Power Quality Management of LED Light Sources in Frequency Domain

Péter Görbe*, Attila Magyar, Péter Csuti

Department of Electrical Engineering and Information Systems, Faculty of Infomation Technology, University of
Pannonia, Hungary
gorbe.peter@virt.uni-pannon.hu

A control method for improving the power quality in low voltage network contains mainly LED Light Sources with simple nonlinear switching power supply is described in this paper. This method implements active power factor correction and lowers the voltage and current extant harmonic distortion in the line. The novel element in the proposed structure is the upper harmonic controller that minimizes the amplitudes of the 3rd, 5th 7th, 9th, and the 11th upper harmonic component in the output voltage using Asynchronous Parallel Pattern Search Method in Frequency Domain. The proposed controller has been investigated by simulation in Matlab environment, and as a result, substantial improvement of the output voltage and current waveform could be achieved. The total harmonic distortion of the voltage and the current has also been radically reduced. This reduction helps to decrease the power loss in the phase conductor, and more radically in the neutral conductor of the transportation line. In the case of production the electric power from fossil sources, it decreases the greenhouse gas emission, what will also decrease the environmental and social-welfare effects of the climate change.

1. Introduction

Nowadays the price of electric energy is raising and many people are making up their minds to lower the emission to save the environment and to lower their cost of living. The first step is to lower the electric consumption of the used electrical devices. Many manufacturers reconstruct and develop their product to compliance the new standards, for example the appliances' standby energy consumption. In practice in our household the first step is to lower the energy consumption to replace the traditional (incandescent) light sources to modern ones, like Compact Fluorescent Lamps (CFLs) or retrofit LED (Light Emitting Diode) lamps. The European Union supports this method by legislation of the prohibition of the trading with light sources with energy efficiency class C or above what means that the traditional incandescent lamps (usually with energy efficiency class E - G) cannot be sold any more. This accelerated the spread of alternative light sources (mainly CFLs) because of their reasonable price relative to their total luminous flux. The last years' LED technology development increased the number of the LED lamps used in households. Those lamps are using - similar to CFLs - simple nonlinear Direct Current (DC) stage to drive the LEDs built inside. These types of applications cause serial distortion in low voltage transformer areas.

On the other hand small domestic power plants are general into use in small scale applications (1 kW-5 kW). In many countries the national law of power supply has been changed in recent years to give possibility for using grid tie inverter systems to inject the spare power to the local low voltage mains. The power injection of these inverters also cause a distorted current shape (Martínez-Patino et al., 2012). This power is utilized in the local neighbourhood, not far from the injection point so the transportation loss is small. In addition, the construction of this type of inverters makes them suitable for conditioning the line, correcting the accurate voltage forms, and repairing the reactive power in the mains. Therefore, this additional functionality doesn't need expensive change of the constructions; we should only modify the control methods and regulators to develop the ability of line conditioning. The cost of changing the controlling processor and control software is negligible to the cost of equipment.

Several papers deal with power injection to the grid; see e.g. (Carrasco et al., 2006) for a recent survey. The possibility of power factor correction in conjunction with power injection has also been realized (Lo et al., 2008), on the other hand, the nonlinear case has been investigated (Cerdeira et al., 2004). Furthermore, its connection with nonlinear distortion reduction has also been explored (Limongi et al., 2009). In this article the authors use the DSP based current control technique for distortion reduction with active power filters (APF) for compensating an exact nonlinear load. Sensing the nonlinear current time function and the ideal sinusoid current with phase locked loop (PLL) technique, they inject the exact deviation current into the grid with radical distortion reduction. This type of nonlinear power sources can be compensated with careful electronic design (for example Active Power Factor Correction, APFC) but it causes non-competitive price.

The aim of our work has been to develop and investigate control methods and devices for performing active power factor correction and lowering the extant harmonic distortion in the line without the need for current measurement. As our earlier paper (Görbe et al., 2009), and its further developed version (Görbe et al., 2010) show, this aim can be achieved in addition to control the maximum power operating point from the renewable source (wind generator or photovoltaic panel) by adding new elements to the schematic construction designed for the built-in elements. It shows the possibility to compensate effects of the nonlinear distortion if a Grid-tie exists in the household. If there is not, we can place a single special electronic ballast into system without any reconfiguration of the cable structure, and no needed additional current sensors to detect the accurate distortion or time function of the electronic loads in the building or building blocks.

2. Background and motivation

The use of low consumption equipments with simple switching power supplies (in our case the LED light sources, but mobile phone chargers, notebooks, networking products, small variable frequency motor drives, telecommunication consumer electronics also) is more and more widespread nowadays. These equipments use a simple performance input configuration that is a capacitive load with high nonlinearities (Diode Bridge).

These appliances create significant 3th and 5th upper harmonic current components, which cause serious distortion in the voltage shape. It is well-known (Görbe et al., 2011), that it is difficult to compensate the reactive power of this type of nonlinear distorted voltage shape with traditional shunt capacitances (compensator).

The distortion of the voltage shape is commonly characterized by the total harmonic distortion (THD) is defined as (Cerdeira et al., 2004):

$$THD = \sqrt{\frac{\sum\limits_{k=2}^{\infty}(|V_k|^2)}{|V_1|^2}}$$

(1)

where V_1 equals to the voltage amplitude of the fundamental frequency and V_n is the voltage amplitude of the n-th harmonic. In applications with capacitive input stage, $THD > 0$ holds.

This type of distortion occurs in every mains plug in every home. In the near future this distortion, this nonlinear reactive power and the THD will probably increase because of the growing rate of simple switching type power sources in household appliances.

Upper harmonic components have many undesirable effects on power grid (Görbe et al., 2010) causing faulty operation of the network:

- Temperature increase in phase conductor,
- Temperature increase in 0 conductor,
- Skin effect,
- Unwanted erase of breakers,
- Unwanted resonance with compensating capacitances (Standard Power Factor Correction),
- Overload of transformers (hysteresis losses frequency square dependence, current loop in delta transformers).

Light Emitting Diodes are rapidly evolving light sources. Increasing luminous efficacy and long lifetime make them suitable to be used for lighting in rural villages. Unlike other technologies, LEDs started showing their applicability in lighting in developing countries before coming to the markets in developed countries. Nowadays, thanks to rapidly developing Solid State technologies, the use of LED light sources

increases widely in almost all lighting application areas to ensure sustainability in terms of energy efficiency.

We examined the electrical behavior several types of light sources (from Bulbs through CFLs to LEDs) in a low voltage network with approximately 3 % distorted voltage shape. Our measuring results show power factor values from 0.4334 to 0.999, and the current total harmonic distortion varies from 2.7 % to 192.7 %. The exact measuring of the optimal and the worst case results can be seen in Figure 1. The 192.7 % value is rather alarming, spreading this type or similar electrical designed ones, can rather make the low voltage network nonlinear.
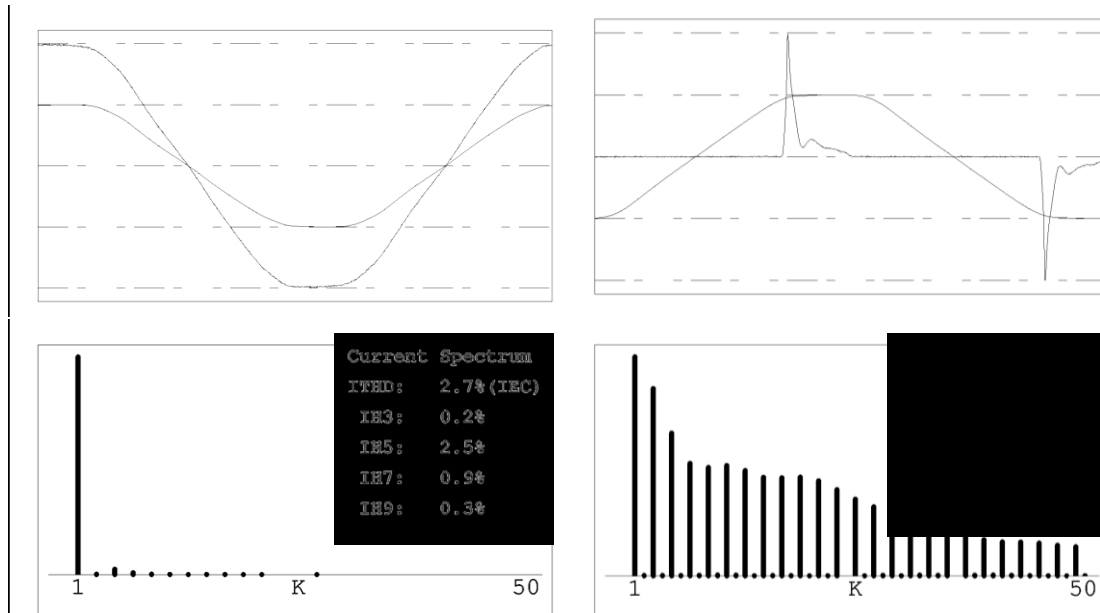

Figure 1: 40 W incandescent lamp (left) and 4 W LED lamp (right) measured values (PF2010 Digital Power Meter)

3. Problem statement

As it is indicated in the above discussion, it is desirable to develop a control method that can compensate the distortion caused by the capacitive nonlinear load using the built-in and available controller of electric car battery charger combined with small domestic power plants (Görbe et al., 2011), causing calculated carbon footpint reduction of an average household (Görbe et al., 2012), with temperature dependent polynomial battery model Göllei et al., 2011) or a separate electronic compensator containing a new controller inside.

The function of this controller that is to be implemented is the compensation of the undesirable effects of the linear network with production base harmonic current being not in phase, by injecting reactive power to compensate the inductive and capacitive loads. The new function to be implemented would be the compensation of the nonlinear distortion that is achieved by injecting upper harmonic sinusoid current components to reduce the harmonic distortion and to lower the reactive power of the upper harmonic load currents. The main goals of the new elements are to approach unity power factor for the overall system for the range of the possible loads and to reduce THD. There is a trade-off between these goals that should be taken into account. The intervention to these factors is limited by the semiconductors of the bridge and the serial inductances, as well as by the speed and cycle time and the computational capacity of the control device. The optimum would be to have a unit PF and zero THD, but unfortunately, this optimum is not achievable in practice, just approachable. The practical aim is to compensate the upper harmonic component. These values will be used to reduce the nonlinear distortion at the output.

3.1 Structure of the controller

An application of a modified simple model of the grid tie inverter (Lo et al., 2008) is used for the controller structure design, but it doesn't contain booster stage but an IGBT bridge, connected to the grid through serial inductance.

The control system is divided to main functional parts as shown in Figure 2 using shadowed boxes.

1. Intermediate voltage controller

   It senses the intermediate voltage, and observes the difference between the measured and the setpoint value. The controller changes the fundamental harmonic amplitude of the injected current using a simple P controller based on the difference. Upper harmonic components have no effect on the intermediate voltage so they are not used by the upper harmonic controller. The controller adjusts the effective power injection to the grid in each 20 ms cycle.

   The measuring device analyzes the investigated part of the network. It measures the assigned voltage or current of the circuit and calculates the 3rd and 5th upper harmonic component amplitude and phase of the distorted shape variables using Fourier transformation. The frequency domain behavior of the currents and voltages are monitored at an assigned point by measuring the inverter's output voltage and calculating the amplitude and phase of the 3rd, 5th, 7th, 9th and 11th harmonic components.

2. Upper harmonic controller

   The main controller of the complex multi-functional unit is the upper harmonic controller. Its inputs are the computed 3rd, 5th, 7th, 9th and 11th upper harmonic component amplitudes of the measured voltage, the outputs are the output current base, and its 3rd, 5th, 7th, 9th and 11th upper harmonic components' amplitudes and phases. These currents are used for compensating the nonlinear distortion (see later in sub-section 3.2).

3. Current waveform generator

   This block calculates the necessary exact time function of the output current setpoint, which is the setpoint of the bridge current controller.

4. Bridge controller

   It calculates the difference between the measured output current and the output current setpoint, and switches the IGBT bridge two half's control signal (S1-S4, S2-S3) on and off in alternate way using a simple Schmitt trigger comparator, that realizes a simple on/off switching hysteresis controller (Limongi et al., 2009). The same compromise has been made between the output current deviation amplitude, the switching frequency of the IGBT bridge (switching time, dissipation), and the output serial inductance value (price and ohmic loss of inductance) as before.

The above blocks influence each other directly, and also through some measurable voltages and currents of the inverter (see Figure 2.).
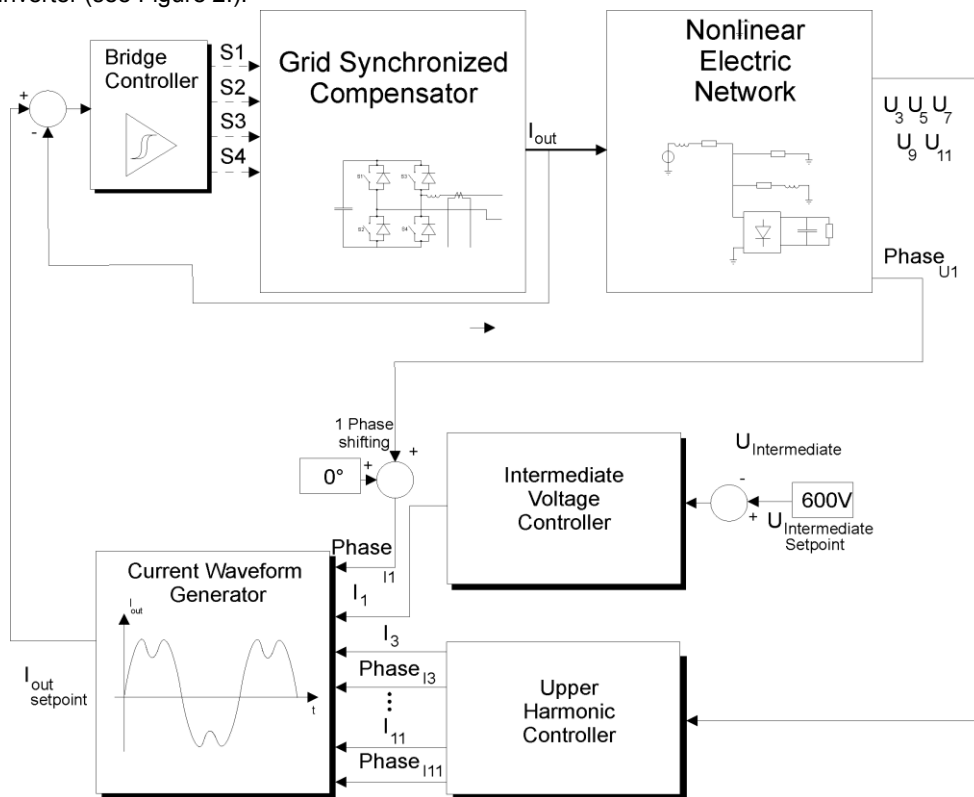

Figure 2: Control Flow Chart diagram

3.2 Nonlinear distortion compensation

The upper harmonic controller calculates the necessary optimal amplitudes and phases of the 3rd, 5th,7th, 9th and 11th injected current components. A simple static optimization algorithm is used for this purpose that minimizes the following error function:

$$Error = \sum_{i=3,5,7,9,11} (U_{i\,ampl} - U_{i\,amplSP})^2 \tag{2}$$

where $U_{i\,ampl}$ are the amplitudes of the 3rd, 5th,7th, 9th and 11th output voltage component, $U_{i\,amplSP}$ are the setpoints, respectively in steady-state conditions. The setpoints are set to zero because we would like to reach or approach the zero 3rd, 5th, 7th, 9th and 11th amplitude to approach the sinusoid voltage and current shape of a linear system.

It is important to note, that by changing the amplitudes and phases of any of the investigated output current components, each one influences all components of the connection point voltage because of the high nonlinear nature of the network.

It is also important to remark, that we use the odd upper harmonic components up to the 11th despite of the fact that the distortion is present mainly in the 3rd and 5th but higher upper harmonic components too. The reason for this lies in the experiences with our earlier simple method (Görbe et al., 2009) that showed that the compensation algorithm pushed the distortion towards the higher upper harmonic components that were orthogonally not affected. The equation system, describing the behavior of our low voltage network, is nonlinear, and isn't differentiable, that's why we used a version of the gradient descent method (Hough et al., 2001), where the ten optimization variables are the amplitudes and the phases of the 3rd, 5th 7th 9th and 11th upper harmonic component. Due to the interaction of the high upper harmonic components we used an asynchronous parallel pattern search method, where the variables are changing after each other. An optimization cycle consists of six steps where each of the above parameters are changed in turns in the direction of its parameter gradient. This way the parameters of the upper harmonic controller converge to a value in the ten dimensional parameter space that corresponds to the minimal error function value.

4. Modeling and simulation

The mathematical model of the nonlinear distorted network has been implemented in Matlab Simulink using the Power Electronics Toolbox (Matlab, 2013).

4.1 Modeling the nonlinear network

Three type of loads have been modeled: (i) an ohmic one, that represents, for example, heating devices, traditional bulbs, (ii) an ohmic with serial inductance representing motors and rotating household appliances (washing machine, lawnmower etc.) and (iii) a capacitive input stage load for representing the LED light sources (nonlinear $R = 104\Omega$ $C = 1,300\mu F$ equal 250 pieces of the investigated 4 W LED lamps, simulated THD_I = 193% at THD_U = 3%)

4.2 Modeling Controller

The most important part of the model is the upper harmonic controller, which realizes the ten variable asynchronous parallel pattern search method.

4.3 Simulation experiments

The performance values of the simulation results can be seen in Table 1. It can be seen that the operation of the upper harmonic controller can lower the THD_U from 14.7 % to 6.54 %, the THD_I from 63.24 % to 20.17 % while the error function radically decreases from 47.03 V^2 to 3.87 V^2. This means that the power loss has been successfully reduced on phase conductor and the zero conductors too.

Table 1: Performance results

Mode	Error	THD_U	THD_I
Upper h.contr. OFF	47.03 V^2	14.75 %	63.24 %
Upper h.contr. ON	3.87 V^2	6.54 %	20.17 %

5. Conclusions and future work

A novel nonlinear compensation concept is described in this paper. It is capable of implementation active PF correction and lowering the extant harmonic distortion in the line without sensing the current of the nonlinear load. There is no need to restructure the wiring in a mixed linear and nonlinear loads case and

decrease the power loss on the phase and zero conductor in symmetrical load case too. One central unit can compensate a building or building block.

The proposed controller has been investigated by using Matlab simulation, and a substantial reduction of the THD could be achieved. In our application it is possible to reduce voltage THD almost as much as current THD in (Limongi et al., 2008), with performing voltage measurement instead of current measurement at the connection point. In addition, it has been shown that the proposed upper harmonic controller is capable of reducing the power loss of the line. This type of distortion reduction can be translated to CO_2 emission reduction (Görbe et al., 2012) Taking into account the proportion of power currently generated by fossil fuels in Hungary (coal 17.3%, gas 38.3 %) and the rate of CO_2 emission during electric energy production (,1000 g/kWh from coal and 430 g/kWh from gas), we can conclude that nonlinear distortion compensation could reduce CO_2 emissions by 1.458 g/kWh.

Our future aim is to investigate parametric robustness and disturbance rejection of the proposed controller. Another possible future direction is the implementation and experimental analysis of the proposed control structure.

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