Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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To cite this article: A. Delle Femine *et al* 2018 *J. Phys.: Conf. Ser.* **1065** 052040

IOP Conf. Series: Journal of Physics: Conf. Series **1065** (2018) 052040 doi:10.1088/1742-6596/1065/5/052040

Synchronized Measurement System for Railway Application

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Abstract. In the light of the recent European directives that regulate railway networks in EU, in order to implement the monitoring and controlling of the railways power supply network, an accurate and reliable knowledge of the exchanged energy between the train and the railway grid is an essential task. Therefore, a measurement system for railway applications must accurately evaluate energy and power quality. In order to do this, the synchronization to a common time reference of all the measurement devices of the network is mandatory. In this paper, a flexible measurement instrument for analysing different types of signals that could be found in railway systems is presented. The proposed instrument has extreme flexibility about the nature of input signals and it implements a synchronization technique to the absolute time via Global Positioning System (GPS). The implementation of the measurement system, along with evaluation of synchronization accuracy, is discussed.

1. Introduction

Considering the overall annual energy consumption of the European railway system, about 36.5 TWh, and the ambitious target of reducing CO_2 railway transport emissions to 50% by 2030, it is clear that an efficient use of the energy in the railway system is mandatory. Considering also the recent European directives [1–3] that regulate railway networks in European Union (EU), it will be allowed the free circulation of trains between Countries and, for this reason, an accurate and reliable knowledge of the exchanged energy between the train and the railway grid is essential for energy billing.

All the trains shall be equipped with an Energy Measurement Function (EMF), whose measurement accuracy has to be assessed and periodically re-verified. Moreover, an accurate knowledge of the real-time Power Quality (PQ) [4–11] is a valuable tool to foster the efficiency of the whole railway system by awarding the good power quality delivered and absorbed. The voltages supplied to trains are often harmonically distorted and subject to residual ripple due to energy conversion from Alternating Current (AC) to Direct Current (DC); these distortions are typically much larger than those experienced on the traditional power network. At the same time, the currents drawn by trains also contain high levels of harmonics, inter-harmonics, ripple and step changes in magnitude, associated with train acceleration and braking. Arcing phenomena, generated by a bad pantograph-to-line contact quality, can further introduce transient distortions. The combination of these effects means that accurate determination of real-time power consumption and cumulative energy (and efficiency) metering are significant challenges. In fixed installations (AC transmission/distribution grids), measurement systems and algorithms related to PQ are currently available; however, these techniques are not all directly applicable to railways, because the time frames of interest are different, the trains are mobile and the PQ phenomena are different. Currently, the existing wide-area measurements on railways are limited to energy consumption with a 300 seconds (5 minutes) time quantization [12]. This provides enough information for the billing of energy used by particular train operating companies, but it provides very little useful data in terms of network management, efficiency assessment, condition monitoring, power quality and network stability. Moreover, the PQ definitions for the DC railway distribution systems are still an open research topic. With respect to the energy measurement on-board trains, the current European standard [3] gives requirements for current/voltage sensors and energy calculation function. In several parts, the same requirements, given for the energy measurement for the fixed installation working at $50\,Hz$, are adopted. This is a crucial point if we consider the dynamic effects (eg: catenary-pantograph contact) of a railway supply system. To improve the energy measurements more bandwidth is needed in order to analyse the described higher frequency phenomena. All this lets us perceive the necessity of a high performance measurement system, that has to collect and analyse railway typical quantities both onboard train as well as in substation. In order to do this, the first requirement of the system is the sampling synchronization of all the measurement devices to a common time reference. Therefore, this paper presents a embedded stand alone Synchronized Measurement Device (SMD), that can acquire with high accuracy various types of railway quantities (electrical and mechanical) synchronously to an absolute time reference, obtained by Global Positioning System (GPS). In the following will be described the system architecture (sec. 2), the synchronization method (sec. 3) and, finally, experimental characterization results (sec. 4).

2. System architecture

The system architecture is composed by SMDs both inside the substations as well as onboard the trains, to monitor and control the power flow from/to the trains. For the implementation of this architecture, an ad hoc network infrastructure will be developed, conceived for the interconnection of the various measurement instruments. The proposed SMD is based on National Instruments Compact Rio 9082. It is a stand alone reconfigurable embedded chassis with integrated real-time controller and, thanks to its reduced size, it could be easily positioned on train as well as in the substations. Compact Rio 9082 is equipped with an Intel Core i7-660UE 1.33 GHz Dual-Core Processor, 2 GB RAM DDR3, 2 RJ-45 gigabit Ethernet ports for data communication and Xilinx Spartan-6 LX150 Field Programmable Gate Array (FPGA) for hard real-time tasks. The used acquisition modules are: NI 9227 ($\pm\,14\,A$, 4 channels, $50\,kHz$, 24 bit), NI 9225 ($\pm 425\,V$, 3 channels, $50\,kHz$, 24 bit), NI 9239 ($\pm 10\,V$, 4 channels, $50\,kHz$, 24 bit). All these modules have an integrated anti-aliasing filter and all the channels of all the modules are simultaneously sampled. A fourth module, the NI 9467, has been used as GPS receiver to achieve absolute time synchronization. This module is able to generate a Pulse Per Second (PPS) with high accuracy (PPS accuracy of $\pm\,100\,ns$) whose rising edge of the pulse corresponds to a whole second of the Coordinated Universal Time (UTC). At power on the GPS receiver automatically begins the satellites survey, then it computes every second the correct time-stamp based on GPS signals.

3. Synchronization and Resampling Method

As previously mentioned, all the measurements must be related to the absolute time. To do this with an adequate level of accuracy, it is necessary to sample the analog signals synchronously with the absolute time reference. However, the used analog-to-digital converters (ADC) are all delta-sigma type, which do not externally accept the sampling clock: for this reason it is not possible to regulate the acquisition system clock with the GPS receiver. Therefore, for the synchronization of the sampling period to the absolute reference time, a software synchronization procedure has been developed. In Figure 1 the ideal behaviour of two SMDs, positioned at different points on the network and having sampling synchronized to PPS, is shown. Figure 1 shows how, in the ideal situation, the sampling period has the nominal value and the first sample of the observation frame, defined by two consecutive PPS events, corresponds to the PPS edge. In the real situation, shown in Figure 2, the internal clocks are not synchronized with the absolute time and therefore it is not possible to accurately correlate the measurements made by the two SMDs. To return to the ideal case starting from the real one, a software synchronization procedure was developed. It estimates the actual sampling instants of the acquired samples and adopts a spline interpolation to resample the data at the desired time instants.

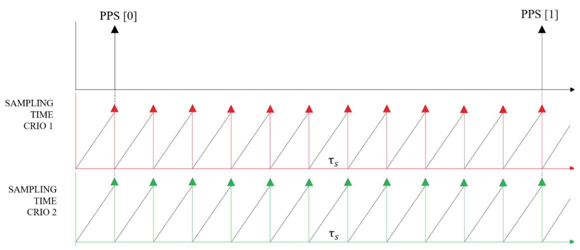

Figure 1. Ideal behaviour of 2 SMDs.

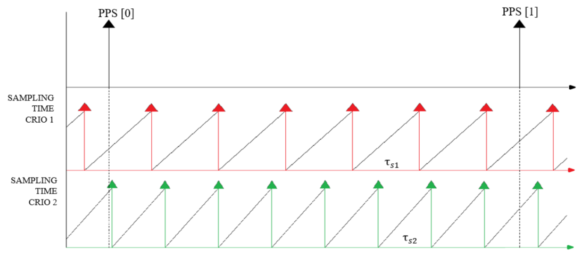

Figure 2. Real behaviour of 2 SMDs.

The SMDs have been programmed in LabVIEW Real Time and LabVIEW FPGA. The FPGA software deals with the acquisition of samples and data related to the synchronization with the time reference provided by the GPS, while the software for the Personal Computer module implements the synchronization technique, the resampling, the measurement and compensation of systematic errors.

The actual sampling instants are evaluated starting from the estimate of the average actual sampling frequency (f_s) in an observation interval (frame). Considering a one second frame, that is the time interval between two consecutive PPS, the necessary data for the estimate of f_s are:

- the number of samples acquired in the frame, n_s;
- the value of system time (expressed in number of clock counts, $systick$) when the last sample of the time frame occurs, LS_{tick};
- the value of $systick$ when PPS event occurs, PPS_{tick};

Considering the $k-th$ frame, f_s is computed as:

$$f_s[k] = \frac{n_s[k]}{LS_{tick}[k] - LS_{tick}[k-1]}, \qquad dt[k] = \frac{1}{f_s[k]} \tag{1}$$

where k is the frame index and dt is the sampling period. Starting from (1) the actual time instants of acquired samples can be computed as:

$$t_{real}[j] = (1+j) \cdot dt[k] - (PPS_{tick}[k-1] - LS_{tick}[k-1]) \tag{2}$$

where j iterates on each sample within the frame. Moreover, (2) is used for spline interpolation in the ideal time instants. As mentioned before, the SMD aims to be flexible, since it could be used for AC or DC electrical quantities (substation and/or trains) but also for other non electrical quantities (train speed or acceleration, etc.). For these reasons, it is possible to configure which channels have to be used and the type of measurements, depending on the input quantities. The metrics for energy and PQ measurements are the same already implemented in other high accuracy field measurement systems [13] and, for sake of brevity, they are not recalled here.

4. Evaluation of synchronization accuracy

To evaluate the performance of the SMDs and, in particular, the synchronization of sampling to the PPS, a Phasor Measurement Unit (PMU) function was added to them: for synchrophasors estimation an algorithm based on Interpolated Discrete Fourier Transform (IpDFT) has been used. A high-performance PMU calibrator, the Fluke 6135A/PMUCAL, capable of generating voltage and current signals synchronized with the GPS, has been used. For the characterization, $230V$ voltage and $5A$ current signals, with a frequency between $45\,Hz$ and $55\,Hz$, have been chosen. Systematic errors compensation has been performed; table 1 shows the maximum errors obtained, after such compensation, for both voltage and current channels at different frequencies. The maximum amplitude error is 0.036%, the maximum angle error is $358\mu rad$ and the maximum Total Vector Error (TVE) is 0.044%. The results of the characterization demonstrate the high accuracy of the system and the reliability of synchronization.

Table 1. Maximum errors of voltage and current channels with frequency in range $45 \div 55Hz$

Frequency [Hz]	$\varepsilon[\%]$		$\Delta\varphi[\mu rad]$		$TVE[\%]$	
	V	I	V	I	V	I
45	0.036	0.022	135	256	0.039	0.039
47	0.032	0.022	33	199	0.037	0.032
50	0.035	0.025	15	231	0.042	0.034
52	0.033	0.024	109	358	0.042	0.041
55	0.032	0.024	8	343	0.044	0.041

Conclusion

In this paper a high performance measurement system synchronized with GPS has been presented. This instrument has been built for railway applications, to measure voltage, current and other non electrical quantities but it is suitable also for fixed electrical system. Thanks to its performances, it can implement various measurement functions such as energy and power quality meter or PMU.

Acknowledgement

The research leading to the results here described is part of the European Metrology Programme for Innovation and Research (EMPIR), 17IND06 Future Grid II project. The EMPIR is jointly funded by the EMPIR participating countries within EURAMET and the European Union.

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