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A novel FPGA-based system for real-time calculation of the Spectral Kurtosis: A prospective application to harmonic detection ☆

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ABSTRACT

Autonomous measurement units are indispensable for the development of the smart grid in order to get faster processing responses, stability, and to provide the user with information regarding power quality (losses, harmonics, outages, steady-state and transient events). In this paper, the development of a novel FPGA-based real-time analyzer is presented. The signal processing nucleus is based on higher-order statistics, introducing the Spectral Kurtosis as an online assessment. Indeed, this fourth-order spectrum enhances non-Gaussian behavior in very unfavorable noise conditions. In the Power Quality assessment frame, the outline of this spectrum can be used to reveal the presence of underlying electrical perturbations. In this paper it is presented an autonomous analyzer that uses the Spectral Kurtosis to detect the presence of low level harmonics. These harmonics are difficult to detect using conventional techniques and can generate problems in power distribution when they are associated to a resonant response in the powered load. The proposed system has been described in synthesizable VHDL and performs an indirect estimator of a poly-spectrum slide, based on the FFT. This synthesizable description has been implemented using a low cost FPGA, enabling a continuous monitoring of the power signal (without dead times) with a high oversampling rate. The proposed solution has been conceived to be introduced in smart grids with high penetration of Distributed Energy Resources (DER).

1. Introduction

The updated electric Smart Grid (SG) uses numerous new technologies for gathering information, communication and control of the grid, making the whole a complex ecosystem. With these features, the SG provides better efficiency and reliability, and allows distributed generation of energy, making it easier to connect renewable but variable and Distributed Energy Resources (DER), like solar and wind power, to the grid. In this scenario, Power Quality (PQ) assessment is an issue of high concern due to the importance of preventing faults that can damage sensitive equipment.

Indeed, smart meters are evolving towards the integrated concept of holistic metering solutions, where the

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focus is on the conception of consulting and analysis tools for developing a SG-based business strategy, as well as a decentralized energy management system for virtual power plants. Further key elements include a compact surge protective device for SG and a system for monitoring power supply networks, that makes it possible to quickly assess particular network scenarios. In this line, holistic smart metering solutions not only record and process energy consumption data, but also include billing via System Application Program (SAP) interface, integrating the energy automation, PQ evaluation and other multimedia functions.

In this communication frame, the new technologies employed in the modern SG are conceived to optimize automation, thus they include High-Availability Seamless Redundancy (HSR) and IEEE 1588 Precision Time Protocol (PTP), which are used in substations for internal communication and time synchronization of electrical measurements. By these means, the equipment monitors, controls, and secures the grid in real time. These exigences make FPGAs an ideal platform to implement real-time switching and measurement solutions.

Precisely, in this paper we take advantage of the FPGA features, along with the potential of the higher-order statistics, to focus on the design of an FPGA-based system which implements the Spectral Kurtosis (SK), which is basically an estimator of the statistical peakedness coefficient of each Fourier frequency of the signal under test. This poly-spectrum has proven its capability to enhance PQ events in several former works, to cite [1,2]. An indirect estimator, based on the FFT is used in the present application.

The goal of the application is to characterize PQ events in the frequency domain by showing the fourth-order spectrum outline, which makes the operator aware of the presence of a PQ event (low level harmonics in this case). Being at a first glance as a signal-quality analyzer, the present prototype has been tested to show its capability to detect harmonics, even under noisy conditions. In fact, while low-level harmonics can be negligible under normal operations, its importance may arise if resonance phenomena is present.

The paper is structured as follows. A brief resume of the role of the FPGA and its measurement potential within the frame of the modern SG is outlined in Section 2. The following Section 3 describes the utility of Higher-Order Statistics (HOS) in the field of PQ. Section 4 explains the mathematical estimator that supports the computational guts of the equipment. The hardware structure is described in Section 5 through block diagrams that show the information flow and clarify the implementation of the algorithm. Then, Section 6 presents the main results, showing graphical examples associated to reference test signals. Finally, the conclusions and the summary of the study are drawn in Section 7.

2. Potential of FPGA-based systems for the smart grid

Delivering energy to the growing global community efficiently and reliably is one of the major challenges of the coming decade. This challenge presents many opportunities with the evolution of the smart grid, which evolved as a result of this need towards a more advanced power delivery mechanism.

The original grid consists of generation at a power plant using traditional fossil fuels, such as coal, or nuclear energy. The energy generated from the centralized power plants was transported vast distances through a series of Transmission and Distribution (T&D) networks until it eventually reached the customer. This unidirectional energy flow is not viable in the 21st century because power generation is not centralized; it is distributed with more worldwide energy coming from renewable sources, such as solar and wind power.

Furthermore, advances in communication technology, both wired and wireless, are being built into the modern grid. This communication feature leads to the so-called the smart grid. However, handicaps stand in the way of smart grid implementation. These obstacles include evolving standards, rock-solid reliability requirements, security, low-cost implementation, and two-way communication for real-time transmission.

Designing smart grid automation equipment and renewable energy sources, such as solar inverter systems for the smart energy ecosystem, is far from simple. In fact, the exigent real-time requirements in a redundant network are ideal for implementing in FPGAs. Indeed, optimal control of new or upgraded smart grids requires end-to-end communications and efficient power networks, especially in T&D substations. To support automation, the equipment needs to monitor, control, and secure the grid in real time for more efficient management of peak demand loads.

More precisely, across substation and utility automation applications, IEC 61850 over Ethernet with IEC 62439-3 Clause 4, Parallel Redundancy Protocol (PRP) and Clause 5, High-Availability Seamless Redundancy (HSR) standards are rapidly becoming the backbone of high-availability networks in smart grid-based systems. Designers will face some exigent challenges related to substation equipment that must support mission-critical systems in real time and long life cycles that place demands on reliability, upgradability, and interchangeability. To sum up, with a single FPGA, you can better comply with evolving standards for your design, increasing at the same time performance and scalability demands for crucial system functions, like the control loop, grid communications, redundancy, and network security.

In this highly-dynamical frame, holistic smart metering solutions are arising, combining metering in Advanced Metering Infrastructure (AMI) and distribution network automation systems, with Meter Data Management Systems (MDMS). It is a major component in the structure of an intelligent power supply network. In its capacity as a data hub, the MDMS incorporates existing power provider systems via a SAP-certified interface into the smart metering infrastructure. With this power, providers can make use of smart metering right across the board all the way from metering to billing, and from system management to network planning.