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Narrowband PLC Channel Workbench to Emulate Transmission in Smart Grid

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Abstract: A real-time workbench able to reproduce the same behavior as an indoor network is in order. Such a tool will help researchers and industrials extend the smart grid technology indoors and have a better acknowledgment of Smart Grid systems interoperability. In order to develop such a tool many approaches should be studied to choose the most suitable one by comparing the models and the technologies. The considered hardware are the embedded systems and the selected approach is the statistical one. It appears that the FIR filter is the most pertinent approach.

Key words: Embedded systems, emulator power line transfer function modeling, FIR (finite impulse response) filters, narrowband PLC (power line communication).

1. Introduction

The main goal of a smart grid is to set up a line of communication between different elements of a network and to optimize and balance the flow of energy and data at any moment in a reliable and reactive way [1]. Therefore, the electric network goes from a simple unidirectional chain to a bidirectional one. The smart grid also places the energy consumer right in the middle of the energy market. He becomes in charge of his own consumption since he has the ability to command, check, and control his devices, even remotely.

One of the main tools which facilitated this energy revolution is the PLC (power line communication). The NB PLC (narrowband power line communication) technology uses the electric network to support transmission resulting in no deployment of any additional infrastructure. The commonly used NB technologies are CPL G3, PRIME and the IEEE 1901.2 to assure communication between the different elements of the electrical network [2]. NB PLC has a frequency range between 3 and 500 kHz. This frequency range includes the different ranges from Europe, USA, Japan, and China. Outdoor oriented NB PLC assures the control of the different components of an electrical grid and handles the metering, France uses the communicating meter Linky to operate remotely [3] and measure consumption and also offers the consumer an easy access to his consumption information.

Using the electrical installation in transmitting data for Smart Grid applications possess various economical and technical advantages, making this technology favorable [4]. However, such a network is not designed for those types of signals; attenuation is caused by the electrical installation reducing the transmission performances, for example, the transformers [5]. The limit of this technology is related to the presence of the electrical devices that have an impact on the PLC.

We chose to evaluate the indoor network so we can reproduce its behavior. Such a network is a vulnerable support of communication because it’s not adapted to it. The domestic electric devices that are connected modify its behavior and make the network a less reliable support for communication.

During the past years, effort has been put onto the

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characterization of power line communication channels indoor [6-8] and outdoor [9] with the aim of knowing the behavior of those installations. The modeling of a PLC can be done in many ways. One example is a representation of the PLC that is based on the S-parameters or the ABCD matrix. These parameters can be used to find the frequency response of the overall electric system. On the other hand, one can also find other representations that are more suitable for stochastic simulations.

The first section of this article explains the different approaches to characterize a transmission channel with a focus on the statistical approach. This approach can be used to build a real-time simulator for a workbench. This paper expands on the measurements from by providing, in the second section, a method exploiting those results to build a workbench capable of reproducing the same behavior as a power line communication channel in the frequency range between 9 kHz and 500 kHz. The last part validates this approach.

2. Channel Characterization Approaches

In order to optimize the NB PLC, a modeling of the communication channel is in order. Until now, there is no precise model or approach [10]. Each approach has its strengths and weaknesses, and that is why researchers and industrials are still on the quest of finding the best approach possible allows them to perfect the NB PLC system and make it more reliable and powerful.

2.1 Deterministic Approach

There are two modes of transmission using NB PLC. The first one is the SISO (single input single output) that uses the neutral cable and one phase to transmit the signal. The second method is the MIMO (multi input multi output) [11]. It transmits the PLC signal using a combination of the neutral, the phase, and the ground cables.

The deterministic model extracts the transfer function from the theoretical cable parameters [12]. It is based on the physical proprieties of the cable itself (loads, length, topology, type of the cable, etc.). The theory used in this kind of modeling is the transmission lines theory. In an NB PLC transmission, the electric cable is considered as a homogenous twin-cable knowing that the information is propagating in a different mode, so the electrical network is redrawn in a shape of series of elementary quadrupoles. Each one of these quadrupoles is represented by its own matrix combining the input and the output variables. The concatenation of those elementary quadrupoles provides the transfer function of the network.

A cable can be modeled by its linear primary parameters R, L, C and G [13], or by using the secondary parameters, the characteristic impedance and the propagation factor. Then, by using them, one can obtain the chain matrix of every single elementary quadrupole. The chain matrix of the entire network is then the product obtained by multiplying the matrices of the different sections. The S matrix is also a way to obtain the transfer function of a network. The elementary quadrupoles can be also modeled using the impedance, admittance matrices, or the S parameters.

There are other methods capable of extracting the transfer function such as the digital filters. The first method that was considered uses IIR (infinite impulse response) filters to model every elementary quadrupole. According to Ref. [14], this approach considers the signal to be an electromagnetic wave that travels over the PLC channel and bounces infinitely between neighboring line discontinuities.

However, this method only helped us to characterize a known network, it's more oriented to outdoor use since the electric companies know their installations. To build our real-time workbench since we did not know all the information about the network. Therefore, we moved to the next approach that is the statistical approach.

2.2 Statistical Approach

This approach consists of modeling the NB PLC channel using a database of measures done on real installations [6, 15]. What this approach offers is that it does not require any knowledge of the electrical network, and it is based on real measures in real conditions. Usually, the characterization of PLC channels is performed on frequency ranges superior to 1 MHz while the NB PLC channels are not sufficiently explored. In this paper, we will use a statistical approach to build an emulator capable of reproducing the same behavior of an NB PLC.

First we needed to define a statistical algorithm that can be used in an embedded system. There are two possibilities to implement convolutional algorithms on an embedded system. The first one is, using a block convolution in the frequency domain. The block convolution uses the principle that a convolution in the time domain correlates to a multiplication in the frequency domain. It transforms the acquired signal into the frequency domain by a DFT (discrete Fourier transform), multiplies the spectrum with the CTF (continuous Fourier transform), and converts the product back into the time domain via IDFT (inverse discrete Fourier transform). This method requires highly efficient FFT (fast Fourier transform algorithms), and is also called “FFT convolution”.

The second algorithm is a conventional time-domain approach using a digital filter. This method obtains the channel impulse respond and saves them as coefficients.

Two main types of digital filters are considered; FIR (finite impulse response) and IIR (infinite impulse response). This notation refers to the type of the filter response. A simple variation on the coefficients and the order can create the desired frequency response.

It was proved that FIR filters can accomplish performances impossibly using a simple analogic filter. Nevertheless high pursuance FIR filters require more performant hardware. Otherwise, IIR filters adopt the performance of the analog one’s using feedback. Due to this feedback IIR filters can have lower orders than the FIR filters.

The system function of an IIR digital filter can be expressed in this way:

$$G(j\omega)=\frac{B(j\omega)}{A(j\omega)}=\frac{b_0+b_1(j\omega)^{-1}+\cdots+b_Q(j\omega)^{-Q}}{1+a_1(j\omega)^{-1}+\cdots+a_P(j\omega)^{-P}} \tag{1}$$

IIR filters have the advantage that a variety of frequency-selection filters can be designed using closed-form design formula. Once the model has been specified in terms appropriate for a given approximation method, then the order of the filter that will meet the specification can be computed and the coefficients of the discrete-time filter can be obtained by straight forward substitution into a set of design equations.

The system function of an FIR digital filter can be expressed in this way:

$$G(j\omega)=\frac{B(j\omega)}{A(j\omega)}=b_1(j\omega)^{-1}+\cdots+b_P(j\omega)^{-P} \tag{2}$$

FIR filters are comparatively easy to design using modern acquisition tools and software. The input represent an impulse acquired, then this impulse travels through the acquisition system, get processed then provides an output impulse same as the filter coefficient. A convolution in the sampled data system presents a multiplication done point-by-point in the contradictory domain. For example, a time domain convolution represents a frequency domain multiplication.

3. Workbench Reproducing the Behavior of NB PLC Channel

Being able to emulate PLC channels using a workbench is an idea that has been developed for many years now [16-18]. The main focus was on the broadband PLC for frequencies higher that 1 MHz. Different embedded systems were used to build a real-time emulating workbench.

The embedded systems as the DSPs (digital signal processors) and the FPGAs (field-programmable gate arrays) are more and more used in the fields of mathematical implementation and real-time processing. Those embedded systems can be the main piece of a workbench able to integrate one of the two filters (FIR or IIR) used in modeling the power line communication behavior [19].

3.1 Digital Filters

Digital filtering is one of the most vigorous tools of DSPs and FPGAs, apart from the evident advantages of virtually cutting off errors in the filter associated with passive component fluctuations over time and temperature.

Digital filtering is capable of achieving almost-impossible performance specifications that were not previously possible with an analog implementation. Additionally, a software control can assure characteristic changes on the filter, so it can easily be adapted to any type of application such as communication, noise elimination, or power line communication.

To design a digital filter, we can follow the same fundamental procedure as the analog ones. We start by characterizing the desired filter response, and then we calculate the parameters of the filter. The same operation can be done for the amplitude and phase. The mean difference between the digital and analogic filter is the concept of the coefficients. They replace the values of the capacitors, inductors, and resistances, so those coefficients are simple numbers that can be used in a DSP or FPGA to design a digital filter by simply performing calculations. Real-time digital filters represent discrete functions created based on digitized data that produce data points using acquisition and sampling. Data samples are attributed from sample (1, 2, 3… n) to an output function x(n) capable of reconstructing the original waveform creating the filtered signal.

The downside of digital filtering is the hardware requirement. To be able to maintain a real-time processing speed, the processor of the DSP, FPGA or the computer needs to be able to process all the steps in the filter creation with a simple timing period (1/f). Also, the sampling frequency can limit the frequency bandwidth.

3.2 Calculation of the Digital Filters Coefficients

3.2.1 Measures Database

In order to model the NB CPL indoor channel, the amplitude responses used to calculate the coefficients are coming from a measurement campaign done by Ref. [20] where 240 transfer functions were collected during 24 hours in different houses and apartments, inside and outside the city. Those results will be used to construct a library including more than 10,000 measurements. Fig. 1 shows an example of the transfer functions measured.

The workbench needs to be able to reproduce the same behavior as NB PLC channels.

3.2.2 Filtering Algorithm

The first step was loading the database into the Matlab software, then extracting one function at a time. The extracted function will help calculate the coefficients for the desired digital filter using the functions already implemented in the software.

a) IIR filter

The algorithm developed by Ref. [21] will be used to calculate the coefficients of the IIR digital filter. The function used is “invreqz”. It looks for a discrete-time transfer function according to a given

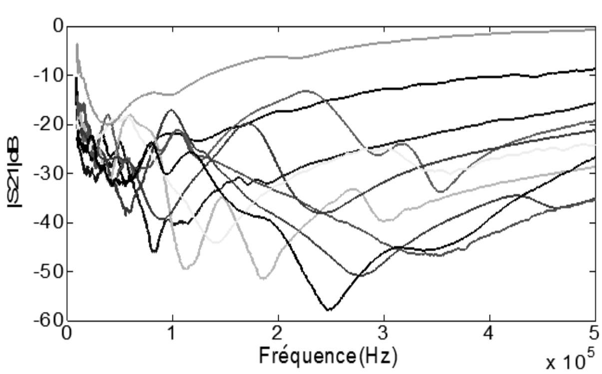

Fig. 1 Examples of measured transfer functions.

complex frequency response. From a laboratory analysis view, "invfreqz" can be used to convert phase and magnitude data into transfer functions.

b) FIR filter

Two FIR filters algorithms will be used in modeling power line communication behavior, the first one is the Parks-McClellan Program. It was created by Mark and McClellan and based on the Remez exchange algorithm and it leads to lower order filter. The second one is the window method which affords the possibility of approximating rather arbitrary frequency-response characteristics.

- The first function is "Firls". It designs a filter with linear phase FIR, which minimizes the quadratic error, integrated between a linear function by ideal filter and the answer, into amplitude of the filter on a set of desired frequency bands. The function sends back a vector line b containing n+1 coefficients of the order n of the FIR filter of which the characteristics of frequency-amplitude approximately correspond to those given by the vectors.
- The second one is "Firpm". It conceives a filter FIR with linear phase by using the algorithm of Parks-McClellan. The algorithm of Parks-McClellan uses the Remez exchange Algorithm and the Chebyshev approximation Theory to conceive filters with an optimal adjustment between the desired and the real frequency response.

c) The selected algorithm

For the IIR filter, the two coefficients "a" and "b" are in a complex form. What made the process time longer and it also showed some instability problems as shown in Fig. 2. To implement a simple filter of -20 dB it can be a better solution but for a transfer function that keeps having attenuation and it's better to go with a FIR digital filter.

The next step of the process of choosing the optimal solution, we had to compare the performances of each algorithm ("Firls" and "Firpm") to see which one is more adapted to our application.

We applied both algorithms on a series of transfer function and we compared their performances based on their stabilities, errors, etc. The next figure shows an example of a function with the two algorithms. As we can see (Figs. 3 and 4), the "Firls" method is more stable and it follows perfectly the original transfer function. That was the case for almost all the transfer function picked randomly from each measurement.

3.3 The NB PLC Workbench

This section outlines the workbench (Fig. 5) used to reproduce the same behavior of a power line communication channel. The workbench is composed of a computer integrating an acquisition board connected to a rack-mount analog breakout accessory with signal-labeled BNC connectors. Then, two connectors (an input and an output) are joined to a network analyzer.

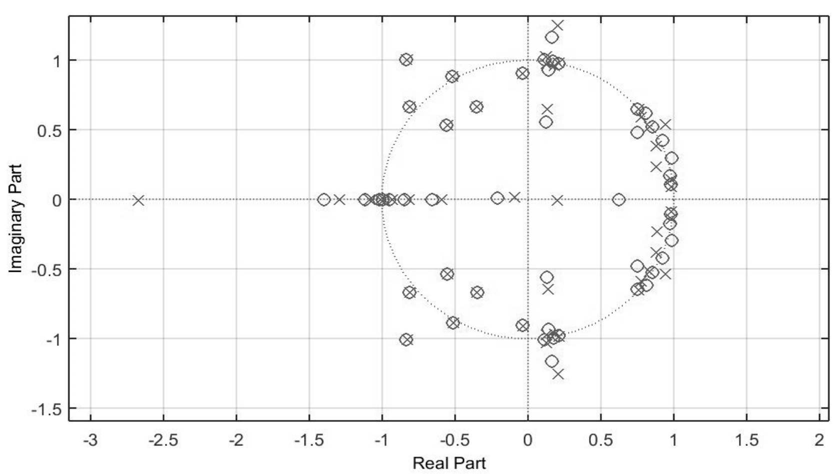

Fig. 2 Examples of measured transfer functions.

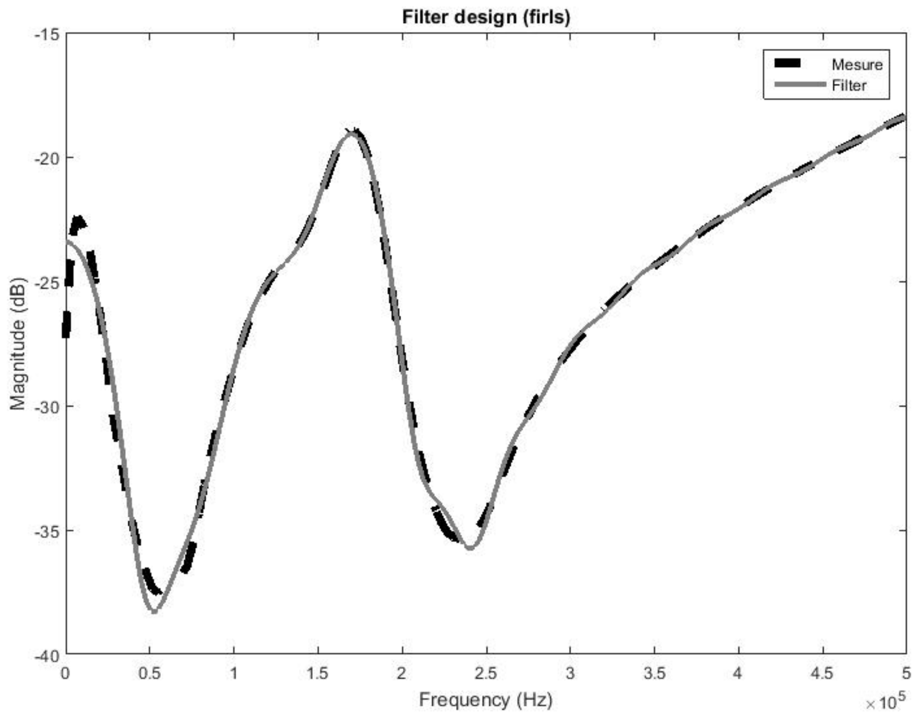

Fig. 3 Filter designed using "firls".

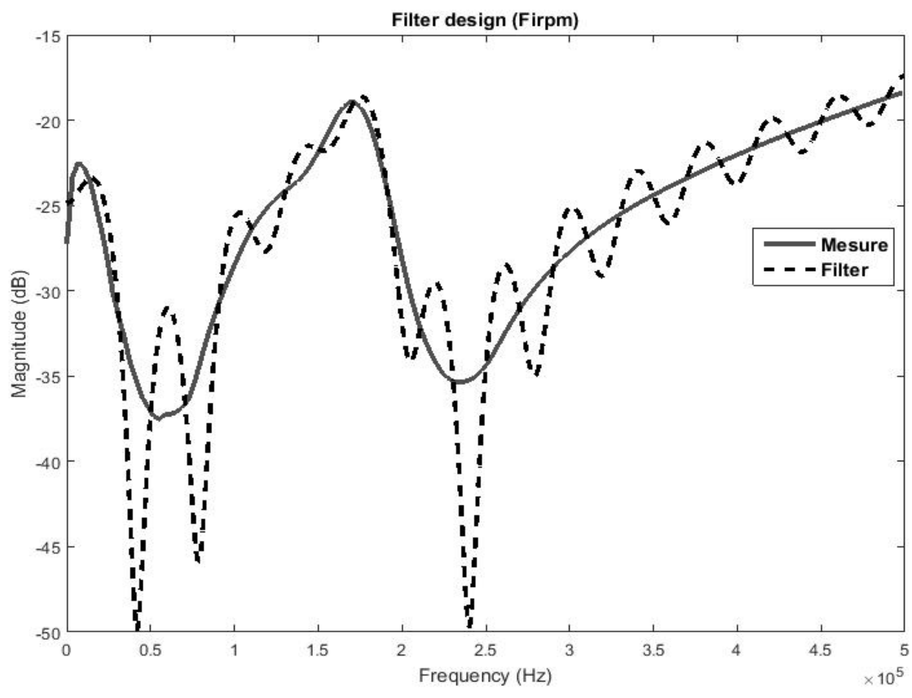

Fig. 4 Filter designed using "firpm".

The network analyzer was set to a frequency band from 9 kHz to 500 kHz with a linear span. The first port of the network analyzer is set to send the signal, while the second port is a receiver. It was calibrated to adapt to the speed of the acquisition board.

The signal acquired by the computer via the acquisition board is then processed using a VI (virtual instrument) developed on LabVIEW (Fig. 6). The VI includes a while-loop that runs infinitely unless an error is generated by the acquisition

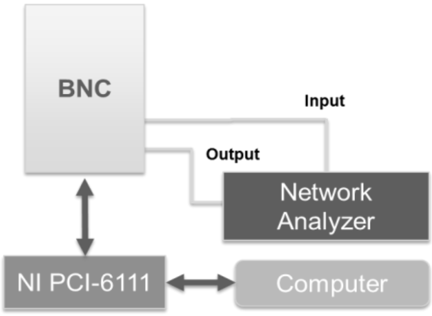

Fig. 5 NB PLC workbench.

instrument or in the case where the user decides to interrupt the process. Inside the while-loop, one can find two similar blocks that are destined to configure the input and the output. Inside those blocks, we can specify the acquisition rate and the number of samples. Then, the main block is the FIR filter sub-VI. The goal of this block is to filter the input signal using the direct-form FIR specified by FIR coefficients.

The use of a computer instead of an embedded system has advantages and disadvantages. Using a computer with a LabVIEW software gave us the ability to change the coefficients while the experiment was running and also change the type of the filter and its order without reprograming every time. The use of a computer represents the feasibility assessment phase. The second phase will be to implement the final solution on a much faster embedded system to get a real time workbench. For the inconvenient part, the speed that can achieve a computer depends on the acquisition, the transfer, and the process time so we are not in a real time application since each sample takes more than one second to be processed and sent back to the network analyzer. The used acquisition card has a sampling rate of 8 M Sample/s.

4. Results and Validation

To model an NB PLC transmission channel we opted to the use of FIR filters with real coefficients. Those have been calculated using the Matlab software and then implemented within the VI that runs the workbench. The results are shown in Fig. 7.

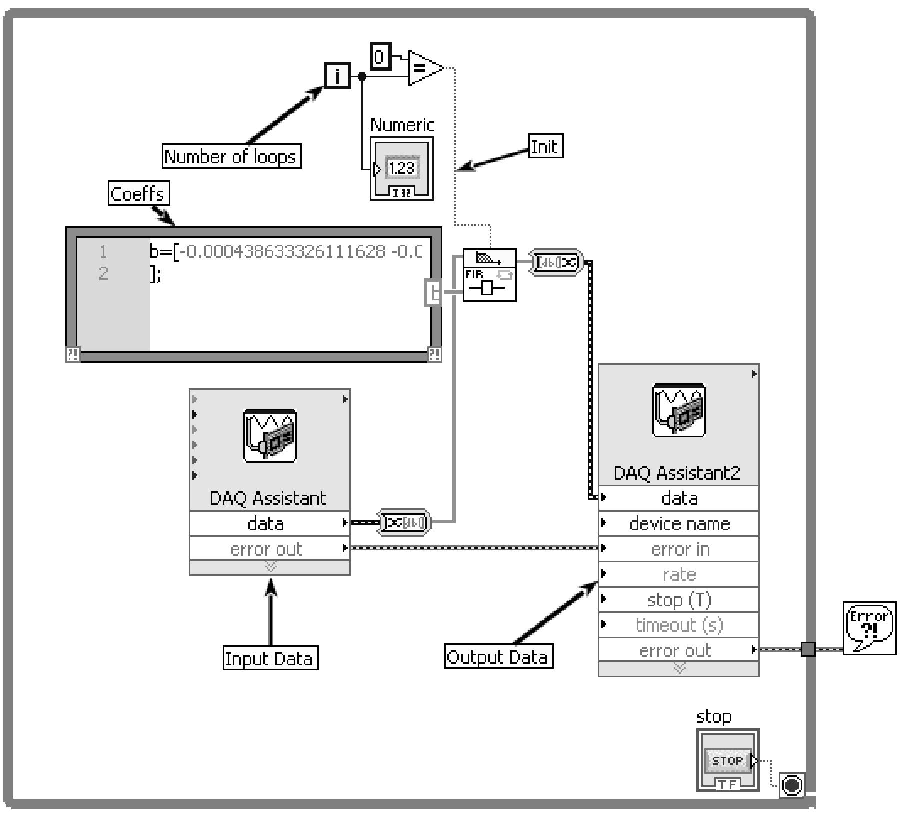

Fig. 6 LabVIEW V.I.

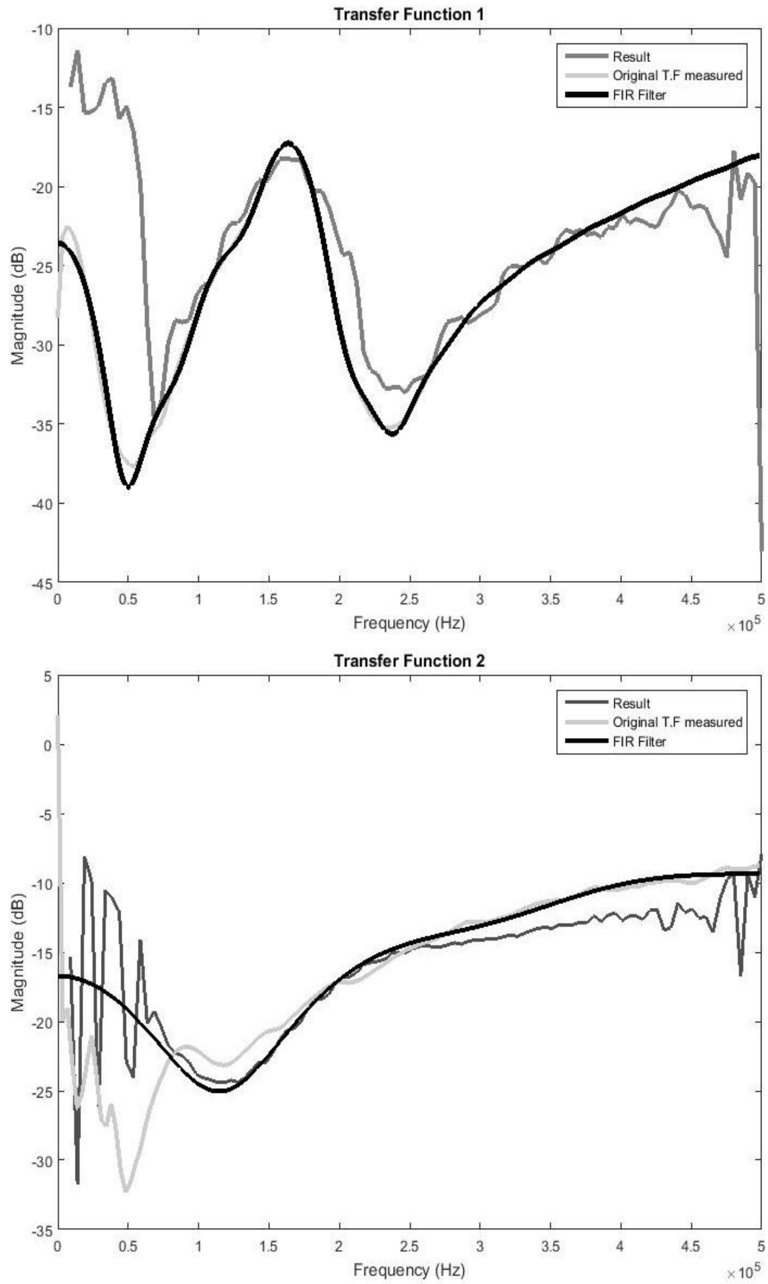

Fig. 7 Results of the emulator.

Using the measured transfer function (grey curve) the Matlab algorithm calculates the channel impulse response and shows the results as coefficients of the FIR filter (black curve). The number of coefficients corresponds to the order of the filter plus on, for example, an order 50 filter is defined by 51 coefficients. The next step will be to implement those filters as an array on the VI that runs the workbench. The filter is activated, then it starts receiving the impulse signal from the network analyzer that swipes in a frequency range between 9 kHz and 500 kHz. The computer receives every sample and processes it in 2 seconds, reconstructs the signal then sends it back to the network analyzer. The results of all the samples give the grey curve.

The method was applied to different signals (or figures), from 80 kHz to 500 kHz we can see that the transfer function follows the original curve with a maximum error of 2 dB. From 9 kHz to 80 kHz the signal is not stable, it's one of the points that should be fixed in the second phase of the realization of the real-time emulator.

5. Conclusion

The smart grid concept is transforming the energy distribution and consumption chain, giving the consumer an important role in managing it. One of the key factors of this revolution is the NB PLC. Therefore, a depth knowledge of this technology will help in this energy transition.

This paper extends NB PLC modeling to create a workbench able of reproducing the same behavior as an NB PLC channel using a statistical approach based on an FIR filter algorithm.

Once the real-time emulator is accomplished, we can find a link between the variations inside a transmission channel and the noises generated in this transmission support. It can be integrated within a workbench that can test NB PLCs by creating different scenarios of transmission.

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