Distribution Grid Monitoring through Pilot Injection and Successive Interference Cancellation

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Abstract

Due to the push for renewable energy in the last decades, European countries have witnessed an exponential growth of Distributed Generation (DG) on the Medium Voltage (MV) network. An increasingly large portion of the electricity demand is fed in through the distribution grid, whose good health and operational status will be important for guaranteeing grid stability. In Luxembourg, the distribution network is sparsely monitored and controlled, thus instabilities arising due to line overvoltage or DG malfunctioning are not rapidly detected and resolved. This research discusses a novel and low infrastructure methodology for online monitoring of the distribution grid. Such a tool will be increasingly necessary in order to guarantee the stability, reliability and security of the power network, as a larger and larger portion of the energy demand will be satisfied by DG in future years. In this research, advanced system identification techniques utilized in communications, such as Pseudo-Random Binary Sequences, Successive Interference Cancellation are applied to estimate the transfer function of power network propagation paths. The developed method proposes an online monitoring tool that computes grid parameters in real time during operation, without extensive infrastructure addition, by utilizing the PWM based inverters on the grid for active system identification.

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1. Introduction

During the last decade, a substantial growth in renewable, distributed energy production has been observed in industrial countries. Due to the renewables penetration goal targeted by the European Community, this trend will continue to accelerate and Distributed Generation (DG) will represent a substantial part of the European energy mix. A large part of the new renewable energy sources will consists of Wind and Photovoltaic (PV), and since these are by nature variable and unreliable energy sources, careful planning is required in order to integrate them harmoniously and efficiently. While the High Voltage (HV) Grid is typically well controlled and monitored, the Medium Voltage (MV) Grid, where DG is feeding most of its energy, is sparsely monitored. Since the MV network could be confronted to excessive power quality and stability issues due to the increase in intermittent renewables, it will require additional infrastructure in order to control, monitor and regulate the MV Network. Replicating the HV infrastructure on the MV would require large investments, thus different tools need to be applied.

Grid parameter identification is a technique that has been used in power systems for a long time, but with the advent of wide spread inverter based DG, new applications and uses have been designed in order to enable the correct behavior of DG. By analyzing the system impedance not only at the fundamental frequency, but on the complete spectrum, properties of the grid can be discovered which are hard to detect through traditional methods. In [1] the solar inverter is injecting a 75 Hz signal in the grid, and detects through impedance changes islanding situation which arise. In [2] impedance measurement at DG is used in order to mitigate the effects of harmonics on the grid and in order to drive an active shunt filter smoothing out the major harmonics. The impedance is calculated through the injection of a sum of sinusoids. An interpolation will provide a complete impedance spectrum at the Point of Common Coupling (PCC). In [3] the impedance at the DG is used for voltage control, and it is measured through periodic triangular bumps injected in at the Voltage Source.

In this paper, we will investigate an implementation of an online impedance measurement technique through the use of Pseudo-Random-Binary-Sequence (PRBS). These sequences have been used thoroughly in other engineering fields such as telecommunications, and their inherent properties suit them well for tasks such as system identification [4]. The identification of the propagation path of the signals will be non-parametric, given that the grid's situation can be vastly different for one location to another, thus no predefined system model needs to be parameterized. This research is an extension of [5], in which the inverter's PWM is altered in order to produce broad spectrum PRBS-like patterns on top of the fundamental. In this paper, these excitations are used as pilot signals and are tracked at various points in the grid, in order to estimate the transfer function of its propagation path. A multi user system will be considered in which up to four emitters can be sending pilot signals simultaneously, and their signals will be tracked at the transformer substation. Upon detection, the transfer function of the propagation path is estimated through correlation. As discussed in further sections, the orthogonality of the PRBS is not perfect, and on low-pass systems, sub-optimal results are obtained when many emitters with different strengths are considered. In order to improve the results and design a scalable system, a modified version of Successive Interference Cancellation (SIC) technique is applied, which permits to improve results for weaker signals by decoding strong signals first and removing their contribution.

A brief description of the PRBS patterns is given in Section 2; notions on their properties for system identification are considered and their spectral and temporal properties are highlighted. Section 3 introduces the SIC algorithm and its application for identification purposes. The system setup with inverter and grid model is presented in Section 4. Methods, calculations and equations for the impedance measurement algorithm are presented in Section 5. Finally, Section 6 illustrates simulations with realistic grid conditions obtained by CREOS, the utility provider in Luxembourg.

2. PRBS & Cross correlation

The Pseudo-Random-Binary Sequences are deterministic bit streams of '1's and '0's occurring 'pseudo-randomly' over their run length after which the complete sequence is repeated. Their temporal and spectral characteristics make them very valuable as a stimulation signal for system identification. They are easy to generate; a schematics of a four bit PRBS is depicted on Figure 1. It consists of a of digital shift registers, combined with logical XOR gates. The number of shift registers and the position of the XORs determine the run length and the polynomial of the PRBS. For the specific case of Maximum Length Sequences (MLS), for a given seed, a polynomial of length L will produce a deterministic pseudo-random binary sequence of '1's and '0's of $2^L - 1$ elements, after which the sequence will repeat itself.

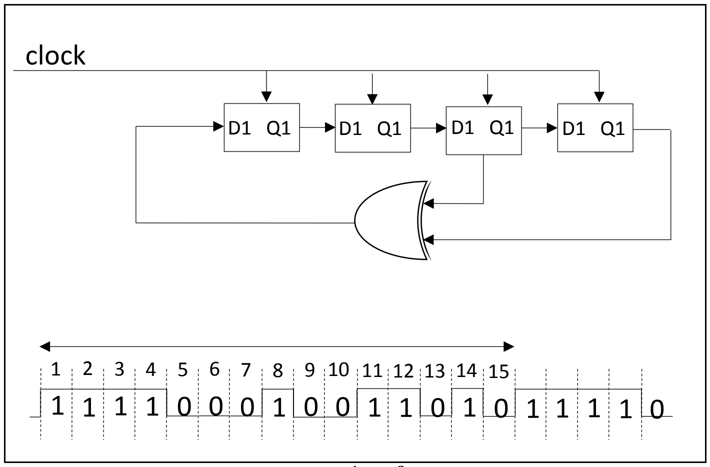

Figure 1: A Pseudo Random Generator with polynomial $x^4 + x^3 + 1$, generating a repeated random sequence of 15 bits

The PRBS sequence has interesting properties applicable for system identification:

- Depending on the relationship between the code-length, sampling frequency and code frequency, the PRBS exhibits an almost flat spectrum for a defined frequency range, with zeros occurring at multiples of the PRBS clock sampling frequency.
- For system characterization, a high amplitude spectrum is necessary in the desired frequency range in order to achieve optimal energy distribution and accuracy. This has to be mitigated with the injected Total Harmonic Distortion (THD) in order to find the adequate compromise between Signal-to-Noise Ratio (SNR) and harmonic pollution. The code length, its sampling frequency and the strength of the PRBS signal permit fine-tuning of these components and in order to select the optimal compromise.
- The logic required for PRBS implementation is very straightforward; it consists of shift registers and XOR gates and can be easily implemented in software, even on a modest digital controller.
- Compared to other active identification techniques mentioned earlier in this paper, the PRBS is the one most likely to pass grid codes such as EN 50160 [9], as small variations are added to the fundamental over a long time period. This is accomplished without compromising accuracy, since the low amplitude pulses, which are aggregated over the complete sequence through cross-correlation, provide sufficient energy for identification. The PRBS can easily be lengthened or have its amplitude increased in order to improve SNR and spectrum range.
- As mentioned in [4] the PRBS exhibits white noise-like properties, and thus correlation techniques, eliminating uncorrelated measurement noise as well as noise from various sources, can be utilized. The plot in Figure 2 shows an autocorrelation of an 11 bit PRBS, and its cross correlation with a second uncorrelated PRBS sequence with a different polynomial, but same code length. It can be seen that a long PRBS sequence therefore behaves almost like white noise as far as the correlation property is concerned, and noise pollution caused by other uncorrelated signals such as other orthogonal PRBS signal are filtered out through correlation.

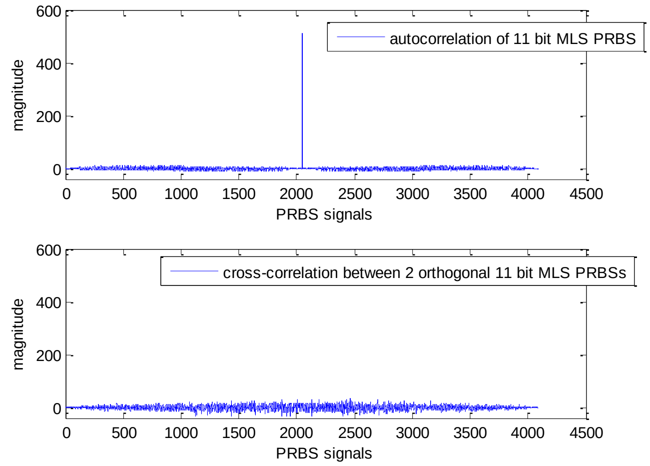

Figure 2: Autocorrelation of an 11 bit MLS PRBS, and cross correlation between 2 orthogonal MLS PRBSs

In addition the cross-correlation of the stimulation with the response of the system to that stimulation allows us to determine the dynamics of the system. Assuming that the system to be identified can be regarded as a steady-state linear time-invariant system, the system output stimulated by the PRBS can be represented by the following equation:

$$y(n) = \sum_{k=1}^{\infty} h(k)u(n-k) + v(n) \tag{1}$$

Where the *y(n)* is the output signal of the system, *h(k)* the impulse response of the system to be identified, *u(k)* the input signal, which is the PRBS pattern in our case. The disturbances, modeled by white noise are represented by v*(k)*. The cross correlation of the input signal with the output signal is given by:

$$R_{uy}(m) = \sum_{n=1}^{\infty} u(n)\, y(n+m) \tag{2}$$

$$= \sum_{n=1}^{\infty} h(n) R_{ii}(m-n) + R_{iw}(m) \tag{3}$$

$R_{ii}(m)$ represents the autocorrelation of the input signal, and $R_{iw}(m)$ its correlation with an uncorrelated white noise perturbation. When the PRBS pattern is long enough, it starts to exhibit white noise properties. Thus $R_{ii}(m)$ becomes a Kronecker delta $\delta(m)$, while $R_{iw}(m)$ becomes zero, as shown in (4).

$$\begin{cases} R_{ii}(m) = \delta(m) \\ R_{iw}(m) = 0 \end{cases} \tag{4}$$

When (3) and (4) are combined, the expression of the cross correlation is simplified greatly, and we obtain:

$$R_{uy}(m) = h(m) \tag{5}$$

Thus, the cross correlation between the input signal represents the transfer function of the excited system. This property enables the detection of the PRBS signal submerged in noise magnitudes larger than the stimulation. The cross-correlation technique becomes efficient with longer sequences, since the orthogonality will be better preserved. Given that the power network is strongly inductive for the considered system, the high frequency components are considerably attenuated at the correlator, and as shown in Figure 3, there is a loss in orthogonality, and interference is not cancelled quite as efficiently. In addition various harmonic sources are correlated and present noise that will not be filtered efficiently.

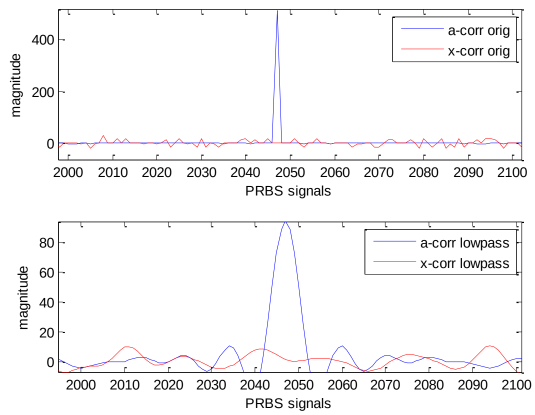

Figure 3: Orthogonality comparison between PRBS and lowpass filtered PRBS

It can be seen on Figure 3 that the autocorrelation peak drop significantly for the PRBS signal processed by a lowpass filter. The impact on the identification will be that the lowpass nature of the power network will decrease the SNR of the system identification, especially for higher frequencies. The research done in [6] shows that good results were obtained with two simultaneous signals. But as we will see in Section 4, when the strengths of the various signals are very different, the weak signals produce sub-optimal identification results. A technique called Successive interference cancellation (SIC) has been developed, and applied extensively in telecommuncations in order to reduce interference between users, especially to address so called ‘near/far effects’, where one elements signals are much stronger than others.

3. Successive interference cancellation

Successive interference cancellation has been successfully applied in telecommunications for many years [7]. In this research, the novelty is the adaptation of this technique for grid parameter estimation, in order to cancel interference from other pilot signals. Successive Interference Cancellation is a technique derived from CDMA research, where it is used as a tool for performance improvement and ‘near/far effect’ mitigation on multi user detection. When correlating with orthogonal codes, a parallel interference cancellation is performed; an alternative is to perform a successive interference cancellation when additional information about the system is known beforehand. The approach involves successively cancelling the interference starting from the strongest users. Equation below transcribes the current signal at the receiver:

$$r(t) = \sum_{k=1}^{K} A_k \cdot a_k(t - \tau_k) \cdot \cos(\omega_c t) + n(t) \tag{6}$$

- $r(t)$ being the received signal,
- K the total number of simultaneous emitters
- A_k the amplitude of the k^{th} user's PRBS sequence
- $n(t)$ additive uncorrelated noise
- $\cos(\omega_c t)$, the fundamental over which the sequence is modulated on each emitter

The PRBS sequences injected by all emitters are known, but no knowledge of the energy of the individual emitters is needed. The strongest value is not known beforehand, but is detected from the strength of the correlation of each emitter's PRBS signal with the received signal. The correlation values are forwarded to a selector which determines the strongest correlation and selected the corresponding signal for system estimation and interference cancellation. The process is repeated until the weakest signal is decoded. The process flowchart is depicted on Figure 4.

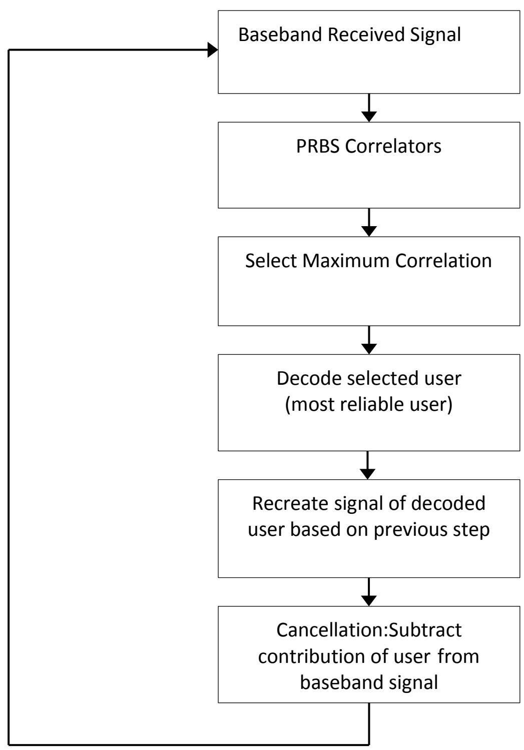

Figure 4: Successive Interference Cancellation flowchart

The plus interference for the nth user after cancellation is described by the equation below:

$$C_{j+1} = \sum_{k=j+2}^{K} A_k I_{j,j+1}\left(\tau_{k,j+1}\right) + n_{j+1} + \sum_{i=1}^{j} C_i I_{i,i+1}\left(\tau_{i,i+1}\right) \tag{7}$$

Where $I_{k,i}$ represents the cross correlation of the different codes:

$$I_{k,i}\left(\tau_{k,i}\right) = \frac{1}{T}\left[\int_0^T a_k(t-\tau_{k,i}) \cdot a_i(t)dt\right] \tag{8}$$

In equation (7), the first term represents the inter-code interference due to imperfect orthogonality of all users that have not been cancelled yet. The second term is due to noise in the system, the third term is due to imperfect cancellation. In this paper, an adapted version of the SIC algorithm will be applied. Performance improvement over traditional PRBS system identification will be measured and quantified for a predefined system model, which is described in the next sub-section.

4. System Model

a. Inverter Model

The model of the grid-tie inverter used for this research is depicted in Figure 5. It comprises a DC Voltage source, with a Pulse Width Modulation based Voltage Source Inverter (VSI) connected to the power network through a low pass LC-filter.

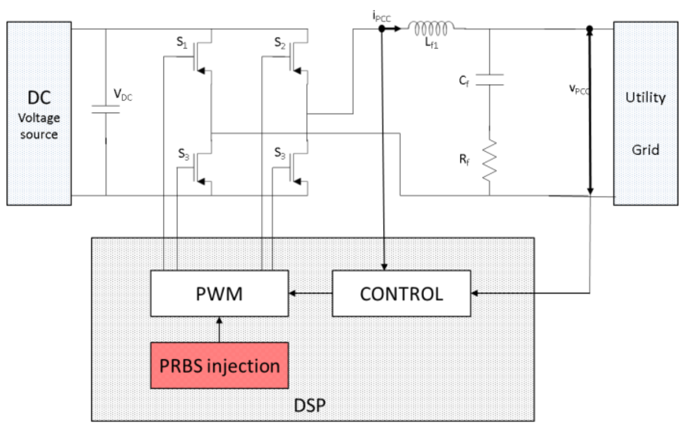

Figure 5: Grid-connected inverter topology with LC output filter

Previous research has provided a detailed description of the PRBS injection mechanism at the DG's inverter. The details of the implementation can be reviewed in [5]; the outcome being that the PRBS is injected at the inverter through the modification of its PWM on each phase.

b. Grid Network Model

A basic sub-grid topology will be considered for channel estimation. The simple distribution grid depicted on Figure 6 represents the studied system. The system configuration is limited to a substation with feeders in order to illustrate the algorithm, and research on extended grid structures with multiple branches will be addressed in further studies. The system is characterized for one phase, and an equivalent procedure can be setup for each phase in order to identify each phase individually. The studied system, shown in Figure 6, consists of a power generator connected to a voltage transformer distributing power through four feeders. Connected to the feeder are residential loads, and inverter-based distributed generators are located at the end of each feeder.

The electrical parameters of all the components of the system are described in Table 1 in the Section 6. As mentioned previously, the intended frequency identification range is up to 2000 Hz, since typically the first forty harmonics are considered for power quality considerations in European grid codes [8]. The grid is considered stiff enough for most harmonic currents flow to transformer [10].

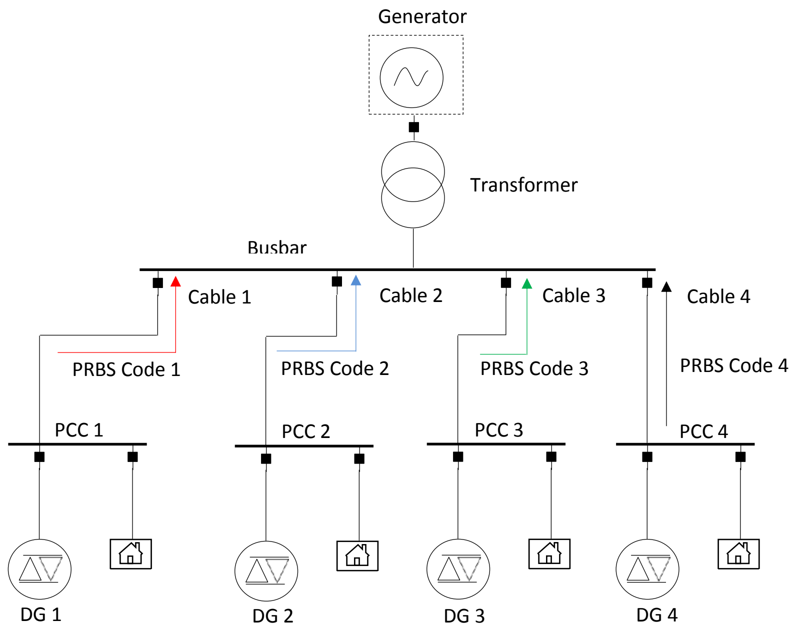

Figure 6: Distribution network model used for system identification

The consumer loads on the line are chosen according to average consumption data based on the Luxemburgish Medium Voltage and Low Voltage network. Given their relative low profile and high equivalent impedance, they can be neglected for the calculations and it can be assumed that current harmonics are propagating exclusively to the transformer. The estimated impedance of the powerlines consists of the propagation path of the stimulation, which includes among other busbars, connectors, switchboard, fuses and the cable itself. For the relevant frequency ranges and for the cable lengths that are considered, an inductive-resistive model represents the system relatively accurately. Nevertheless, this is not a limitation of the described non-parametric identification method, as no parametric constraints are set as far as the model evaluation is considered. Further research, taking into more complex cables models is foreseen, but this is out of the scope of this research, and it would merely affect the interpretation and modelling of the system identification procedure.

The electrical model of one of the feeders of the system is depicted in Figure 7. The modeled consumer loads are comparatively small with a high cos phi. The equivalent electrical model rendered is a high impedance and reactance, such that the PRBS related harmonics currents are propagating almost exclusively to the substation busbar.

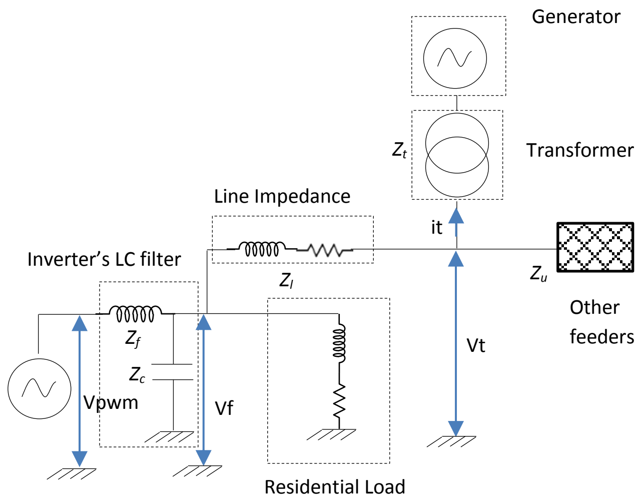

Figure 7: Electrical representation of distribution network model

5. Measurement with PRBS and SIC

At the substation the PRBS code generated by each inverter is known in advance. In addition each inverter's filter parameters are supposed to be known by channel estimator at the transformer substation. The unknowns of the system are the Z_l of each line, which have to be estimated. The electrical diagram of the system, shown in Figure 7, is used to calculate the resulting impedance. The generated current swings will be detected through measurement instruments that capture the current at the transformer secondary. The voltage is assumed stiff enough at the substation that the voltage harmonics are low enough that they can be neglected. The generated PWM patterns at the inverter can be predicted if the PRBS pattern is known, and based on the attenuation of the patterns at the substation, the parameters of the line can be determined.

As mentioned in Section II, a correlator is able to extract weak signals submerged in high amplitude noise. The longer the pattern is, the higher the power of the signal is over which the correlation will aggregate. Therefore, the low amplitude PRBS signal generated at the inverter is detected at the receiver. The equations described in (5), transcribed to the frequency domain are applied to the current at the transformer. By correlating the PRBS code with the transformer current, the equivalent transfer function can be obtained. The frequency domain representation of the correlation is given by:

$$v_{pwm}(t) * i_t(t) \quad = \overline{V_{pwm}}(\omega) \cdot I_t(\omega) \tag{9}$$

The current at the transformer is the response of the inverter pulse-pattern, convoluted by the transfer function of the propagation path of the signals.

$$I_t(\omega) = H_l(\omega) \cdot V_{pwm}(\omega) \tag{10}$$

Multiplying both sides of the equation by $\overline{V_{pwm}}(\omega)$, the transfer function can be isolated, the result being equation (12), which is used to solve for obtaining the systems transfer function, based on the stimulation a the PWM, and the resulting current at the transformer.

$$\overline{V_{pwm}}(\omega) \cdot I_t(\omega) \ = H_l(\omega) \cdot \left|V_{pwm}(\omega)\right|^2 \tag{11}$$

$$H_l(\omega) = \frac{\overline{V_{pwm}(\omega)} \cdot I_t(\omega)}{\left|V_{pwm}(\omega)\right|^2} \tag{12}$$

$H_l(\omega)$ represents the transfer function of the propagation path of the signals, and is the result of correlation the current at the transformer with the voltage patterns at the inverter's PWM. Assuming that the high voltage grid is infinitely stiff and that the interference cancellation between individual feeders is optimal, the following equations are obtained using Kirchhoff's law, in Figure 7:

$$\frac{V_f}{V_t} = Z_l \cdot I_t \tag{13}$$

$$\frac{V_f}{V_{pwm}} = \frac{Z_l \cdot Z_c}{Z_f \cdot Z_l + Z_f \cdot Z_c + Z_l \cdot Z_c} \tag{14}$$

Combining (12) and (13) and (14), the impedance of the propagation path can be inferred based on the knowledge of the transfer function pf the propagation path H_l and the inverters filter parameters Z_f and Z_c:

$$Z_l = \frac{\left(\frac{1}{H_l} - Z_f\right) Z_c}{Z_f + Z_c} \tag{15}$$

That operation is done for each PRBS code of the different inverters. The identification results are reliable, if interference from other PRBS signals being sent simultaneously is filtered out. Simulation results show that the operation exhibits good results with small scale networks, but when there is a significant discrepancy between the powers of the different stimulation signals, results start to degrade. This reduces the scalability of this method, and in order to improve the performance of the filtering for larger systems, Successive Interference Cancellation is applied.

The CDMA based algorithm is revised for our purposes of grid parameter estimation. The first step consists on continuously correlating the transformer current with all the PRBS codes of the system. When a correlation peak for any code is obtained, the steps shown on Figure 8 are performed. The strongest peak detected is selected for identification and the propagation path of that code is characterized through correlation with the PRBS code using equation (12) and (15). This provides an estimation of the impedance of the propagation path from the inverter to the transformer. This information is used to recreate the current harmonics injected by the inverter at the transformer, taking into consideration the PRBS pattern generated at the inverter. The recreated current is subtracted from the transformer current, and the resulting current is used for identifying the second strongest. The powerline corresponding to the second strongest signal is then estimated using the resulting current I_{rec} from Figure 8. This operation is performed recursively until all simultaneous peaks are treated, as shown in Figure 8.

In traditional system estimation, every signal is decoded treating the other signals as interference. In contrast, the SIC receiver is a multiuser receiver: one of the users, say user 1, is decoded treating the others as interference, but user 2 is decoded with the benefit of the signal of user 1 already removed. Thus, it can immediately be concluded that the performance of the conventional receiver is suboptimal. The benefit of SIC over the conventional receivers is particularly significant when the received power of one user is much larger than that of the other: by decoding and subtracting the signal of the strong user first, the weaker user can get a much higher accuracy than when it has to contend with the interference of the strong user.

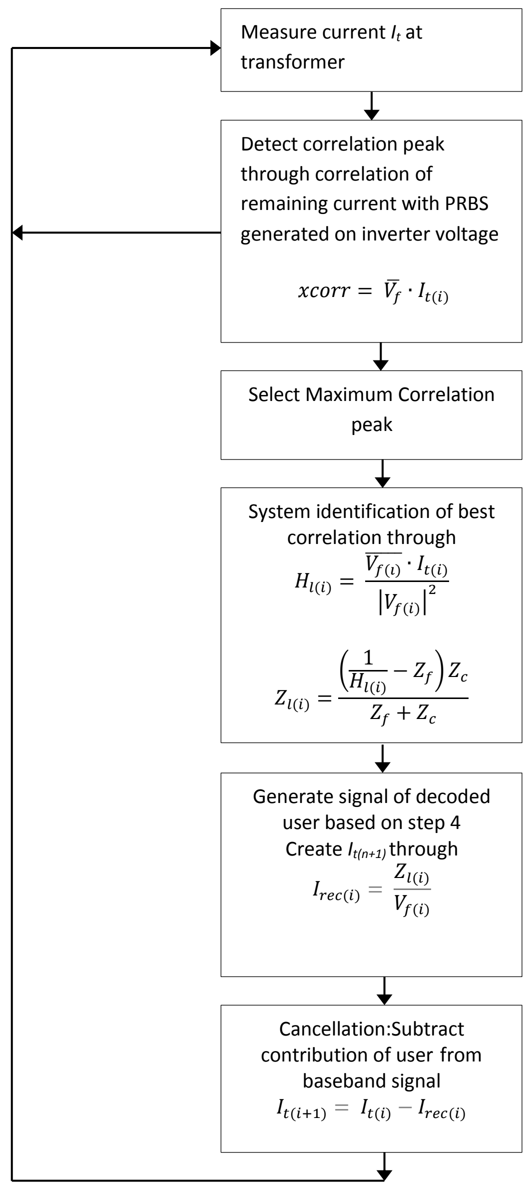

Figure 8: Flowchart of SIC algorithm for Grid Parameter Identification

6. Simulation results

Simulations have been performed using the setup described in Section 4 and Section 5. Inverter and system parameters are shown in Table 1.

Table 1: System Parameters

STIMULATION PARAMETERS	
PRBS code length	2047
Sampling frequency	20 Khz
PRBS polynomial line 1	$x^{11} + x^9 + 1$
PRBS polynomial line 2	$x^{11} + x^9 + x^6 + x^5 + 1$
PRBS polynomial line 3	$x^{11} + x^9 + x^7 + x^2 + 1$
PRBS polynomial line 4	$x^{11} + x^9 + x^6 + x + 1$
Carrier frequency	12800 Hz
Codes per 50 Hz cycle	256
PRBS carrier duty cycle	4 %
ELECTRICAL PARAMETERS	
Zc	5 Ω , 9.45e1 μF
Zf	10 mH
Zt	12 mΩ , 0.2 mH
Zl1	10.2 Ω , 3.2 mH
Zl2	20.4 Ω, 6.4 mH
Zl3	40.8 Ω, 12.8 mH
Zl4	81.6 Ω, 25.6 mH
Load active and reactive power	P = 10e-3 MW Q= 1e-3 MW

All codes are 11 bit MLS PRBS and pseudo orthogonal to each other. On the start of a fundamental cycle, a 2047 bit PRBS pattern is injected in the system, using 4% of the carrier cycle at the inverter for pilot injection [5]. Given that the carrier frequency is 12800 Hz, there are 256 PRBS codes injected per carrier cycle. The complete PRBS pattern is sent over 8 fundamental cycles, which corresponds to 0.16 seconds. In order to avoid spectral noise due to the limited time window, a Hanning window is used to process the data. Given the sharp low-pass characteristic of the RL filter beyond the filter's resonance frequency, an additional lowpass filter for data processing is not necessary to avoid anti-aliasing.

a. System estimation without SIC

Current is measured at the transformer substation, and the voltage patterns at the inverter are estimated, based on the knowledge of the PRBS pattern and the operation of the PWM inverter. The PRBS excites the complete frequency range in interest. The detection process is performed as described in Section 2 based on equation (15), with the knowledge that the pattern always starts at the positive edge of the fundamental. In this example the worst case situation is considered where the four emitters emit simultaneously, the stronger signals overshadowing the weaker ones. In order to highlight the advantages of SIC, the impedance of the lines are doubled from one line to the other, while all other parameters are kept the same. This makes the generated harmonics much weaker of the high impedance lines, and they are going to be submerged with very strong interference for other lines. Figure 10 plots the estimated impedance of the powerlines based on equation (15), using the PWM pulses as V_{Pwm} . The continuous lines correspond to the theoretical impedance of the line as programmed in Matlab, while the dotted lines represent the result of the system estimation procedure. The results of the identification are accurate for the strongest signal and relatively good for the second strongest signal. For the weaker signals, the identification becomes inaccurate. This is due to the fact that the cross correlation with the code is not able to completely eliminate broadband noise that is much larger than the signal itself. Nevertheless, system identification without SIC can be successfully applied, if we can guarantee that no more than two senders are emitting simultaneously for our system configuration. In order to improve scalability and the results of the identification of the weaker lines, SIC is performed.

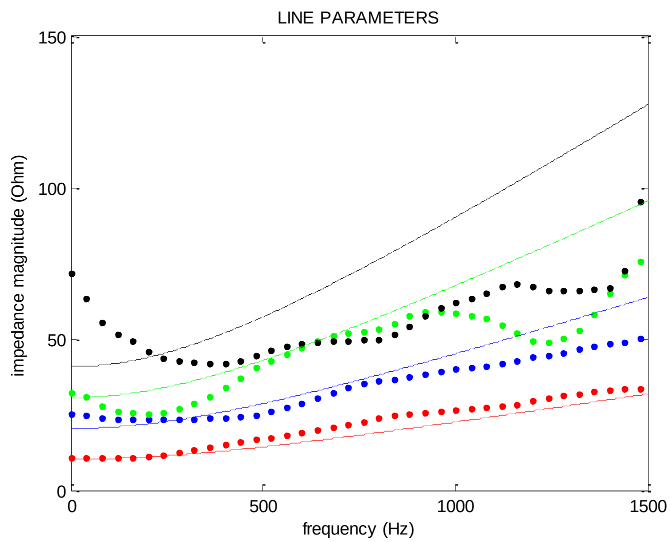

Figure 9: Grid characterization of four power lines using 'parallel' identification

b. System estimation with SIC

The correlation with the different codes allows us to detect the sequences. It also gives an indication about the strength of each signal, allowing us to rank them according to their strength. The procedure described in Figure 8 is followed in the simulations. The user doesn't need to know which emitter is the strongest, it will infer this based on the strength of the correlation peak. Figure 10 shows the correlation with the four codes, and highlights their respective strengths.

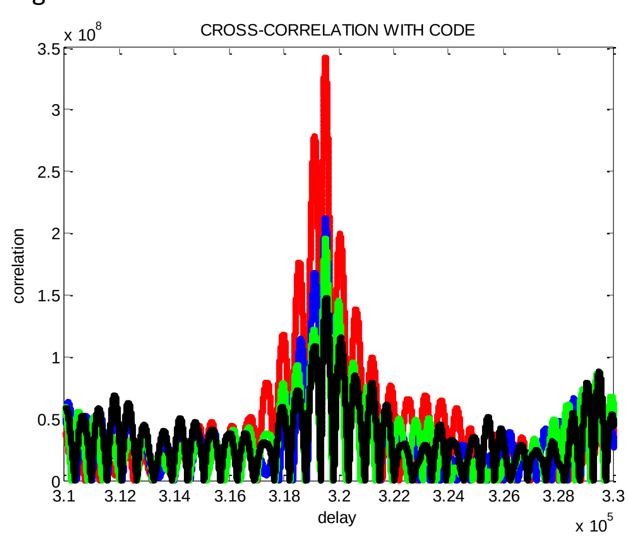

Figure 10: Cross-correlation of the four PRBS codes at the receiver

Thus the red correlation, corresponding to line 1 is the strongest. Impedance for line 1 is determined according to equation (15), its current contribution to I_t is subtracted from I_t, and the same procedure is started over again for line 2. Apart from the interference cancellation procedure, which subtracts the contribution of the current from stronger signals, the detection procedure is identical to the preceding method. All system parameters have been kept the same so that the two results can be compared. The results, shown in Figure 11, highlight the improvements, especially for the weak signals.

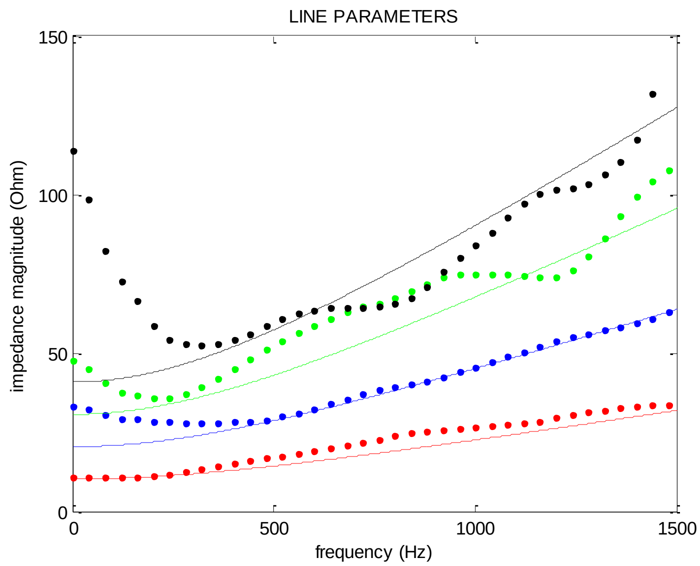

Figure 11: Grid characterization of four power lines using SIC identification

c. Estimation Error Improvement

For the strongest signal, the results are identical, given that no interference cancellation has been performed on that one. But it can be seen that on the other signals, the relative improvement is considerable, apart from the low frequency end of the spectrum, where the SIC method constantly overestimates the impedance. This is also the case in the non-SIC method, but to a much lesser degree. This can be explained by the fact that the fundamental is present on all signals, and has not been considered for the identification procedure, since we only use the PRBS code to correlate with the current. Its effect is corrupting the surrounding frequencies, making the transfer function for these frequencies less responsive, thus with a higher impedance. This effect is magnified by SIC, due to the cumulative effect of the recursive algorithm. Current research is addressing this issue. Investigations are done to resolve this problem by:

- Increasing the spectral resolution by lengthening the PRBS sequence
- Taking into account the fundamental which will make the algorithm more complex and dependent on inverter control
- Additional filtering and signal processing

Therefore, for this research, in order to quantify the improvements, the cumulated error over the 150-2000 frequency range is considered. Results on the lower frequency range are typically corrupted by the fundamental and its spectral leakage, which remains strong, even if windowing is applied. The equation used for error qualification is the following:

$$Cumulated\ Err_{method} = \sum_{f=150}^{2000} \frac{Z_{l\ method}(f) - Z_l(f)}{Z_l(f) * 1850} \tag{16}$$

And the results, based on Figure 10 and Figure 11, are show in Table 2.

Table 2: Accuracy improvement over standard PRBS over the 150-2000 Hz range

	Cumulated Err PRBS	Cumulated Err SIC	SIC over PRBS improvement
Line 1	12.9%	12.9%	0%
Line 2	9.9%	5.7%	173%
Line 3	25.1%	10.1%	249%
Line 4	39.2%	10.5%	373%

Thus the results confirm the proposed implementation can be used for multi-generator systems. A system identification of a complex power network structure will be considered in further research tasks. It can be seen that SIC clearly improves results, especially for weak signals, and that adding that functionality to the proposed grid monitoring tool improves significantly results at no additional cost.

7. Conclusions

In the next decades, the electricity provided by distributed inverter based generators connected to the power network will keep growing and the influence of DG on grid infrastructure, stability and reliability will be more and more prevalent. A grid assessment method, such as the one described in this research, can assist network operators in handling the modern and complex smart grid that is being created in European countries.

An advanced multi-purpose real-time estimation method for frequency dependent grid parameter determination has been presented in this paper. The method is based on PRBS sequences, which are injected as pilot signals from the inverter. PRBS sequences have been extensively used in system identification, as they exhibit useful properties, such as wideband spectrum, ease of implementation and orthogonality. Simulation results show that the proposed method operates accurately in systems with multiple injectors, as long as each injector operates with codes orthogonal to the others. In order to improve results in more complex grid situations with 'near/far' effects, where some pilot signals are much stronger than others, a technique borrowed from telecommunication, called Successive Interference Application, has been adapted for grid identification, and has shown to increase estimation results significantly when many inverters emit pilot signals simultaneously.

The proposed method characterizes the propagation channel over a significant frequency range with a high resolution. It provides a high degree of flexibility; longer injections provide higher frequency resolution and accuracy, shorter patterns reduce latency and THD. The proposed technique is currently being implemented in a converter at SnT's Netpower Laboratories in order to verify the performance in real settings and confirms the simulations research. Further research aiming to identify more complex grid networks will be carried out as well.

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