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Inrush Current Detection based on Linear Prediction

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Abstract: The occurrence of inrush currents in power transformers is directly related with the reduction of its lifetime, as well as safe operation of electric power systems. In this paper, a new method for inrush current detection, based on linear prediction, is proposed. Linear predictors of order 2 and four are implemented, and the linear prediction error is employed as main parameter on the detection process. The methods performance is evaluated making use of a database built from simulations on Alternative Transients Program, and the modeled electric system is based on real distribution network. Aiming to evaluate the reliability of the method, Gaussian noise is added to the signals, and a noise sensitivity analysis is performed. The results indicate viability of linear prediction as a tool for fast and robust detection of inrush currents, which performed successfully in situations with SNR of 55 dB.

Keywords: Failures, Inrush Current, Linear Predictor, prediction error.

1. INTRODUCTION

Electric Power Systems (EPS) operation should take into account the vulnerability of its devices and equipment to transients, which may lead to outages and permanent failures. In this context, monitoring of power transformers has been the object of various studies in the area, after all, these devices play a large role in the transmission and distribution of electricity, impacting both in continuity and quality.

According to Cigre (1983), the nature of failures in power transformers has, mostly, mechanical origin, as shown in Fig. 1.

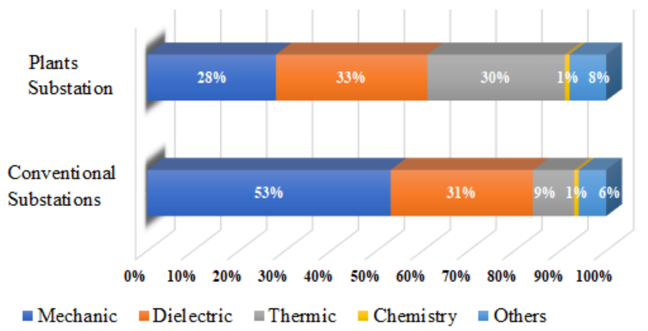

Fig. 1 Nature of failures in transformers of conventional substations and transformers of plants substation (Cigre 1983).

Dielectric failures in windings insulation are the main cause of failures in transformers, however the fail process is usually started by a mechanical defect (Cigre 1983). For this reason, it is clear that mechanical failures in transformer windings are of undeniable interest for manufacturers and power companies.

Among the several transient events that may lead to transformers mechanical failure, Inrush Current (IC) is one of the most concerning given its consequences on EPS. This phenomenon, typical of transformers energizing process, reduces its life (Sen 2007). During energization, high dynamic magnetic fluxes are generated in the core, which results in the saturation of one or more limbs, giving rise to magnetization currents of great amplitude and distorted waveform.

According to Balachandran (2007), ICs have short duration, high magnitude, high harmonic content, DC component and are unbalanced between phases. Due to its high magnitude (Balachandran 2007, Gopika 2017), some undesirable effects happen, such as: mechanical stress on the transformer windings, insulation failure, unwanted tripping of protective relays and fuses, oscillatory torque in motors, resonance in the system and, mainly, voltage sags. It is important to notice that last three effects impact more directly in the Power Quality (PQ), while the first two impact mostly in the transformer's lifetime. Also, when high magnitude ICs misguides relays and fuses to operate, problems in power transformer protection systems can be triggered. According to Saleh et al. (2003), false positives may arise since this current has, in some cases, magnitude equal to or greater than the nominal current of a transformer, and may be confused with short-circuit currents.

Several inrush current identification techniques are available in the literature. Detection of second harmonic (Rahman et al. 1988, Yabe 1997) is a viable technique, since ICs have notorious second harmonic presence when compared to the short-circuit currents, for example. However, according to Abbas et al. (2016), internal faults in power transformer windings may also include second (2^{nd}) and sometimes the fifth (5th) harmonics presence. In addition, due to advanced power electronics techniques used, power transformer also may produce magnetizing inrush current with second harmonic components. So, comparing the ratio of the 2nd and 5th harmonics with 1st to a predefined threshold value is not useful to discriminate the inrush current from internal faults currents.

In this context, other methods are employed, considering approaches that involve impedance-based techniques (Al-Tallaq et al. 2003), Least-Square Method or Ordinary Least Squares (Rahman et al 1982), Artificial Neural Networks (Gondane et al. 2018), Fuzzy Logic (Deshmukh et al. 2016). Also, more broadly and recently, wavelet transform (Saleh et al. 2003, Abbas et al. 2016, Sendilkumar et al. 2010, Megahed et al. 2008, Jettanasen et al. 2012). Many of those techniques have dependence on the transformer's parameters, which may be seen as a disadvantage.

In this paper, a new method for inrush current detection, based on linear prediction, is proposed. The linear predictor (LP) is a mathematical method aimed at predicting the value of a sample of a sequence as a linear combination of the former ones. The weighting coefficients are obtained by comparison between observed and predicted values. The Linear Predictor (Dalzell et al. 2011, Riahy et al. 2008) has been applied to a test distribution system modeled in the Alternative Transients Program (ATP) software, based on a real distribution system data, formed by 57 bars, owned by EDP Brasil, a distribution company. Lastly, a sensitivity analysis of the method is performed considering the addition of artificial white Gaussian noise.

2. INRUSH CURRENT

Inrush current is the maximum instantaneous input current given by an electric device when it is switched on (Gondane et al. 2018). In general, when a power transformer is energized, a transient current of magnitude much greater than the magnitude of the nominal current is established for several cycles. According to Rahman et al. (1988), this magnitude comprises 20 times the normal current value and can last from a few cycles to tens of milliseconds. It requires about 30 to 40 cycles for the current to settle down to its normal current value. In Fig. 2 a curve describing the typical shape of IC, obtained from ATP simulations, is shown.

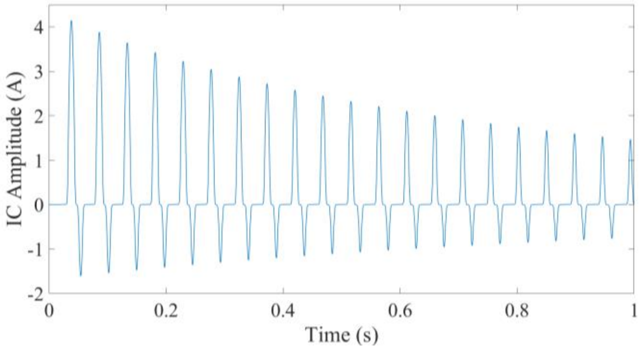

Fig. 2 Inrush Current in the transform.

IC is usually attributed to the rise of the magnetizing current of a transformer energization process, with or without load in its secondary, due to magnetization and the saturation of the nucleus (Sen 2007). However, according to Gopika (2017), other situations can give rise to IC: parallelism of an already energized transformer with another in the same situation; fault evolution during contingencies; external faults and; occurrence, after elimination of an external fault, of a recovery voltage.

In general, the magnitude and duration of the transient IC depends upon four factors (Hudson 1966):

i. Switching angle, that is, the instant in the voltage waveform in which the power transformer is energized;
ii. The impedance of the circuit responsible the power transformer supply;
iii. The signal and value of the residual magnetic flux in the core after the power transformer has been de-energized;
iv. The characteristics of the magnetic saturation in the core of the power transformer.

3. LINEAR PREDICTOR

The Linear Predictor (LP) is an algorithm responsible for predicting the value of a sample of a sequence from a linear combination of the other samples. That way, combination coefficients are obtained from a comparison between the actual value and the predicted value (Dalzell et al. 2011).

The LP's aim is to form a model of a Linear Time Invariant (LTI) digital system through observation of incoming and outgoing sequences. Therefore, must be estimated a set of coefficients that describe the behavior of an LTI system when the project is not available and when the choice of which input to present cannot be accomplished.

According to Dalzell et al. (2011), a LP may be used for equalization, as it operates by minimizing autocorrelation, and it operate as a channel-shortened, for high and low signal-to-noise ratio scenarios.

Being the set of coefficients that provide an estimate - or a prediction - for a next outgoing sample $\hat{x}(n)$ and given the knowledge of incoming samples $y(n)$ and/or previous output $x(n)$, the $\hat{x}(n)$ is given by:

$$\hat{x}(n) = \sum_{k=0}^{p} a_k y\,[n-k] - \sum_{k=1}^{q} b_k x\,[n-k] \quad (1)$$

where a_k and b_k are called prediction coefficients.
The most common form of an LP applied in signal processing is that in which the coefficients (a_k) is equal to zero, so that the output estimate is made entirely from previous output samples, that is:

$$\hat{x}(n) = -\sum_{k=1}^{q} b_k x\,[n-k] \quad (2)$$

Thus, it is noticeable that this method includes a mathematical operation in which future values of a discrete time signal are estimated as a linear function of previous samples (Riahy et al. 2008).

In Fig. 3 it is possible to observe a block diagram of the LP algorithm. A Forward Linear Predictor will predict the most recent sample of the sequence from older samples. It is important to note that $x(n)$ corresponds to the original signal, $\hat{x}(n)$ is the signal provided by LP, $f_p(n)$ is the prediction error and C1, C2 and Ck are the prediction coefficients.

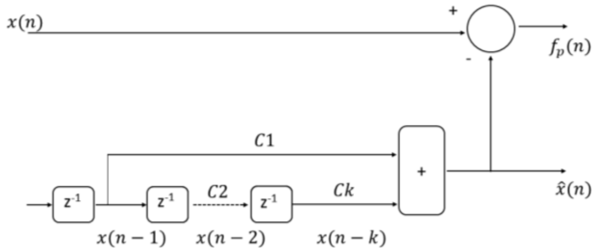

Fig. 3 Forward linear predictor.

Considering a LP (C1 and C2) of 2-order, based on (2), it is possible to obtain (3):

$$\hat{x}(n) = C1 \cdot x\,[n-1] + C2 \cdot x\,[n-2]. \quad (3)$$

The relation of (3) with LTI system equation may be more readily understood by introducing a prediction error signal, $f_p(n)$, defined as the difference between the actual output and the prediction:

$$f_p(n) = x(n) - \hat{x}(n). \quad (4)$$

Thus, it is possible to write (5), for the 2-order system:

$$x(n) = f_p(n) + C1 \cdot x\,[n-1] + C2 \cdot x\,[n-2]. \quad (5)$$

From (5), it is verified that the error signal takes on the role of the excitation signal, and the prediction coefficients defines the filter.

It is evidenced that for the 4-order LP, namely, C1, C2, C3 and C4, it is possible to reproduce what has been demonstrated previously from the respective prediction coefficients.

4. METHODOLOGY

4.1 Database

Simulations were performed based in a test system built in the ATP software, parameterized with data of a real distribution system, owned by EDP Brasil. A graphical representation of the system is presented in Fig. 4.

The following characteristics are considered for the proposed modeling:

- Non-transposed three-phase lines at distributed and constant parameters;
- Loads close to the points along the feeder, grouped in a single node, resulting from a feeder with 57 bars;
- Stretches composed for homogeneous conductors' Poppy type;
- Skin factor for cables equal to 0.5;
- Soil resistivity of 100 Ω/m;

In this system, the addition of non-linear loads was considered in order to monitor the increase in the levels of harmonic currents found in electrical systems.

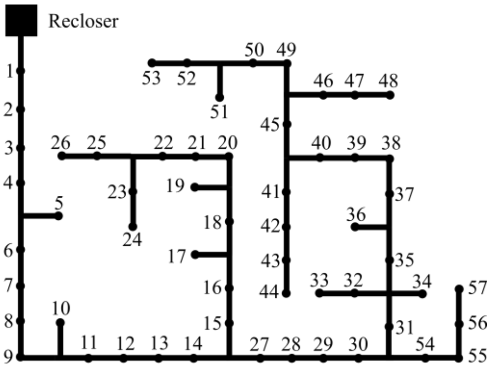

Fig. 4 Single line diagram of the modeled feeder.

A three-phase saturable distribution transformer model was used, considering the following characteristics: grounded Δ-Y connection; rated line voltages of 13.8/0.380 kV; rated power at 30 kVA. The choice of a relatively low power transformer is deliberate and aims to demonstrate the sensitivity of the method. In total, 30 different configurations were executed, and in each one of them the saturable transformer was placed in a different bar. During the simulation, the three-phase current signals were recorded from bar 1 (substation recloser). The choice of the bars in which the saturable transformer was connected was random, so several distances from the IC source and bar 1 were considered, covering most of the possible situations in the test system.

In order to ease the visualization of the results, the moment of inrush occurrence is always 0.333 ms in all simulations. Since the current observed from bar 1 is the sum of load currents of the whole system. It is assumed that a share of the current observed in bar 1 contains the IC signature. Therefore, it is expected that the proposed method is able to detect this IC signature. This current acquired from bar 1 is the only input parameter for the IC identification process.

In each execution of the simulation the transformer was connected to a different bar of the system, associated with a switch - added between two bars of the test system, for example, between bar 7 and 8 - that carried out the energization phenomenon.

All current signals generated in the database underwent downsampling for the typical sampling rate adopted by digital fault recorders, 15.360 samples/second. Gaussian noise was also added to the current signals, so that the signals approached the real conditions of a distribution system.

4.2 Inrush Current Detection

According to Riahy et al. (2008), the model order may be carefully selected for curve fitting, aiming to provide stability of the LP. In addition, a compromise between computational effort and success in the detection must be admitted. The database was object of tests in order to define the best predictor order, considering success rate and computational effort. LPs of order two and four were built according to the theory presented in Section III.

It is expected that components of IC present in the total current (monitored from bar 1) to cause an increase in the Prediction Error (PE) value. Therefore, the detection of IC can be pointed by a significant variation in the PE. In order to quantify this variation, the maximum variation ratio (VAR_{max}), is calculated according to (6):

$$VAR_{max} = \frac{V_{pduring} - V_{pbefore}}{V_{pbefore}} \cdot 100\% \quad (6)$$

where $V_{pbefore}$ is the peak value of the signal before the occurrence of IC and $V_{pduring}$ is the overshoot during the occurrence of the phenomenon. If the VAR_{max} value is exceeded for 5 cycles (whole observation window), it is assumed that inrush has occurred. This value is less than defined in the resolution (ONS 2009, ANEEL 2017), in which a time equal to 150 ms is defined for protection devices to act properly during the detection of disturbances.

In addition, a noise sensitivity analysis was performed, which made possible estimate the noise tolerance of the method. Gaussian noise was added to the database with Signal-to-Noise Ratio (SNR) of 55 dB, 60 dB e 65 dB. The whole process, from database generation to IC detection, is presented as a flowchart shown in Fig. 5.

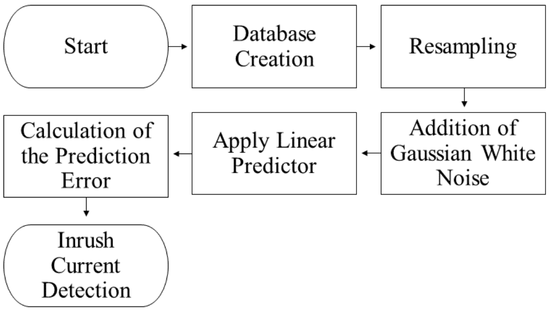

Fig. 5 Flowchart of identification process.

5. RESULTS AND ANALYSIS

As already mentioned, the IC may have different amplitudes, depending on several parameters. For some particular cases of this event, such as transformers located near bar 1, these currents report high amplitudes and can be easily identified, even by visual inspection. However, in cases where the IC source is distant from Bar 1, the amplitude variation in the total current may be visually imperceptible. The success rates of sensibility analysis for distinct values of the SNR are shown in Table 1. In this case, the IC detection was done considering a single phase.

Looking the Table 1 and considering the single-phase IC detection, for two and order 4 of the LP, it is noticeable that the IC detection with SNR equal to 55 dB is more difficult. In all cases the maximum success rate was about 16%.

When it comes to results obtained to a SNR equal to 60 dB and 65 dB, the algorithm presents superior results. Applying the two and order 4 LP, respectively, is obtained a success rate of 97% and 100% for phase A, 90% and 93% for phase B and 97% and 93%, to phase C, with SNR equal to 60 dB. For SNR equal to 65 dB the algorithm does not fail in any of the characteristic cases of IC.

The proposed method is well suited for very high SNR, ranging between 60 dB to higher values. There are situations where peak variations before and during the IC occurrence are very small. However, considering the three phases, it was always possible to detect the IC occurrence in at least one of the phases, among the analyzed cases with noise greater than 60 dB.

Table 1. Method's Performance in the Presence of Gaussian Noise

	Order 2									Order 4								
SNR	55 dB			60 dB			65 dB			55 dB			60 dB			65 dB		
Phase	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Bar																		
3				■	■	■	■	■	■				■	■	■	■	■	■
5	■			■	■	■	■	■	■	■			■	■	■	■	■	■
7				■	■		■	■	■	■			■	■		■	■	■
11	■			■	■	■	■	■	■				■	■	■	■	■	■
13	■		■	■	■	■	■	■	■			■	■	■	■	■	■	■
15				■	■	■	■	■	■				■	■	■	■	■	■
17				■	■	■	■	■	■				■	■	■	■	■	■
20		■		■	■	■	■	■	■				■	■	■	■	■	■
23				■	■	■	■	■	■				■	■	■	■	■	■
25			■	■	■	■	■	■	■				■	■	■	■	■	■
28		■		■	■	■	■	■	■		■		■	■	■	■	■	■
29			■	■	■	■	■	■	■				■	■	■	■	■	■
32				■	■	■	■	■	■				■		■	■	■	■
33				■	■	■	■	■	■			■	■	■	■	■	■	■
34				■	■	■	■	■	■				■	■	■	■	■	■
36				■	■	■	■	■	■				■	■	■	■	■	■
38				■	■	■	■	■	■	■			■	■	■	■	■	■
40	■			■	■	■	■	■	■				■	■	■	■	■	■
41				■	■	■	■	■	■		■		■	■	■	■	■	■
43			■	■	■	■	■	■	■				■	■	■	■	■	■
44				■	■	■	■	■	■				■	■	■	■	■	■
46				■	■	■	■	■	■			■	■	■	■	■	■	■
48				■	■	■	■	■	■			■	■	■		■	■	■
49				■	■	■	■	■	■			■	■	■	■	■	■	■
51				■		■	■	■	■				■	■	■	■	■	■
53				■	■	■	■	■	■				■	■	■	■	■	■
54				■	■	■	■	■	■				■	■	■	■	■	■
55						■	■	■	■				■		■	■	■	■
56				■		■	■	■	■				■	■	■	■	■	■
57				■	■	■	■	■	■				■	■	■	■	■	■

From Table 1 it is clear that bars 53 and 57 are among the more challenging for IC detection, probably due to its distance from bar 1. Aiming to illustrate the detection process, these two bars were chosen for a graphical explanation of the results. The applied noise in the presented cases is 60 dB and 65 dB.

In Fig. 6 and 7, for illustrative purposes, it is possible to observe the ICs, as found on the IC source itself (transformer), when allocated on bars 53 and 57, respectively.

Aiming at comparing the proposed method with one already disseminated in the literature, as it was presented in works as (Abbas et al, 2016; Wang et al, 2008), the Fourier Transform was used in order to estimate the presence of the second harmonic. Taking into account the noisy conditions imposed and the special cases, characterized by low amplitudes of IC signature, it has been found the method based on the second harmonic is not able to detect the occurrence of the phenomenon in any of the scenarios presented. In Fig. 8, when the transformer has been allocated to bus 57, with noise equal to 60 dB. In all simulated cases, this component has negligible values (very close to zero).

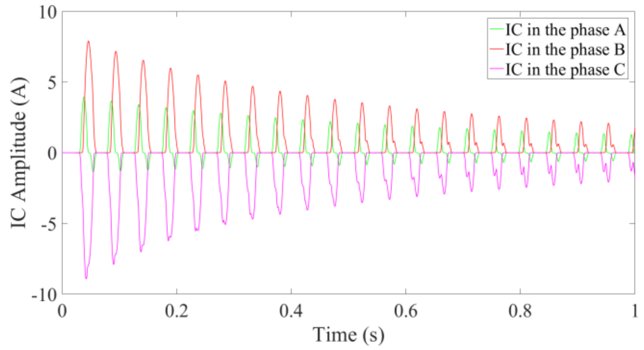

Fig. 6 Inrush current measured at bar 53 in the phases A, B, and C.

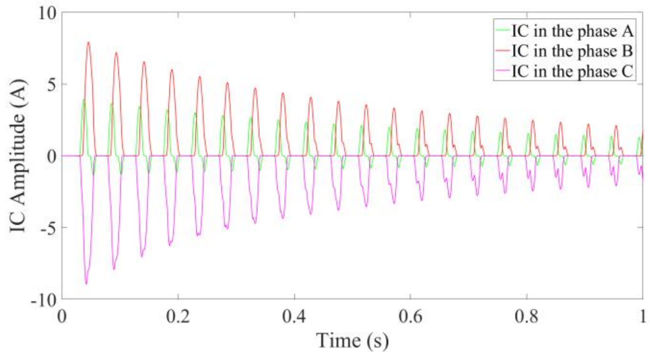

Fig. 7 Inrush current measured at bar 57 in the phases A, B, and C.

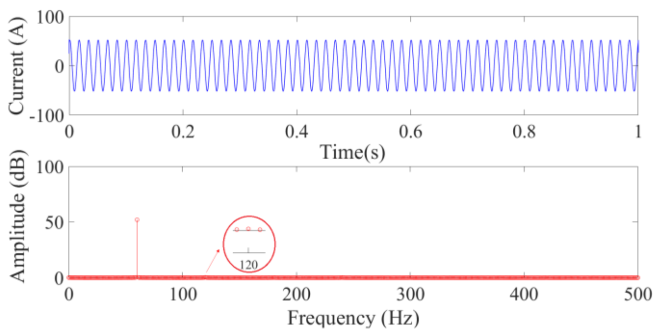

Fig. 8 (a) Current registered in bar 1 (Ia), IC in bar 53; (b) Fourier spectrum measurement.

In Fig. 9, 10 and 11, the currents in phases A (Ia), B (Ib) and C (Ic) are shown, respectively, and the Prediction Error (PE) from the prediction of order 2 and 4, for bar 53.

Considering the peak value of PE before and during the IC occurrence, the representative parameter VAR_{max} is used to evaluate the presence of IC in the total current. For the order 2 LP, a VAR_{max} of 270.2%, 207.5% and 417.4% of the currents of phases A, B and C are extracted respectively. On the other hand, for the order 4 LP, the VAR_{max} values are 232.5%, 132.1% and 257.1%, in that order, for the currents of phases A, B and C. Thus, it is possible to verify the high sensitivity of the method. In addition, it is possible to observe the decay of the amplitude of the peaks in the PE as the IC attenuates over time.

From another perspective, when comparing the order 4 LP with the order 2 LP, a similarity between the values of the VAR_{max} extracted is observed. In this case, the PE comprises a model that fits very well with the event data.

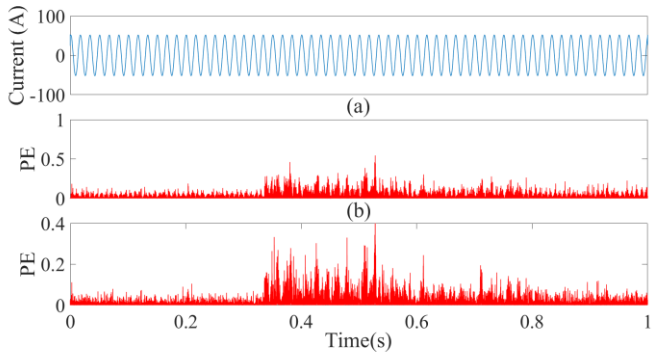

Fig. 9 (a) Current registered in bar 1 (Ia), IC in bar 53; Prediction Error: (b) order 2; (c) order 4.

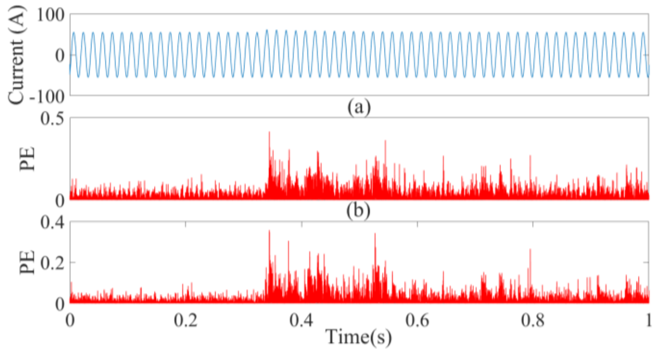

Fig. 10 (a) Current registered in bar 1 (Ib), IC in bar 53; Prediction Error: (b) order 2; (c) order 4.

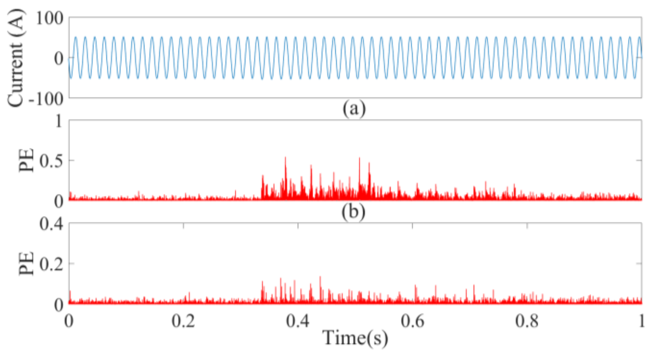

Fig. 11 (a) Current registered in bar 1 (Ic), IC in bar 53; Prediction Error: (b) order 2; (c) order 4.

From another perspective, when comparing the order 4 LP with the order 2 LP, a similarity between the values of the VAR_{max} extracted is observed. In this case, the PE comprises a model that fits very well with the event data.

Similarly, the two and order 4 LP were applied to bar 57, with noise equal to 65 dB, the results are shown in Fig. 12, 13 and 14. For these cases, the PE presents a VAR_{max} in the implementation with order 2, from 550.5%, 250.5% and 681.4%, for the currents of phases A, B and C, respectively. However, in cases where the order 4 LP was applied, a VAR_{max} of 1128.6%, 806.8% and 1096,6% is observed for the currents of phases A, B and C, in that order. Comparing the two and order 4 LP an optimized performance of the order 4 LP method was observed. The characteristic values of the VAR_{max} are mostly higher.

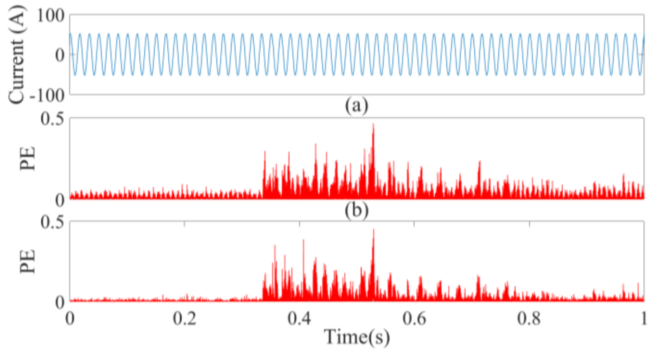

Fig. 12 (a) Current registered in bar 1 (Ia), IC in bar 57; Prediction Error: (b) order 2; (c) order 4.

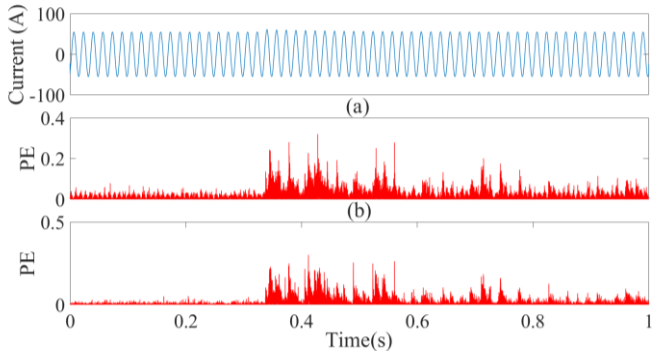

Fig. 13 (a) Current registered in bar 1 (Ib), IC in bar 57; Prediction Error: (b) order 2; (c) order 4.

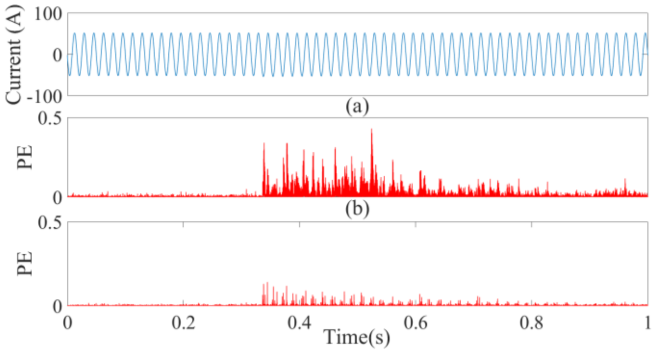

Fig. 14 (a) Current registered in bar 1 (Ic), IC in bar 57; Prediction Error: (b) order 2; (c) order 4.

The IC influence on the currents is naturally observed elapsed the 0.33 ms, and, as the phenomenon extinguishes, there is a decrease in the PE amplitude. In this case, it may be verified, mathematically, that the extracted VAR_{max} is much larger than that obtained in the first case with SNR equal to 60 dB.

It has been concluded that the IC detection method proposed in this work has performed satisfactorily in all cases, proving to be effective to values of SNR greater than 60 dB, even in cases where the energized transformer is distant from the recording point.

Finally, in order to distinguish the IC occurrence with a normal condition of the distribution system, 30 cases of notable load input (or load energization) were simulated and the proposed method based on the LP of 2 and 4 orders has been implemented. In Fig. 15, the current in phase A (Ia) and the PE from the prediction of order 2 and 4, for bar 25, with noise equal to 60 dB are shown. It is noticeable the amplitude does not remain high, becoming extinct in the first PE sample. Thus, it appears that this phenomenon may not be confused with IC and, consequently, it may not cause false positives in the distribution system, after all, the durations of these phenomena are different.

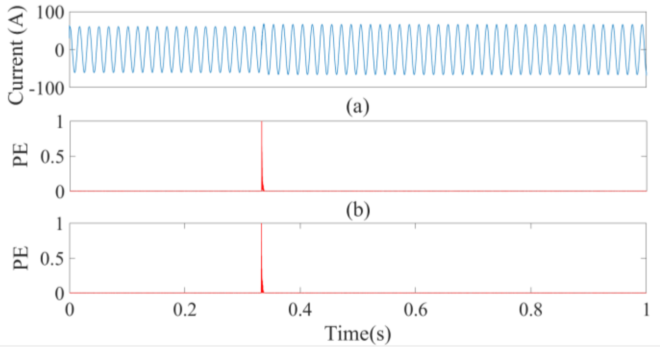

Fig. 15 (a) Load Energization in bar 1 (Ia), IC in bar 25; Prediction Error: (b) order 2; (c) order 4.

6. CONCLUSIONS

This paper proposed an IC identification method using linear prediction. This technique uses the energy of the linear predictor error as indicator of the phenomenon. The advantages of the technique include the independence of transformer and system parameters, high sensitivity and detection capability based only on current waveform.

The results obtained with the LP presented that this method is able to distinguish correctly the transient occurrence period from the rest of the signal, indicating reliability.

Observing the three phases of the current, it is always possible to identify the occurrence of the transient by at least one of them, whether with the use of LP of two or order 4 for the cases with noise greater than 60 dB. However, the order 4 LP demonstrated greater sensitivity and efficacy, presenting higher values of the representative parameter VAR_{max}, when compared to the values extracted with the application of the order 2 LP.

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