drives (ASD)
_Energy-efficient lighting
_DC converters

These appliances are based on semiconductors devices like diodes, IGBT's, GTO's. The different generated harmonics (frequency and amplitude) depend on the topology, design and operating principle of the switching circuits. For example, a 6-pulse rectifier will cause harmonic at the 5th, 7th, 11th, 13th, etc. order. In this case, the amplitude of each harmonic is estimated to be inversely proportional to the harmonic order). The one generated by the 12 pulse rectifier are the 11th, 13th, 23th, 25th, etc. with amplitudes of about 10 percent of those for the 6-pulse rectifier [1]. Generally, line-commutated devices (such as the ones mentioned before) will also have harmonic characteristics different from those of forced commutation devices (such as PWM converters)

The major effects generated by the harmonics are resonance, increase of RMS voltage and current values and excessive neutral currents [2]. These may have as direct consequences:

_Overheating of equipment and grid components,
_Malfunction of circuit breaker,
_Capacitor damage,
_Malfunction or damage of sensitive electronic equipment,
_Motor shaft torque perturbation,
_Equipment lifetime shortening,
_Noise in communication signals.

On a second level, once an equipment is damaged, part of the whole power supply can be interrupted and most of the time it's only at this stage that the harmonics distortion problem is visible.

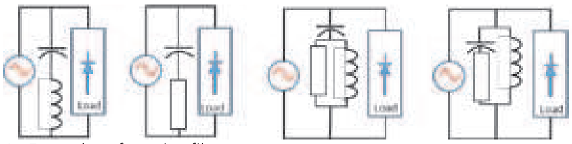
The economic impact due to these material-related effects, which can lead to power outages, is very big. The digital economy (data storage, retrieval and processing), the continuous process manufacturing (paper, oil, clay, steel, glass) and the fabrication and essential services (railroads, wastewater treatment) are the three sectors most sensitive to the power quality problems [3].

In the USA, they are collectively losing 6.7 billion dollars every year due to the power quality disturbances [3]. A survey realized by the Electric Power Research institute (EPRI) reveals that the harmonics are the source of 22% of all the power disturbances [4].

Harmonics mitigation technics

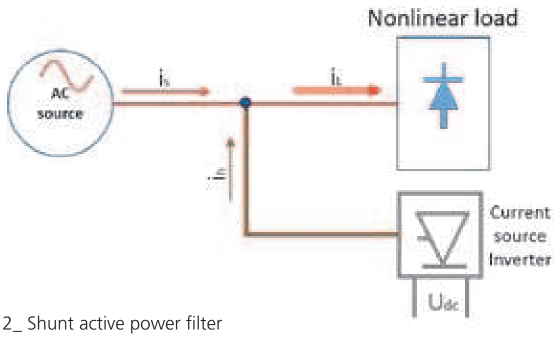
Many solutions have been developed to overcome the problem of the harmonic pollution [2] [5] [6]:

_Passive power filters (PPF): They are based on combining passive electrical components like inductances and capacitors to obtain a specific resonance frequency that counteracts a chosen harmonic frequency. Due to their proven efficacy and low cost, they are widely used in industry. Because they are built up from specific elements they are hardly adaptable and the combination of more passive filters creates a resonance phenomenon between the filters that can cause the destruction of the filters elements.

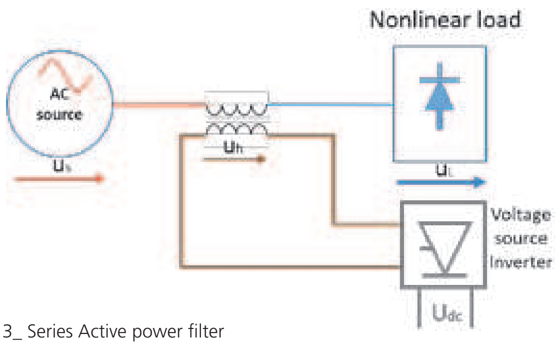


1_ Examples of passive filters

_Active power filters (APF): Based on controlled power inverters working as current or voltage sources, they create, in parallel (shunt APF) or in series (Series APF), harmonic currents or voltages in the power grid that are in opposition to the existing harmonics. The main advantages for APFs compared to PPFs is their better harmonics attenuation efficacy and their adaptability to the system changes (harmonic amplitude and frequency). They are also able to compensate more than one harmonic order without leading to the resonance problem. In contrast the use of power electronics (Semiconductors, current and voltages sensors, microcontroller) makes them quite expensive and the high switching frequency creates HF disturbances and noise that also needs to be eliminated through additional filtering.

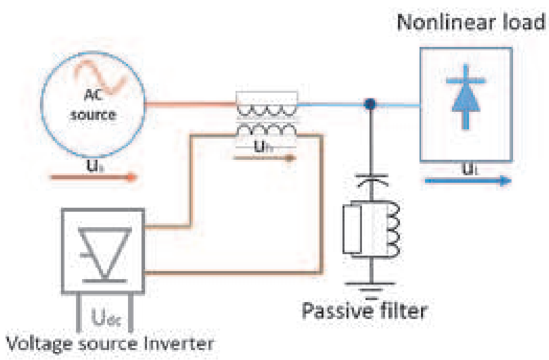


2_ Shunt active power filter

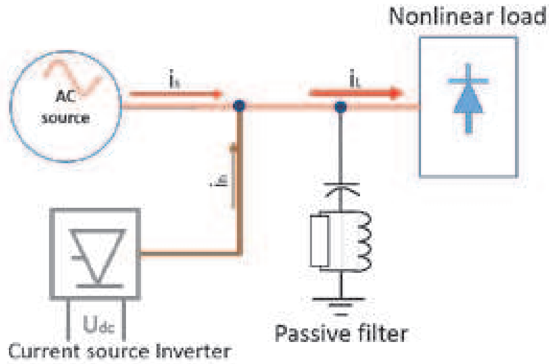


3_ Series Active power filter

_Hybrids power filters: They benefit of the advantages of PPFs and APFs with improved performance and cost-effective solution. The harmonic mitigation task is shared between the APF and the PPF. The most common task distribution is to let the APF filtering the harmonics of lower frequency, while the PPF filters the high frequencies harmonics.



4_ Hybrid series active filter

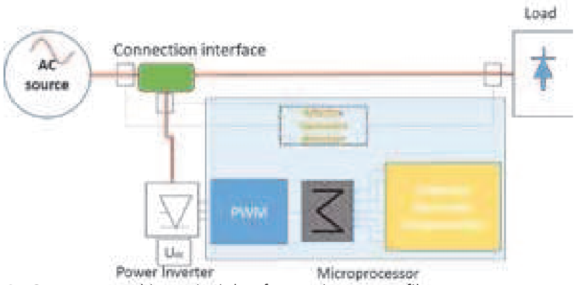


5_ Hybrid shunt active filter

The project at the University of Luxembourg

An original active power filter concept is now under development in the Research Unit in Engineering Science of the University of Luxembourg. The filter helps the supply voltage of the grid it is connected to, to meet the harmonics requirements defined by the European standard on the electric power quality EN50160. The developed APF is therefore a voltage harmonics filter because the standard focuses only on the utility grid voltage; guidelines for current waveform characteristics being almost impossible to realize due to the individual intrinsic functional behaviour of each electric equipment.

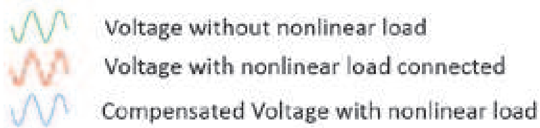
Figure 6 presents the drive (in an electrical cabinet shape), as a conventional active power filter with the selective harmonics detection and compensation ability of the filter. Synchronized to an existing power grid that supplies a non-linear load, the filter is a pure power conditioning element: it generates and injects into the grid the inverse of the harmonics generated by the load so that the resulting waveform has a lower harmonic distortion (due to those not compensated by the filter).



6_ Common working principle of an active power filter

The system, besides the ability to work as a conventional APF, has dedicated specifications that make it work as:

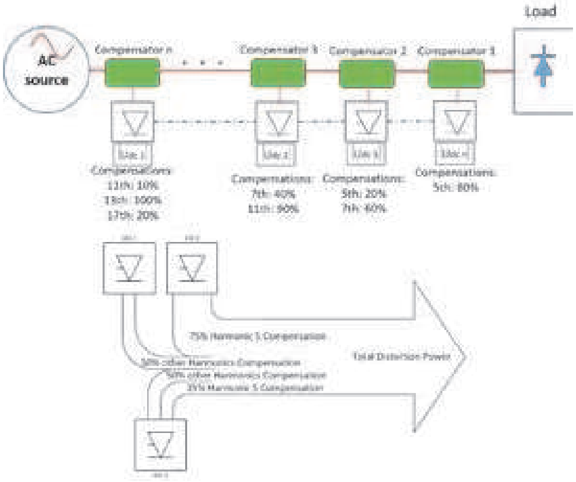
_An auto-compensated power voltage source or backup power supply:
In an off-grid situation, electrically fed by any renewable energy source (photovoltaic, wind or hydro turbine), the filter does not only provide the rated power system voltage and frequency (230V and 50Hz) but also removes the possible harmonics that might have been caused by any non-linear load connected on the local grid. The inverter generates an output voltage being a distorted waveform so that, combined with the harmonic distortion created by the non-linear load, the resulting waveform tends to a pure sine wave.



7_ Power inverter as voltage source with harmonics compensators

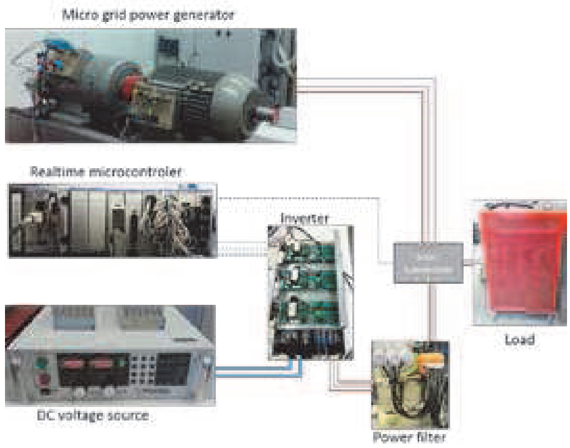
_A part of an harmonics compensators network:
Having the feature of a selective compensation, one can figure out a global compensation work done by a number of interconnected filters connected on the same power grid. For example, tied on the same grid and having

different renewable power sources available, two filters could cooperate to improve the power quality. The first will mitigate only 50% of the 5th harmonics and the second, with more power available, will removes the other 50% of the 5th, 100% of the 7th and only 20% of the 11th harmonic.



8_ Interconnected APFs (top) for a distributed harmonics compensation (bottom)

Figure 9 illustrates the actual state of the test rig used for the fulfilment of the project. The central element is the microprocessor: the CompactRio realtime microcontroller of National Instrument (NI). It's a reconfigurable, embedded, modular acquisition and control system that includes a reconfigurable FPGA chassis and a real-time controller programmable in the NI LabVIEW programming language. The grid-fed DC voltage source is used to simulate the power supply from renewable sources. The power inverter, fed by the DC voltage source, is a 15 kHz IGBT-based inverter. The passive power filter is used to eliminate the high switching frequencies of the inverter from 4 kHz on, i.e. there is no low-frequency harmonics mitigation by this filter; neither the ones created by the load nor the compensation's frequencies generated by the inverter.



9_ Current test rig at the University of Luxembourg

A MATLAB simulation with concluding results has already been done for a resistive non-linear load. The simulated model will be extended to the most realistic resistive-inductive and capacitive load. Meanwhile, the implementation of the core elements on the test rig for real-time operation has started: Sensors data acquisition, voltage source inverter command by a pulse width modulation (PWM), numeric filters. Different compensation methods (algorithms) will be tested to determine, according to different goals (compensation dynamic, efficacy, adaptability to load changes), which one is the most appropriate.

This project contributes to the evaluation of the technologic, energetic and economic costs of the harmonics compensation with respect to the current quality standards, taking into consideration the evolution of the power generation systems trending to low power distributed units as well as the consumption systems made of numerous and multiple small electronic devices (TV's, smartphones, computers, teeth brushes etc.).

Abbreviations

APF:	Active Power Filter
CSI:	Current Source Inverter
PPF:	Passive Power Filter
PWM:	Pulse Width Modulation
VSI:	Voltage Source Inverter

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References

1_R. G. Ellis, „POWER SYSTEM HARMONICS. A Reference Guide to Causes, Effects and Corrective Measures," Rockwell Automation, 2001.

2_C. Surajit, M. Madhuchhanda und S. Samarjit, Electric power Quality, Springer, 2011.

3_David Lineweber und Shawn McNulty, „The Cost of Power Disturbances to Industrial & Digital Economy Companies," Primen, 2001.

4_Sharmistha Bhattacharyya and Sjef Cobben, „Consequences of Poor Power Quality – An Overview," In Tech, 2011.

5_Zainal Salam, Tan Perng Cheng und Awang Jusoh, „Harmonics Mitigation Using Active Power Filter: A Technological Review," Elektrika, Bd. 8, Nr. 2, pp. 17-26, 2006.

6_Hirofumi Akagi, „New Trends in Active Filters for Power Conditioning," IEEE Transactions on Industry Applications, Bd. 32, Nr. 6, pp. 1312 - 1322, 1996.