Influence of Data Resolution in Nonlinear Loads Model for Harmonics Prediction

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***Abstract*— This paper describes the influence of data resolution in the agreement of models to predict harmonics generated by nonlinear loads (NLL), basically formed by single phase and three phase rectifiers, eventually combined with linear loads. We assume that the network supplying the NLL has significant impedances and that it is disturbed by other parallel, random and unknown neighbor loads, sharing part of the supply system. The aim of building NLL models is to make predictions on the amount and flow paths of harmonic currents generated by such NLL in case of using parallel filters. In this paper, the models are obtained from sets of *(V,I)* data taken at a certain point, called measuring point (MP) and are valid to predict the NLL behavior when random known or unknown parallel loads are connected upstream of this point. The technique used to obtain the models studied here is based on Multivariate Multiple Outputs Regression (MMOR) and will not be described in detail in this paper. This method allows obtaining a set of equations giving the current harmonics as a function of voltage harmonics observed at the measuring point (MP). The accordance between model and the experimental results is very dependent on the resolution and accuracy of *V* and *I* measurements at the MP and is the core matter of this paper.**

Keywords—Nonlinear Loads; Harmonics Modeling; Power Quality; Influence of Measurement Errors.

I. INTRODUCTION

Nowadays, a large amount of nonlinear loads (NLL), mainly consisting of single-phase and three-phase rectifiers, are connected to supply networks. Such loads cause voltage distortion, which increases as the short-circuit impedance of the network increases [1] [2] Such voltage distortion is limited by international standards [3] and that has led to the necessity of limiting the harmonic currents generated by each utility user, according to standards [4]-[6]. In case that a certain network section does not comply with the international rules, the user must provide some filters to fix the problem of power quality. Nevertheless the behavior of the NLL when the filter is included results unpredictable due to the phenomenon of harmonics amplification [7]. It's because of that, that we need a model of the NLL, allowing the prediction of harmonics flow when the filter is inserted in the system.

Usually, the simplest models of harmonics produced by rectifiers used in the literature, consider that such loads behave as ideal current sources (Norton model with infinite impedance) [8]-[11]. If such behavior were true, the harmonic currents generated by the nonlinear loads (NLL) would not depend on external circumstances such as: harmonics of the supply voltage, supply impedance, harmonics produced by other parallel disturbing loads or on the eventual parallel connection of an active or passive filter (APF) (Fig. 1) [7].

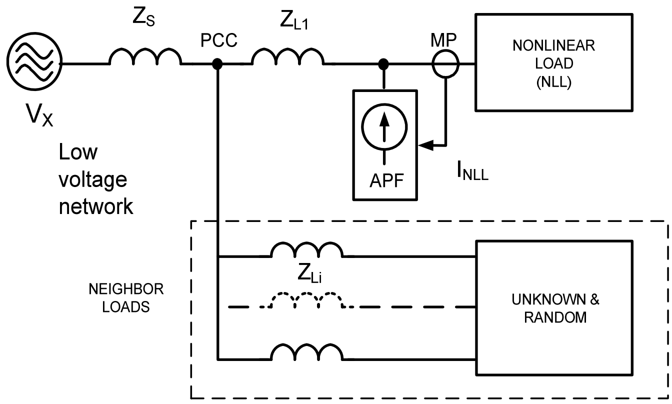

Fig. 1 .- Network simplified schematic, including an hypothetic active filter (APF).

Nevertheless, in practice the harmonics amount and flow depend on all the above mentioned environmental circumstances. The real experiences show that the Norton model with infinite impedance can only be applied in case that the supply network has an infinite short-circuit capacity. In such case, the harmonic currents generated by the NLL or by the neighbor loads, would not influence the supply voltage, neither to each other. However, the transformers and line impedances shared by the load of interest and other unknown loads (Z_S in Fig. 1), bring to a behavior where harmonic currents generated by the NLL depend on such Z_S and on the harmonics generated by other neighbor loads. In order to take into account this non ideal behavior, some authors propose more accurate models based on Norton equivalent circuits with finite impedance for the NLL, combined with a Thevenin equivalent circuit, having known internal impedance, to describe the low voltage network [12]. Other authors use analytical models based on the admittance matrix at the point of filter connection (MP) [13]. Nevertheless, the neighbor loads are usually unknown and have random changes over the time, so, even if they were known, it would not be possible to find a unique admittance matrix, valid for all the possible neighbor and load conditions. Moreover, as described in [7], the insertion of parallel filters at any point of the network changes the supply conditions and modifies the NLL harmonics pattern and values. So, we must conclude that the model cannot be described by an admittance matrix obtained from a single set of voltage and current data. Recently, several authors propose new methods of modeling NLL branched in networks with unknown and variable parts, based on the admittance matrix, where the matrix coefficients are obtained, using statistics methods, from several sets of data representing the different NLL conditions and different environmental circumstances [14]-[19]. In our case, beside the harmonic voltages and currents, which are the origin of the admittance matrix, such data sets include other variables, as the NLL power, the total available power, etc., to better describe the load and the network. In this paper, we use statistical procedures based on Multivariate Multiple Outputs Regression (MMOR) to obtain the model of the NLL, consisting of a sort of enhanced admittance matrix, explained below.

The input variables that we have chosen to describe the model are: The fundamental and the harmonic voltages at MP (Fig. 1) and the active power drawn by the NLL. The output variables (model output) are the fundamental current and the harmonic currents generated by the NLL. Notice that both, voltages and currents, are phasors with two components: module and phase (in polar representation) or real and imaginary part (in Cartesian representation). Since the polar representation gives some problems when the phase of a certain harmonic is close to π/2 [17], we preferred to use the Cartesian representation.

To get the model coefficients (model training in the language of neural networks, NN) we use several sets of data, obtained as described in section II. The model will consist of a set of equations (as many as harmonics we want to model), giving each I_h as a function of all V_h and the NLL power, P. The model will be validated using the same network structure as used to obtain the training data, but with different neighbor loads and under different load conditions.

Section II gives a brief description of the modeling procedure and describes the model variables. Section III describes how the data sets to train the model were obtained and section IV is dedicated to analyze the influence of data resolution on the model accuracy. We analyze the errors, using different wave parameters and discuss the possible influence of data truncation, just to give a realistic point of view for the case that the training data come from real measurements, using limited resolution instruments. Despite the model is worked out in the frequency domain, the validation will be performed both: in frequency domain and in time domain. Finally, in section V we summarize the conclusions.

II. Brief model description

The NLL model used in this paper is described by a set of equations (1) ,which can be grouped in a sort of modified admittance matrix, as will be explained later.

$$Y_k = \beta_{0k} + \sum_{j=1}^{J} X_j \beta_{jk} \quad k = 1,..,K \tag{1}$$

where $Y_1, Y_2 . . . Y_K$ are the output variables of the model, consisting of the fundamental and harmonic currents drawn by the NLL ; $X_1, X_2,. . . X_J$ are the model input variables, namely the fundamental and harmonic voltages at MP and the NLL power. Coefficients β_{jk} are, in fact, the terms of the modified admittance matrix. We call it modified admittance matrix because most of the coefficients are a quotient between a current and a voltage (admittance), but there is a column in the matrix which coefficients are quotients between a current and a power. Such β_{jk} coefficients are calculated by means of an statistics method, namely Multivariate Multiple Outputs Regression (MMOR).

The model coefficients are calculated, using several sets of data obtained in different load and environmental conditions. In the following, we name such data sets “training data”. For the purpose of this paper all the data, either for training and for model validation, were obtained from circuit simulations using Matlab-Simulink® and the SimPowerSystems® toolbox. The circuit used for the simulations is based on Fig. 2, which represents a generic case, consisting of a Thevenin equivalent of the supply network, formed by a voltage source (V_X) and a line impedance (Z_S) upstream of the point of common coupling (PCC).

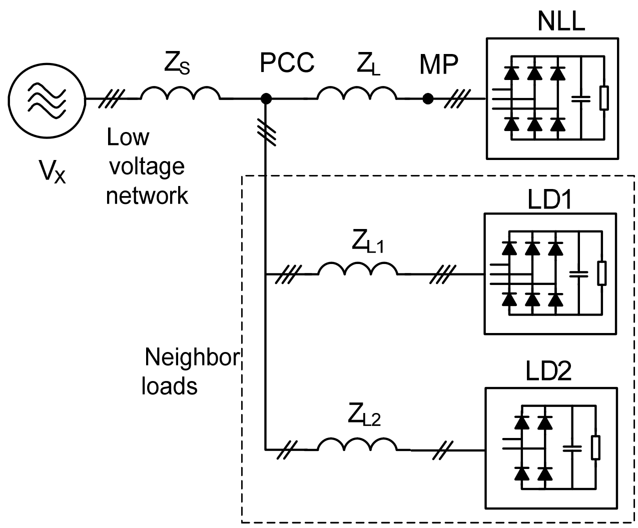

Fig. 2.- Generic circuit for data generation.

We considered that the NLL is a three phase rectifier or a set of three phase rectifiers and the set of neighbor loads (NL) consists of a mix of single and three phase rectifiers causing random variations of the voltage at the PCC and by extension at MP. Therefore in the equivalent circuit of Fig. 2, there are several loads connected to PCC: namely, the load of interest (NLL); and the unknown neighbor loads. We assumed that all the neighbor loads can be represented by two blocks: LD1, gathering all the three phase loads (not using neutral) and LD2 gathering all the single phase loads using neutral. We also assume that the NLL and the neighbor loads are connected to the PCC through impedances Z_L, Z_{L1} and Z_{L2}, where Z_L represents the line impedance between PCC and MP and Z_{L1} and Z_{L2} represent the line impedances from PCC to the different neighbor loads.

The model output consists of a set of equations like those represented in (2) (3) (example for the 5th harmonic of NLL current). Such equations relate harmonic currents with harmonic voltages and input power. Notice that voltages and currents are split up into real and imaginary parts. Notice also that not all the harmonic voltages are significant and some of them may not appear in the model equation of a particular current harmonic.

$$\begin{aligned} Re(I_5) = &-57{,}366 + 0{,}251\,Re(V_1) - 0{,}193\,Re(V_5) + \\ &+ 0{,}575\,Re(V_{11}) - 0{,}530\,Re(V_{15}) + 0{,}859\,Im(V_3) - \\ &- 0{,}453\,Im(V_9) - 0{,}492\,Im(V_{13}) + 1{,}152\,Power \end{aligned} \quad (2)$$

$$\begin{aligned} Im(I_5) = &\ 89{,}247 - 0{,}394\,Re(V_1) - 0{,}697\,Re(V_3) - \\ &- 2{,}531.Im(V_3) + 1{,}298.Im(V_7) - 0{,}117.Im(V_{15}) + \\ &+ 1{,}605\,Power \end{aligned} \quad (3)$$

III. TRAINING AND VALIDATION DATA SETS

Training data sets and validation data sets have been obtained from simulations of the above described circuit. Specifically, we have simulated 200 cases, with different configurations of nonlinear and neighbor load parameters. The 200 cases do not follow any pre-determined order, but they change the circuit parameters using a random algorithm which assigns different values to the NLL power and to the neighbor loads power, each within a certain range of values. For each case we have an input vector (X_j) containing the harmonic voltages plus the NLL power and an output vector (Y_k) containing the estimated harmonic currents. More precisely, in the data generation process, the range of values for NLL was between $5A_{RMS}$ and $65A_{RMS}$ and for LD1+LD2 between $12A_{RMS}$ and $60A_{RMS}$. The combinations of NLL and neighbor load were chosen randomly within the limits.

After obtaining the 200 sets of data they have been split up in two subsets: namely, the training and the validation subsets (150 and 50 cases respectively). The training subset was used to make the statistical calculations of MMOR method, leading to the calculation of β_{jk} coefficients and the validation subset has been used to evaluate the model accuracy (namely the error between model predictions ("estimated values") and values obtained from circuit simulation ("real values").

A first model using maximum data resolution given by Matlab was used to validate the MMOR method in optimal conditions, i.e. assuming a perfect instrument resolution (6 significant places or more). From this test we could realize that the model is able to predict the NLL harmonics of current with a great accuracy, in all the cases. Fig. 3 and Fig. 4 present a comparison of real and imaginary parts of the current harmonics and a reconstruction in time domain for one of the cases used to train the model. The agreement between circuit model and MMOR estimation, for the cases used for training, is so good that in the comparison in time domain the real values (blue points) and estimated values (green points) are overlapped. Then, we made the same comparison using data not included in the training subset. Fig. 5 and Fig. 6 show the comparison for one of the worst cases (low current).Notice that the agreement is also very good, and only a few blue points are visible.

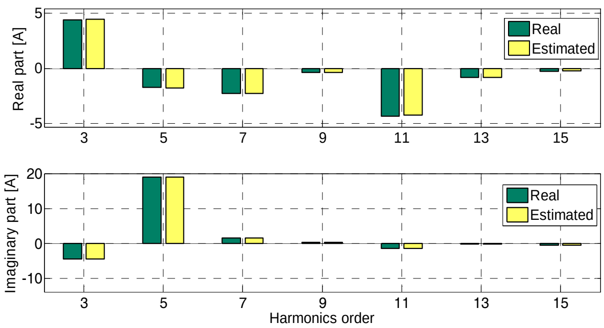

Fig. 3. Real and imaginary parts of real and estimated currents. Case used for training. Current close to full scale

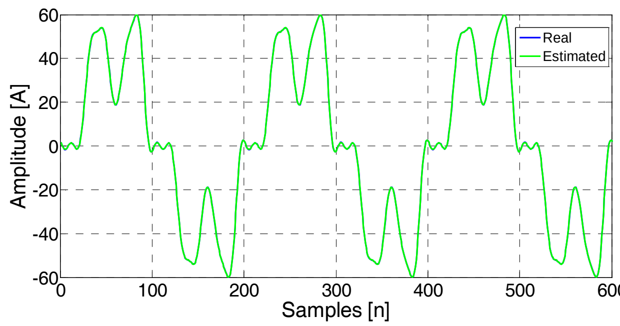

Fig. 4.- Real and estimated currents reconstruction in time domain. Case used for training. Current close to full scale

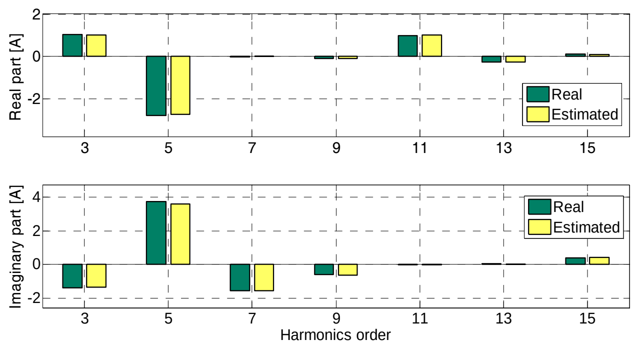

Fig. 5.- Real and imaginary parts of real and estimated currents. Case not used for training. Low current.

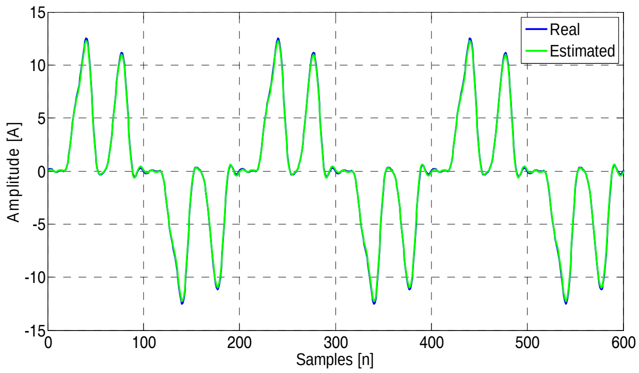

Fig. 6 .- Real and estimated currents reconstruction in time domain. Case not used for training. Low current

Notice, in the previous nomenclature, do not confuse real value (value coming from circuit simulation) with real part of complex quantities (*V*,*I*).

In Fig. 7 we represent the % error between the real and the estimated values of THD(I). We can observe that the deviation increases for low current values, that suggesting that the data errors influence the MMOR model accuracy.

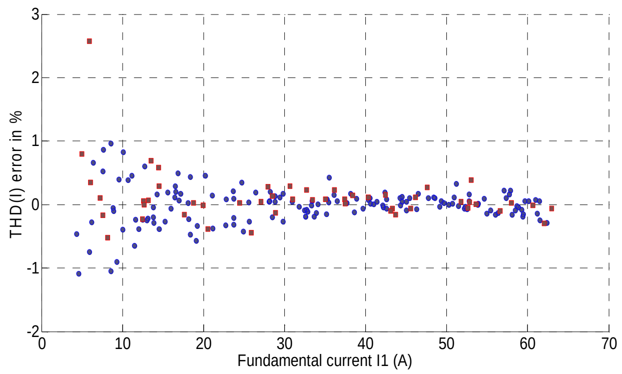

Fig. 7 .- Error in the prediction of THD(I). Blue spots are cases used for the model training. Red spots are cases not used for the training

IV. Influence of Data Resolution

Since the model aims to be useful to predict harmonics in real situations, where data will be measurements in a network with a real instrument, we have to take into account that measuring instruments have a limited resolution. In order to evaluate the effects of such limited resolution on the accuracy of the MMOR model, we generated different models, using different data resolutions.

In fact, what we did was using the same set of data that we used to get the MMOR with maximum resolution (the 200 cases with different loads). We considered the result of circuit simulation with maximum resolution as the "real values" of variables. From this set of data, we derived other data sets, by truncating the voltage and the current values to different number of decimal places, which we considered equivalent to change the resolution of measuring instrument.

For each resolution, we obtained a different MMOR model and we used it to predict current harmonics of the NLL. Then we compare the different MMOR model results with the "real values". In the following paragraphs and figures we present the comparison for different resolutions. Notice that the model accuracy with maximum resolution is as presented in the preceding section, Fig. 3 to Fig. 6.

Fig. 8 to Fig. 10 show the comparison between real and MMOR model results for a case NOT used in the training data set and for a resolution of 0,1V and 0,1A over a full scale of approx. 800V and 85A. We can see in Fig. 9 (current close to full scale) an excellent agreement of MMOR model obtained with the above defined resolution. We can also realize in Fig. 10 that the agreement is much better when the currents are close to the full scale value, but the errors increase for low currents, since the measured values approach the magnitude of the resolution.

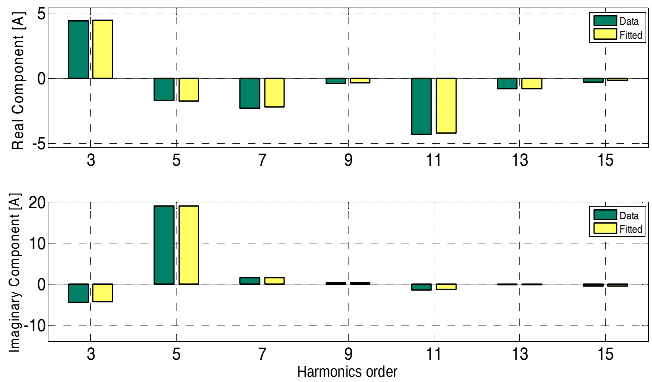

Fig. 8. Real and imaginary parts of real and estimated currents. Resolution 0,1V, 0,1A over 800V/85A

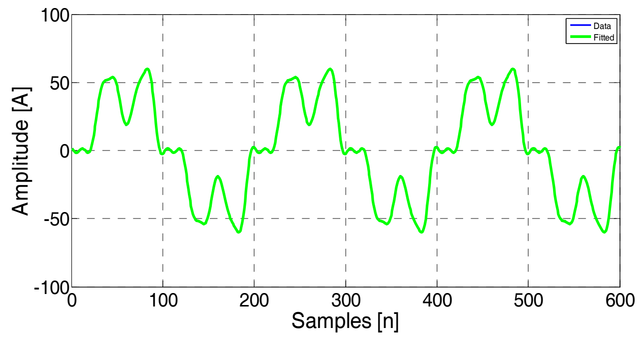

Fig. 9.- Real and estimated currents reconstruction in time domain. Resolution 0,1V, 0,1A over 800V/85A

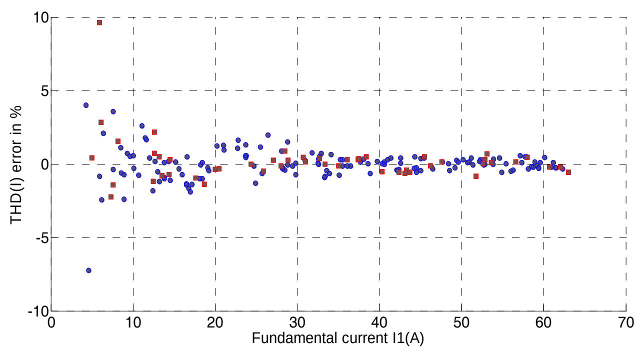

Fig. 10.- THD(I) error in % as a function of fundamental current. Resolution 0,1V, 0,1A over 800V/85A

In Fig. 11 to Fig. 13 we present the same comparisons for a resolution 10 times lower. Fig. 11 and Fig. 12 correspond to a case with low current and not used in the training data set. Fig. 13 shows the THD(I) deviation for all the cases and we can observe that for high currents there is still a good agreement, but for low currents the deviations are very significant. Again the explanation is that real current values approach the magnitude of the resolution.

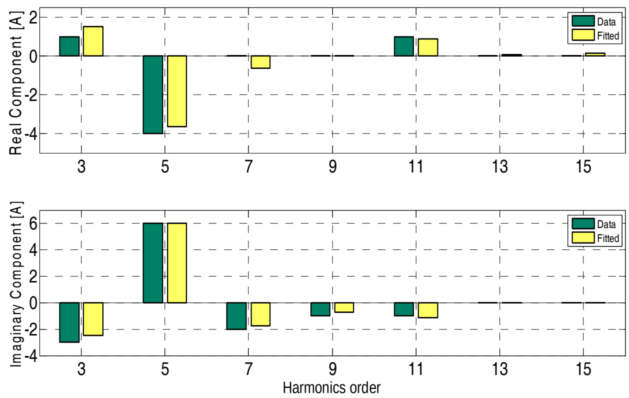

Fig. 11. Real and imaginary parts of real and estimated currents. Resolution 1V, 1A over 800V/85A

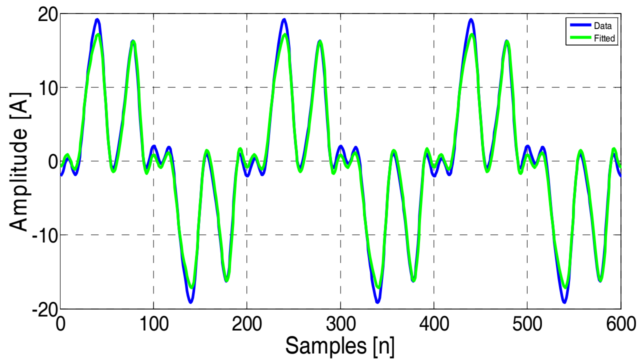

Fig. 12.- Real and estimated currents reconstruction in time domain. Resolution 1V, 1A over 800V/85A

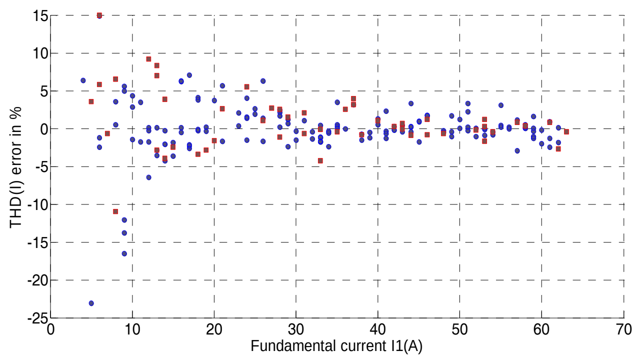

Fig. 13.- THD(I) error in % as a function of fundamental current. Resolution 1V, 1A over 800V/85A

V. CONCLUSIONS

In this paper, we have investigated the effects of data truncation on the accuracy of NLL models for harmonics prediction. The MMOR model validation in case of using maximum resolution of Matlab-Simulink SimPowerSystems has been done in the time and in frequency domain, showing, in both cases, a very good agreement between the model and the real data. Namely, the difference between harmonic currents obtained with the model and those obtained in the real circuit, are less than 0,5A over a peak current near to 90A.

The effects of data truncation, presented in section IV, show that the MMOR method gives a good agreement with the reality if the resolution of voltage is 0,1V over a full scale of 800V and current resolution is 0,1A over a full scale of 85A. Lower resolution of 1V and 1A, still give acceptable results for high currents, but present significant deviations when the current values approach the measuring instrument resolution. That suggests that an instrument having an automatic current scale change could improve the predictions of MMOR models.

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