A Virtual Instrument for Time-Frequency Analysis of Park Power Components

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This paper presents the implementation of a virtual instrument to perform wavelet analysis of the Park Power components. A justification for the approach is presented, followed by details about the specific implementation and practical issues. Finally the results of a preliminary testing activity, based on the use of Hardware in the Loop approach are presented.

1. Introduction

Load signature analysis has been widely studied in the last ten years. It is possible to recognize a progressive growth of complexity in the approach adopted. One of the most significant changes has been the shift from quasi-steady-state analysis approaches to fully transient analysis. A case for this shift is well made in [1]. While the steady-state analysis of power components can be successfully completed in a residential environment, the same approach is very likely to fail in an industrial environment. The main reason for this failure is the fact that the signature-space becomes quickly crowded with undistinguishable loads. The use of transient data widely enriches the amount of information available allowing for the identification of a wider set of loads.

In a previous paper the authors presented an approach to signature analysis based on the combination of the Park transform and a wavelet transformation [2]. The main concepts behind this approach are the following. In order to get meaningful signatures the use of current or voltage is not enough. An interesting approach is proposed in [3], where the signature is reconstructed by using instantaneous power and current. As already demonstrated in [2] through some examples a significant amount of information can be reconstructed by the instantaneous components of the power in Park domain. A comprehensive analysis of the physical interpretation of these power components can be found in [4] and [5].

In [2], in order to cope with transient data, the Park power components have been analyzed through wavelet transformation. The idea of using wavelets to analyze transient power has also been proposed in [6] and [7]. In this case though, the work focuses on single phase systems and the use of 90 degree shift filter is proposed to obtain information about reactive power.

Wavelets are widely applied in power quality analysis [8] for the same reasons why the authors believe they can have a significant impact on load signature analysis: possibility to analyze non-stationary components, multi-resolution capability.

In particular, by using dyadic-orthonormal bases we can extract significant information for the frequency domain analysis of power.

In the following, we briefly report some basic remarks about Park Transformation and Wavelet and then focus on the implementation of the algorithms in a distributed monitoring environment.

The details of the LabVIEW implementations as well as data about the hardware adopted are reported. Finally a hardware-in-the-loop (HIL) testing procedure is presented to validate the developed software.

The HIL experiment is based on the Virtual Test Bed (VTB) Real Time Extension (VTB-RT) developed at the University of South Carolina. Thanks to this platform, as shown in the following, we have been able to replicate the scenarios presented in [2] without the need of actually create a real flow of power but nevertheless using the real data acquisition system and the embedded hardware for measurement.

2. Park Domain and Wavelet Transform

The Park transformation can be applied generally speaking to any multi-phase system: in the simplest case a three-phase scenario.

Given the three phase quantities \(x_a, x_b, x_c\) the corresponding Park domain quantity is obtained applying a suitable matrix \(T\) to the vector \(X\) defined as:

\[
X = \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}
\]

thus obtaining a new quantity in the new domain as:

\[
X_p = TX
\]

The vector \(X_p\) will have three elements as well that are defined as: direct, inverse and zero.

If we focus on three wire systems we can disregard the zero component and introduce the so-called Park vector as:

\[
\bar{x}_p = x_d + jx_q
\]
The matrix $T$ can be defined according to different criteria including the relative speed between the three-phase phasor and the reference Park system [7]. In the result herein presented, the following definition has to be assumed:

$$T = \begin{bmatrix}
\cos(0) & \cos\left(\frac{2\pi}{3}\right) & \cos\left(\frac{4\pi}{3}\right) \\
-\sin(0) & -\sin\left(\frac{2\pi}{3}\right) & -\sin\left(\frac{4\pi}{3}\right) \\
\frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2}
\end{bmatrix}$$

This $T$ matrix that holds for the case of fixed Park reference defines an orthonormal transformation so that:

$$T^{-1} = T'$$

Given the definition of the transformation we introduce the power in the Park domain as the product between the voltage Park vector and the conjugate of the current Park vector:

$$\mathbf{p} = \mathbf{v}^T = (v_d + jv_q)(i_d - ji_q) =
(v_di_d + v_qi_q) + j(v_qi_d - v_d i_q)$$

Two comments complete this brief introduction:

- In the case of a steady-state sinusoidal system the real and imaginary part of the Park power match the classical active and reactive power
- Because of the properties of the transformation the power does not depend on the specific reference adopted (this is a classical property of any tensor analysis)

Following the approach proposed in [2] the instantaneous values of $p(t)$ and $q(t)$ are then processed with the wavelet transform to obtain time-frequency information. Different wavelet bases can be adopted to perform the operation. In the previous paper we considered Haar wavelet and Malvar wavelet, while for the experimental implementation we focused only on Haar transform. The Haar wavelet basis is an orthogonal basis used in the applications described in the following sections. The Haar wavelet is defined as:

$$\psi(t) = \begin{cases} 
1 & 0 \leq t < 1/2 \\
-1 & 1/2 \leq t < 1 \\
0 & \text{otherwise}
\end{cases}$$

The other functions of the basis are obtained by rescaling and shifting the so-called mother wavelet previously defined. In particular the other functions of the basis are obtained according to:

$$\psi_{j,k}(t) = 2^{j/2} \psi(2^jt - k)$$

so that the scaling factor $j$ turns the length of the support to $2^j$, $k$ is the shift factor and $2^{j/2}$ is the normalization factor.

The scaling function of the Haar wavelet system is defined as:

$$\varphi(t) = \begin{cases} 
1 & 0 \leq t < 1 \\
0 & \text{otherwise}
\end{cases}$$

This orthogonal system allows for the decomposition of any $L_2(\mathbb{R})$ function into the sum of a coarser representation related to the scaling function, possessing an averaging meaning, and a sum of finer and finer details related to the wavelets [9].

3. Hardware structure of the measurement platform

![Figure 1: The HW structure used for the experiment](image)

The hardware implementation of the proposed analysis is based on a standard desktop PC and a National Instrument Compact RIO (Figure 1). The National Instruments Compact RIO 9002 is an embedded real-time controller based on a 200-MHz Pentium-class. The device’s core has built-in data transfer mechanisms to pass data to the embedded processor for real-time analysis, post processing, data logging, or communication to a networked host computer. The Compact RIO provides direct hardware access to the I/O circuitry of each I/O module using Lab View FPGA elementary I/O functions. This project uses only the analog input module (NI cRIO 9201).

4. Software Implementation: LabVIEW Programming

The data acquisition is performed through the analog input module 9201. Six channels are needed in this application (a total of eight is available). Three are used for voltages and three are used for currents. The timing and processing of the acquisition is managed through the FPGA board of the Compact RIO. The overall software structure can be split in three main tasks:

- Task 1 performs the data acquisition. The processing at this level is based on integer numbers. This task is downloaded and execute onto the FPGA
- Task 2 performs the signal rescaling, Park transformation of voltage and current Park transform, calculation of the Park power components. This task is downloaded onto the embedded processor of the Compact Rio and constitutes the main task.
- Task 3 performs the wavelet transform and the 3D-graph visualization. This task runs on the PC.
4.1 FPGA Program (Task 1)
This task acquires the signal and stores the data in a buffer. Figure 2 shows the six channels on the left hand side. The buffer is based on a FIFO structure. Time out is set on 0 (if the queue is full, the program waits until there is an empty space).

![Figure 2: Block Diagram of the FPGA Program](image)

4.2 Compact RIO Program (Task 2)
The Compact Rio program is the main component of the project. Because of limitations of the Real Time Operating System, the Compact RIO can not execute tasks with a sampling rate higher than 1 kHz and then the algorithm can not be applied at a single sample. The problem is overcome by processing a batch of data stored in the FPGA FIFO (see Figure 3). In every cycle, 1024 samples acquired with a sample frequency of 30.72 kHz are elaborated for each channel.

Within the while loop, a block reads the FIFO where the data are stored. The number of elements read from the FIFO is 6144, or 1024 samples for each channel. The size of the FIFO is larger than 6144, thus the samples are not lost. The “timeout” specifies the number of milliseconds that the VI waits before timing out. This parameter is set to -1, meaning that the program waits until there are enough samples. Also, the “elements remaining” block returns the number of elements remaining in the host memory part of the FIFO.

The output data of the FIFO.read is an array of elements (6144) with the data from different channels. The program executes three sequences in series as shown in Figure 4. The first sequence involves taking the samples from the FIFO and redistributing them into the different channels. The second sequence converts binary to nominal. This operation must be done on the Compact RIO because the FPGA does not manage numbers in floating point format. This second sequence is made of six sub-sequences that rescale the signals (three for the voltage and three for the current).

The last of these three consecutive sequences produces the fixed-axes Park transform. The zero component is not calculated considering that we are working with a three-wire system. Finally, the last sequence simply computes the component of the power according to the Park reference.

![Figure 3: Reference to FPGA and FIFO on block diagram of the RIO program](image)

![Figure 4: The sequences of the Compact RIO Program](image)

4.3 Wavelet Program on PC (Task 3)
The data previously stored in the buffer may be read by devices external to the Compact RIO, in particular by the PC where they are processed by a resident program. The last operation is the wavelet transform. The computational effort of this part may be significant and therefore it is not advisable to execute this operation on the RIO platform in that it may adversely affect the satisfaction of real-time constraints. The PC-based LabVIEW program loads the buffer previously filled and computes the wavelet transform after every cycle of the Compact RIO program. The transformation is calculated by means of a set of Matlab-based routines executed in LabVIEW thanks to the LabVIEW/Matlab interface. This solution allowed the authors to quickly port the software developed on the Matlab platform avoiding any possible coding error.

The calculated coefficients of the wavelet decomposition are sent to a 3D color-map data visualization.
access to some hardware features that may not be available in software-only simulation models, hence reducing the risk of discovering implementation errors in the very last stage of the field testing [12][13]. Real-time HIL simulation is widely applied, in the investigation of power quality disturbances, as well as in modern control unit development for automotive electronic.

Among the different HIL platforms, even those commercially available, VTB-RT has unique properties, in particular multi-platform, multi-solver, and hard real-time. While not intended to compete with commercial systems, VTB-RT is designed to provide a very low-cost alternative for real-time HIL applications while maintaining acceptable resolutions.

In VTB-RT, Linux and RTAI [16] were adopted as the underlying real-time operating system. On the other hand, VTB-RT is fully based on the VTB Technology developed at the University of South Carolina [14][15]. It reads the same file format created by the VTB schematic editor under Windows, thus making it convenient the export of simulations from the non-real-time platform, the VTB, into the real-time platform, the VTB-RT.

For what concerns this work, VTB-RT has been used to generate the testing data for the Virtual Instrument. The schematics used in previous work, [2], have been executed in real time on the Linux platform to obtain physical data out of Digital to Analog Converter board then fed to the new measurement platform.

The hardware running VTB-RT is a PC desktop equipped with Pentium 4 at 2.8 GHZ, and with NI DAQ board NI PCI-6733. The simulation scenarios have been executed with a time step of 100 microseconds to achieve enough waveform details.

7. Experimental results

Here we report some examples of measurements performed by using the proposed architecture. We focused the preliminary experimental activities on three cases: a first scenario without distortion, a second scenario with an unbalanced load and a third one with a non linear load.

The scenarios for the HIL simulation has been set up porting to Linux some of the examples presented in [2]. Figure 7 shows the imaginary part of the Park power for a scenario with an unbalanced load and a third one with a non linear load. As expected, the \( q(t) \) has only component for the first level of decomposition and this quantity is constant.

The same very simple schematic is then modified making the three phase load unbalanced. Two different levels of unbalance behavior are tested increasing the resistance in one of the phases from 1 \( \Omega \) to 5 \( \Omega \) and then 10 \( \Omega \).

If we assume, as we did in the experimental activity, to synchronize the sampling with the main frequency, it is to identify the presence of an unbalance in the load.
In effect, from the theoretical standpoint, if we consider the movement of the Park current vector and Park voltage vector, and the fact that the power is product of the two vector, we can easily determine the a linear unbalance load will create a power term that rotates at twice the frequency in opposite direction. In the wavelet domain this is reflected in the creation of a significant component for the order 3 of decomposition with negative value. The signature is then embedded in these two information: significant presence of this order, and negative, constant in time value. If the unbalance is more significant the value of this order grows in magnitude (Figure 8).

More interesting is the analysis of the example reported in Figure 9. In this case we have a three-phase distribution system connected to a reversible Graetz bridge. Figure 10 reports the results of the experiment when the bridge is control with zero delay, so that it behaves like a diode converter. Under this operating condition it is possible to detect a significant signature. The signature can be analyzed in Figure 11. The contour plot has been obtained rescaling the wavelet coefficient to the mother wavelet and the applying a thresholding at 0.01. This process allows the detection of a periodic pattern that can be used for the analysis. The analysis can then be focused on the 4th, 5th and 6th order to detect this kind of load.

While this result can be considered very positive, it is also interesting to analyze how this signature is deeply influenced by the firing angle. In particular if the firing angle becomes very close to 90 degree the contour plot becomes very hard to analyze (Figure 12). On the other hand, under the same condition though, the imaginary part presents a much more reliable contour plot suggesting a combined analysis of the two components (Figure 13).
Some of the complexity in the analysis of this signature is given by the fact that the dyadic structure of the Haar wavelet does not help on detecting the periodicity of operation of this converter.

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