Monitoring and Compensation of Harmonics in Smart Grid

Dejan Stevanović, Marko Dimitrijević, Miona Andrejević Stošović,
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Abstract - In this paper we will try to present the current state concerning monitoring and compensation of harmonics in smart grid. We will discuss the existing harmonic detection techniques, and present harmonic reduction techniques that are usually used. We will give some measured results that will show that existing techniques are not good enough, suggesting that new techniques should be proposed.

Keywords -Compensation, Filters, Harmonics, Monitoring, Smart Grid.

I. INTRODUCTION

Nowadays, when electronic devices became ubiquitous, we are witnessing changes in the demand and energy use. It is presumed that the overall household consumption for electronic appliances will rise with a rate of 6% per year so reaching 29% of the total household consumption in the year 2030. In the same time, the household consumption is expected to reach 40% of the overall electricity demand. The immense rise of the office consumption due to the enormous number of computers in use is also to be added. That stands for educational, administrative, health, transport, and other public services, too. One may get the picture if one multiplies the average consumption of a desktop computer (about 120 W) with the average number of hours per day when the computer is on (about 7), and the number of computers (billion(s)?)[1].

Also, efficiency of electrical distribution is rarely planned or managed by utilities. The unfortunate result is that most utilities waste substantial amounts of electricity. In fact, annual electricity transmission and distribution losses average 6% in the European Union (assuming that 2% is for transmission and 4% is for distribution losses) [2]. That represents 7 billion Euros in energy wasted every year in distribution. This number includes losses in the medium and low voltage lines and in primary and secondary substations. Many countries have brought the law that demands from utility to reduce the losses for 1.5% each year [2].

Understanding grid losses, their origin and determination, is important considering energy efficiency and grid regulation. These losses can be classified as *technical losses* and *non-technical losses.*

Technical losses are the result of the inherent resistance of electrical conductors, which causes electrical energy to be transformed to heat and noise whenever current flows through them. This is usually referred to as 'physical (or ohmic) losses'. Technical losses vary with the level of utilization of the network capacity, i.e. the quantity of electricity being transmitted/distributed. In particular, they are proportional to the square of the current. As a result, transmission networks experience a lower level of losses because at higher voltages a lower current is required to transmit the same amount of electric energy. Conversely, distribution networks (at lower voltages) are subject to a higher level of losses.

On the other hand, non-technical losses comprise electricity that is delivered mostly for consumption but which is not paid for. They are mainly caused by in-house consumption (also known as "hidden" losses); the illegal abstraction of electricity (energy theft); non-metered supplies (such as public lighting); as well as errors in metering, billing and data processing. Additionally, there are errors resulting from the time-lag between meter readings and statistical calculations. According to Schneider Electric about 90% of non-technical losses occur in the medium and low voltage (MV/LV) grid. It is assumed that they range between 1.000€ to 10.000€ per MV/LV substation per year in European countries [2]. This brought MV/LV grid at the top of the priorities for loss reduction.

In order to reduce the level of losses at a power grid, many different approaches exist, some of which are published in [2]. In this paper, we will consider non-technical losses.

The first step in cutting the losses is to monitor and to detect their sources. This request was hardly feasible and very expensive in the past. Fortunately, that is not the case today. Smart meters give inexpensive and precise insight into the current status of particular parameters of the grid. They allow the utility to measure many parameters that define quality of the delivered electric power. Unfortunately, due to the inertia of the acceptance of facts, some decisions affecting the power system are not timely made.

The most obvious misconception is related to

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understanding the character of consumers connected to the electricity grid. The standpoint of the power grid measurement theory assumes that all loads are entirely linear resistive or reactive. This implies that the current follows voltage sine waveform (with possible phase lead or lag at reactive loads). In general, for centuries the loads in households were basically resistive (heaters, incandescent light) while in industry they usually have large inductive character (AC motors). Consequently, it was sufficient that power meters register only active power in households and/or reactive power with industrial customers. However, the character of loads has been drastically changed since the last quarter of the 20th century. Namely, electronic loads nowadays are strongly related to the power quality thanks to the implementation of AC/DC converters that in general draw current from the grid in bursts. The current-voltage relationship of these loads, looking from the grid side, is nonlinear, hence nonlinear loads. In fact, while keeping the voltage waveform almost sinusoidal, they impregnate pulses into the current so chopping it into seemingly arbitrary waveform and, consequently, producing harmonic distortions. Having all this in mind the means for characterization of the load from the nonlinearity point of view becomes one of the inevitable tools of quality evaluation of smart grid.

Due to the nonlinearities, measurement of power factor and distortion, however, usually requires dedicated equipment. For example, use of a classical ammeter will return incorrect results when attempting to measure the AC current drawn by a non-linear load and then calculate the power factor. A true RMS multi-meter must be used to measure the actual RMS currents and voltages and apparent power. To measure the real power or reactive power, a wattmeter designed to properly work with non-sinusoidal currents must be also used.

In this paper, we will first give some existing solutions (...), and after that we will propose how to upgrade the meters and billing policy in order to reduce economic losses at utility [3]. We will also propose a measurement system in order to establish a comprehensive picture about the properties of a given load, i.e. to perform complete analysis of the current and voltage waveforms at its terminals. In that way the basic and the higher harmonics of both the current and the voltage may be found.

II. HARMONIC DETECTION AND MEASUREMENT

In linear circuits, consisting of linear loads, the currents and voltages are sinusoidal and the power factor effect arises only from the difference in phase between the current and voltage. When nonlinear loads are present one should introduce new quantities in the calculations emanated by the harmonics and related power components. Now the power factor can be generalized to a total or true power factor where the apparent power, involved in its calculations, includes all harmonic components. This is of importance in characterization and design of practical power systems which contain non-linear loads such as rectifiers, and especially, switched-mode power supplies. Phase difference between current and voltage, as well as harmonic distortion has negative impact on distribution system.

Since the problem of distortion becomes ubiquitous, it can be either observed at the distribution system level, or one has to take local measurement of the properties of this kind of loads.

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In recent papers [4], a new approach to polyphase load analysis is presented: system for nonlinear load characterization which is flexible, scalable, with advanced options.

This solution brings all benefits of virtual instrumentation, keeping main advantage of classical instrument – determinism in measurement. The hardware component of the system is implemented using field programming gate array (FPGA) in control of data acquisition. The software part is implemented in two stages, executing on real-time operating system and general purpose operating system. Described realization provides possibility for calculating a large number of parameters that characterize nonlinear loads, which is impossible using classical instruments. This is of great importance particularly in calculation of alternate definitions of reactive power. The system is scalable; it can be upgraded in number of calculated parameters, as well as in number of independent measurement channels or functionality. The system is open; it can be modified to be a part of harmonic compensation circuitry or aimed for hardware-in-the-loop simulations. The system is flexible; it is implemented on different platforms for different purposes: as laboratory equipment for real time measurements (PXI controller equipped with PXI-7813R FPGA card and expansion chassis), as compact industrial device for real time operation (installed on programmable automation controller) or simple portable instrument equipped with computer interface. It consists of three subsystems: acquisition subsystem, real time application for parameter calculations and virtual instrument for additional analysis and data manipulation.

Acquisition subsystem consists of acquisition modules for A/D conversion, FPGA circuit and interface for computer or programmable automation controller. A/D resolution is 24-bit, with 50 kSa/s sampling rate and dynamic range ±300 V for voltages and ±5 A for currents. Function of FPGA circuit is acquisition control and harmonic analysis.

Real time application calculates power and power quality parameters deterministically and save calculated values on local storage. The application is executed on real time operating system.

Virtual instrument for additional analysis and data manipulation represents user interface of described system. It runs on general purpose operating system, physically apart from rest of the system. Communication is achieved by TCP/IP. Parameters and values obtained by means of acquisition and calculations are presented numerically and graphically.

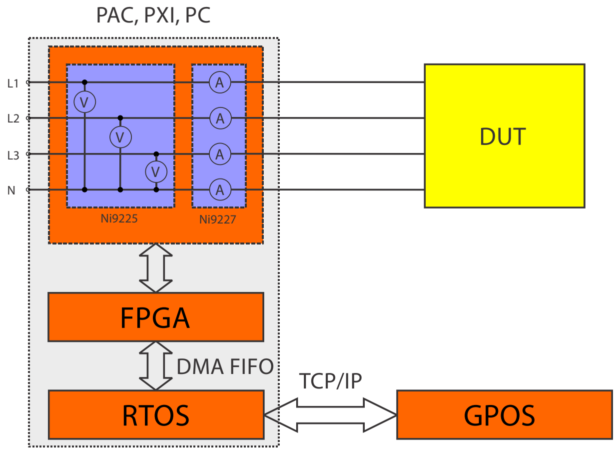

Fig. 1 System architecture

III. HARMONIC REDUCTION TECHNIQUES

The permanent growth of the number and types of nonlinear loads aggravates the problems caused by harmonics. That enforced almost every country to introduce its own standard that restricts the allowed amount of each harmonic. Two widely known standards in this area are the IEEE 519-1992 and IEC 61000 series. The both standards regulate limits for the harmonics pollution but do not specify what happens if a customer exceeds them. There are two possibilities: the first suggests that the utility could disconnect that customer, but that is stressful and not profitable solution. The better way and the most effective tactic is to charge the harmonics producers a penalty tax if they exceed limits of harmonics pollution. The penalty tax should be proportional to the pollution levels. However, the tax driven regulation may be obstructed by two technical problems: the identification of the harmonics producers, and isolation of the system from the effects of impedance variation.

The harmonic mitigation at power system can be solved in two ways that can be divided to preventive and corrective. The preventive solution includes: phase cancellation or harmonic control in power converter and developing procedure and methods to control, reduce or eliminate harmonic in power system equipment; mainly capacitor, transformers and generators.

If harmonic isn't eliminated at load's level, then some of corrective techniques must be used to reduce existing harmonics at power grid. The corrective techniques are based on few different types of harmonic filters. Traditionally, passive filters have been used but some problems are associated with them. A passive filter consists of a series circuit of reactors and capacitors. Harmonic currents generated by, for example, a frequency converter are shunted by this circuit designed to have low impedance at a given frequency compared to the rest of the network. Figure 2 illustrates schematically the described function with a harmonic generator, impedance representing all other loads, a filter and a network.

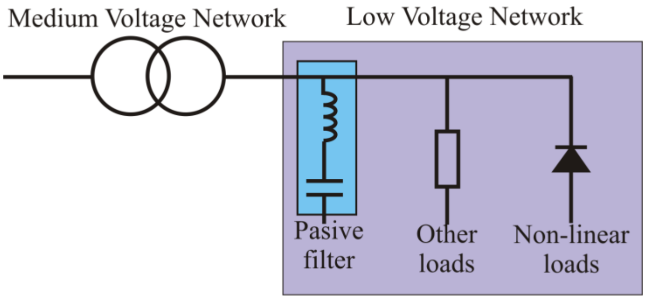

Figure 2. Passive filtering of harmonic

As the passive filters offer very low impedance at the resonance frequency, the corresponding harmonic current will flow in the circuit whatever its magnitude. Passive filters are then easily overloadable under which condition they will switch off or be damaged. The overload may be caused by the presence of unforeseen harmonics on the supply system or be caused by structural modifications in the plant itself (such as the installation of a new drive). Passive filter provides always a certain amount of reactive power. This is not desirable when the loads to be compensated are AC drives which have already a good power factor. In that case the risk of overcompensation exists as a result of which the utility may impose a fine.

The degree of filtering of the passive filter is given by its impedance in relation to all other impedances in the network. As a result, the filtration level of a passive filter cannot be controlled and its tuning frequency may change in time due to ageing of the components or network modifications. The quality of the filtration will then reduce. It is also important to note that a passive filter circuit may only filter one harmonic component, so a separate filter circuit is required for each harmonic that needs to be filtered.

Fortunately the number of manufacturers being aware of the problems caused by their product increases. So, they try to improve their product using different filtering methods in order to reduce value of generated harmonics. For example, most of Phillips branded LED use the Valley-fill circuit [5, 6]; Toshiba lamp contains a passive filter [7, 8], while Osram decides to embed an active filter [7, 8].

Despite the used filter the current of these loads is not sinusoidal [7]. In order to overcome the problems associated with traditional passive filters and in order to answer to the continuing demand for a good power quality, active filters for low voltage applications are developed.

The principle of active filtering is fundamentally different from that of the passive filter. It was noted previously that the passive filter is not controlled and that the filtering is a result of the impedance characteristics. The active filter instead measures the harmonic currents and generates actively a harmonic current spectrum in opposite phase to the distorting harmonic current that was measured. The original harmonics are thereby cancelled. The principle is shown in Figure 3.

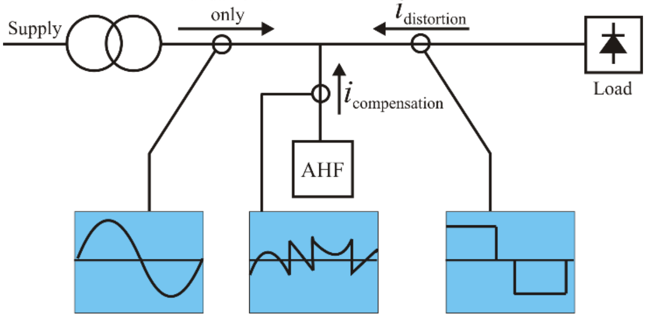

Figure 3. Principle of active filtering

The control of the active filter in combination with the active generation of the compensating current allows for a concept that may not be overloaded. Harmonic currents exceeding the capacity of the active filter will remain on the network, but the filter will operate and eliminate all harmonic currents up to its capacity. It can also be noted that the active filter we are considering here has a parallel topology. Active filters also exist in series topology but they do not offer the same advantage as the parallel topology: the connection is much less flexible; it has higher losses and is overloadable like the passive filter. From this point onwards, "active filter" will only refer to the parallel topology. The principle of active filter showing currents and spectra is clarified in Figure 4.

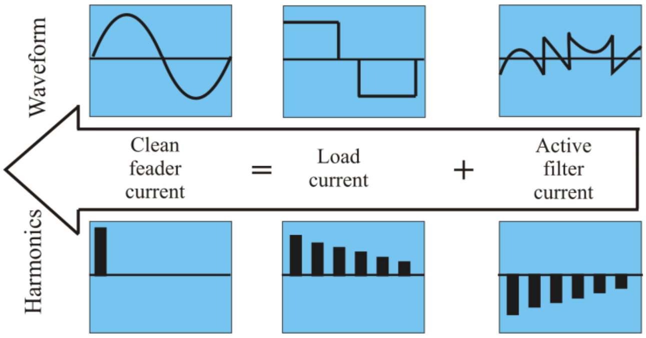

Figure 4. Active filter principle illustrated in the time and frequency domain

IV. MEASUREMENT RESULTS

As we said in previous section many manufacturers of nonlinear loads are aware of problems that are caused using their product. So they start with implementing different filters inside their gadget. By implementing these filters the level of harmonics is reduced, but they are not eliminated. Therefore, we will here show the current waveform for different type of CFL and LED bulb. These waveforms are obtained by using measurement equipment described in section II. Figure 5 presents current waveform of different CFLs manufactured by General Electric.

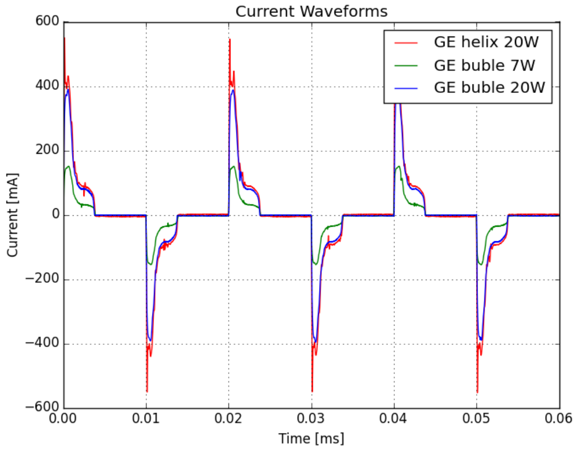

Figure 5. Current waveforms of different types of CFL

From Figure 5, it is clear that the current waveforms of different wattage lamps have the same shape, although the magnitude of current increases with the increase of power rating. In the Figure 6 we presented the current waveforms obtained from different LED lamps. This figure indicates that dissimilar LED bulbs use different filtering methods to reduce harmonic generation. Some of these methods are more efficient than others.

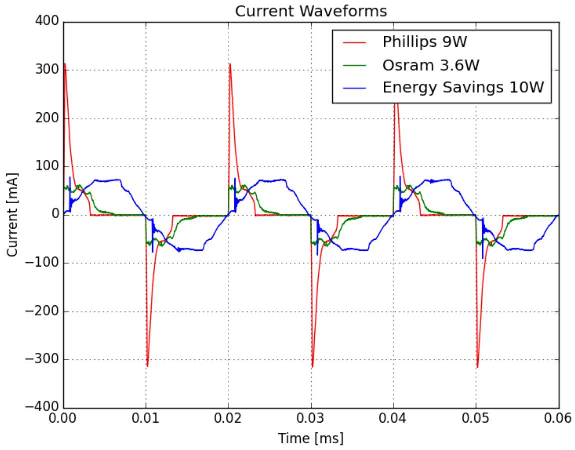

Figure 6. Current waveforms of different types of LED bulb

The Figure 5 and 6 clearly show that harmonics still exist, despite the filters that are implemented to reduce them. Consequently, loads with these filters still produce the considerable value of harmonics and some improvement of these filters is necessary. However, the question is whether it can be paid off to the manufacturer. An alternative is to employ some active harmonic compensation systems at PCC [9]. Therefore, harmonics produced by all nonlinear loads connected at PCC will be diminished and manufactures cost will be less. However this opens a new topic - who should to pay for this system: customer or utility.

V. CONCLUSION

In this paper we discussed the existing harmonic detection and harmonic reduction techniques that are usually used. Principles of passive and active filtering are explained. Measured results are given for different types of LED and CFL bulbs, showing that despite the filters that are implemented to reduce them, harmonics still exist. The conclusion is that some more efficient techniques must be proposed.

ACKNOWLEDGEMENT

Results described in this paper are obtained within the project TR32004 founded by Serbian Ministry of Science and Technology Development.

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