THIRD ORDER LOW-PASS FILTER USING SYNTHETIC IMMITTANCE ELEMENTS WITH CURRENT CONVEYORS

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Abstract. *The paper deals with a theoretical proposal of the resulting circuit of the frequency filter using synthetic immittance elements of higher order with current conveyors. The text pays particular attention to design process of synthetic immittance elements, explains the principle of increasing of order, which is then reflected to the frequency filter order. The text then deals less with the theory of current conveyors, which has already been discussed, in detail, in previous papers. Universal current conveyor (UCC) is discussed more. This active element is used for the theoretical implementation of the synthetic element solution used in the frequency filter. The theoretical knowledge is then demonstrated in the design of 3rd order low-pass frequency filter. The final functionality of the proposed frequency filter circuit solution is validated by PSpice simulation.*

Keywords

Current conveyor, frequency filter, low-pass filter, synthetic immittance element.

1. Introduction

Method of the synthetic elements is primarily based on the needs of classical inductors substitution by synthetic equivalents in electronic circuits. It is not a new method, but its use in combination with new modern active components (current conveyors), for the design and realization of frequency filters, is a relatively new idea [1], [2], [3], [4], [5], [6], [7], [8].

The basic advantages of using current conveyors [1] include a wide frequency range, ease of integrability of the resulting circuit solutions, low supply voltage of active elements and the possibility of use of battery supply in resulting circuit, when it is used in the mobile devices.

Current conveyors [1] can be basically regarded as universal elements, because four basic functional block structures can be realized by combinations of these active elements.

However, the basic disadvantage is low commercial availability of current conveyors and commercial unavailability of universal current conveyor (UCC), which was selected for the realization of filter proposed in this paper. Selection of UCC has its important reasons. This element seems to be very promising, especially in the design of circuit solutions with current conveyors, because it could be used for the implementation of all current conveyors variations. Universal current conveyor currently exists only as a laboratory sample and the wider extension yet to come. The paper tries to show its importance and the advantages.

2. Synthetic Immittance Elements of Higher Orders

Synthetic dipoles with immittance of higher order [2] are divided into four groups – DP, DS, EP, ES. They are consisting of serial or parallel elementary dipoles connections. Synthetic elements DP, DS are created by elementary D type dipoles of order 0 to $N_{D,max}$. Synthetic elements EP, ES are created by elementary E type dipoles of order 0 to $N_{E,max}$.

The linear circuits theory discusses that stable frequency filters can be realized, if the elementary dipoles of all orders from the lowest ($n_{d,min}$, $n_{e,min}$) to highest ($n_{d,max}$, $n_{e,max}$) will be connected in the synthetic elements. Most of the values of $n_{d,min}$, $n_{e,min}$ equal to 0 or 1, values of $n_{d,max}$, $n_{e,max}$ set the order of the synthetic element. In the most cases, these values also set the order of frequency filter transfer function, respectively.

As stated above, there are four connections of synthetic elements with immittance of higher order [2]:

- dipole DP $N_{D,\min}$ $N_{D,\max}$ consists of a parallel connection of synthetic elementary dipoles of type D_n for $n = N_{D,\min}, N_{D,\min} + 1, ..., N_{D,\max} - 1, N_{D,\max}$,
- dipole DS $N_{D,\min}$ $N_{D,\max}$ consists of a serial connection of synthetic elementary dipoles of type D_n for $n = N_{D,\min}, N_{D,\min} + 1, ..., N_{D,\max} - 1, N_{D,\max}$,
- dipole EP $N_{E,\min}$ $N_{E,\max}$ consists of a parallel connection of synthetic elementary dipoles of type E_n for $n = N_{E,\min}, N_{E,\min} + 1, ..., N_{E,\max} - 1, N_{E,\max}$,
- dipole ES $N_{E,\min}$ $N_{E,\max}$ consists of a serial connection of synthetic elementary dipoles of type E_n for $n = N_{E,\min}, N_{E,\min} + 1, ..., N_{E,\max} - 1, N_{E,\max}$.

2.1. The Conditions of Synthetic Immittance Elements Realization

If suitable synthetic immittance elements of higher order should be designed, then an appropriate form of input impedance, respectively input admittance is searched [3].

The required input impedance respectively input admittance form of synthetic immittance elements of DS and ES type should be:

$$Z_{IN} = \frac{Y_U}{Y_V Y_W} + \frac{1}{Y_V}, \quad Y_{IN} = \frac{Y_V Y_W}{Y_U + Y_W}. \qquad \text{(1a, b)}$$

Increase of synthetic element order is done by repeatedly replace of admittance Y_V with circuit with input admittance (1b). Increase of order of synthetic immittance element can also be achieved by replacing the admittance Y_U with circuit with the input admittance (2b).

For synthetic immittance elements of DP and EP type, it is required input impedance respectively admittance in form:

$$Z_{IN} = \frac{Y_W}{Y_U (Y_V + Y_W)}, \quad Y_{IN} = \frac{Y_U Y_V}{Y_W} + Y_U. \qquad \text{(2a, b)}$$

Admittance Y_V is repeatedly replaced with circuit with the input admittance (2b), if we want to increase order of synthetic immittance element.

3. Universal Current Conveyor

Universal current conveyor (see Fig. 1) was created on the base of the universal element idea, which could easily implement every current conveyor generation or variation in practice. This element would allow a different application use of current conveyors and their wider expansion. Universal current conveyor has met these requirements [4].

It can realize all the known types of current conveyors. It is the basic principle of its versatility. Implementation of the various types of current conveyors is provided by use of only certain input and output terminals of universal current conveyor, the remaining terminals are properly connected or grounded.

Another advantage of the element is that it contains several input and output terminals, which provides an opportunity to sum signals at the input of conveyor or to divide the output signals to multiple locations [4]. The active element is not currently mass produced, and therefore not widely available.

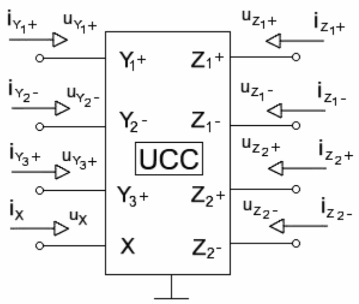

Fig. 1: Schematic symbol of universal current conveyor (UCC).

Terminals Y_{1+}, Y_{2-}, Y_{3+} are the voltage inputs, X is the current input (see Fig. 1). Terminals Z_{1+} and Z_{2+} are current outputs with a positive transfer of current, Z_{1-} and Z_{2-} are current outputs with a negative transfer of current from terminal X.

The universal current conveyor is generally described by equations [4]:

$$u_X = u_{Y1} - u_{Y2} + u_{Y3}, \; i_{Y1} = i_{Y2} = i_{Y3} = 0,$$
$$i_{Z1+} = i_{Z2+} = i_X, \; i_{Z1-} = i_{Z2-} = -i_X. \qquad \text{(3a, b, c, d)}$$

4. Realization of Synthetic Immittance Elements with Current Conveyors

If the appropriate structure of synthetic immittance dipoles of type DP, DS, EP and ES type is searched, then the particular form of input admittance or impedance is primarily required. It is very difficult to find the exact expressions that equal to the formulas (1a, b) respectively (2a, b). We can more often find the expressions approaching these forms than exact forms. They can be also used.

However, it is necessary to theoretically verify their suitability for use in frequency filters. The main target is to get forms of equations that will be most similar to the equations (1a, b) respectively (2a, b).

The general circuit network for searching of suitable circuit structures was used to implement synthetic immittance element. The general circuit network consists of nine passive elements (admittances) and one general four-port current conveyor [2]. Final structure is shown in Fig. 2.

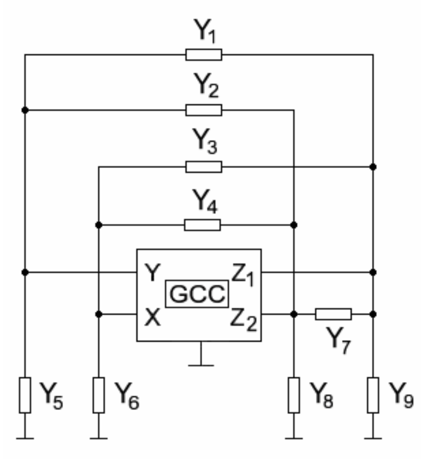

Fig. 2: Default admittance network to search the synthetic element solution.

The synthetic element searching procedure is quite simple. The selected admittances are removed from the general circuit network. The resulting circuit structure should consist of three admittances and general four-port current conveyor. Three admittances are enough to realize the synthetic immittance element. Any of the general current conveyor terminals Y, X, Z_1 or Z_2 can be used as the input of the resulting circuit structure [5]. The input admittance form is then edited again by the suitable choice of the general current conveyor coefficients *a*, *b*, c_{11}, c_{22}. It is final change of the input admittance. The final input admittance of the resulting circuit is then deducted, if it equals (1a, b), (2a, b) or forms close to these equations. Several dozens of combinations were examined this way.

Figure 3 shows one of the found structures that can be used for the realization of synthetic element. The circuit is suitable for implementing filters of higher order.

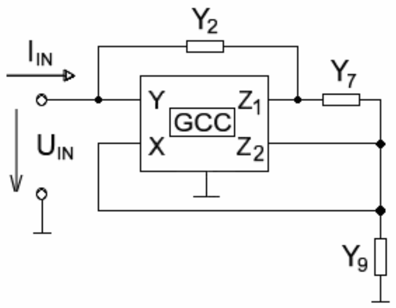

Fig. 3: Circuit structure suitable for realization of synthetic element.

The input admittance general form of the circuit shown in Fig. 3 has the form:

$$Y_{\mathrm{IN}}=\frac{\begin{array}{c}Y_2Y_7-Y_2Y_7a+Y_2Y_7b-Y_2Y_7ab+Y_2Y_7c_{11}-Y_2Y_7ac_{11}\\+Y_2Y_7c_{22}-Y_2Y_7ac_{22}-Y_2Y_9ab-Y_2Y_9ac_{22}-Y_7Y_9ab\end{array}}{Y_2+Y_2c_{11}+Y_7+Y_7c_{11}+Y_7c_{22}}. \tag{4}$$

There the values of the general current conveyor coefficients from the possible combinations were chosen. Best suited combination is *a*=-1, *b*=0, c_{11}=-1, c_{22}=1. This combination of values simplifies the input admittance general form and brings it to its ideal form. General circuit structure is suitable to implement the synthetic immittance elements DP or EP (1a, b). Selected coefficients correspond to the inverting current conveyor of second generation ICCII+/-. After this adjustment, the input admittance of the circuit is transformed into the form:

$$Y_{\mathrm{IN}}=\frac{Y_2Y_9}{Y_7}+2Y_2\,,\; Z_{\mathrm{IN}}=\frac{Y_7}{Y_2(Y_9+2Y_7)}\,. \tag{5a, b}$$

Targeted selection of passive elements and their substitution for general admittance in the circuit structure create the synthetic immittance element DP of second order. The circuit structure is shown in Fig. 4.

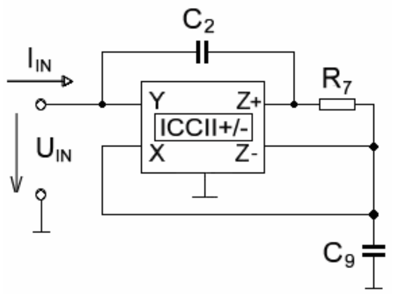

Fig. 4: Circuit structure of second order synthetic element DP.

The resulting input admittance of synthetic immittance element shown in Fig. 4 has the form:

$$Y_{\mathrm{IN}}=p^2R_7C_2C_9+p2C_2\,. \tag{6}$$

4.1. Synthetic Immittance Element Order Increasing

Increasing of the synthetic element order will be demonstrated on the synthetic element shown in Fig. 4. Increasing of the synthetic element order is cascade, i.e. there is a repeated replacement of a passive element for a whole circuit structure of identical synthetic element in the structure of synthetic element. Increasing of order of synthetic element in Fig. 4 to third order shows Fig. 5.

As can be seen from Fig. 5, the capacitor marked in Fig. 4 as C_9 was replaced by circuit structure of synthetic element DP shown in Fig. 4.

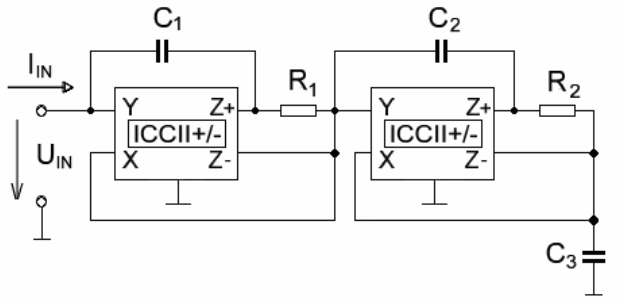

Fig. 5: Third order synthetic immittance element DP.

The number of capacitors in the structure of a synthetic element was increased. The result is also increasing of the synthetic element order. The input admittance of the newly created synthetic element of third order has form as follows:

$$Y_{IN} = p^3 R_1 R_2 C_1 C_2 C_3 + p^2 R_1 C_1 C_2 + p2C_1 . \qquad (7)$$

The new increasing of order of synthetic element would be made by replacing the capacitor C_3 for the whole synthetic element structure shown in Fig. 4. Forms of other input admittance caused by increasing of the synthetic immittance element order are shown in Tab. 1.

Tab.1: Input admittance forms.

Order of Synthetic Element	Input Admittance Form
4.	$Y_{IN} = p^4R_1R_2R_3C_1C_2C_3C_4 + p^3 2R_1R_2C_1C_2C_3 + p^2R_1C_1C_2 + p2C_1$
5.	$Y_{IN} = p^5R_1R_2R_3R_4C_1C_2C_3C_4C_5 + p^4 2R_1R_2R_3C_1C_2C_3C_4 + p^3 2R_1R_2C_1C_2C_3 + p^2R_1C_1C_2 + p2C_1$
6.	$Y_{IN} = p^6R_1R_2R_3R_4R_5C_1C_2C_3C_4C_5C_6 + p^5 2R_1R_2R_3R_4C_1C_2C_3C_4C_5 + p^4 2R_1R_2R_3C_1C_2C_3C_4 + p^3 2R_1R_2C_1C_2C_3 + p^2R_1C_1C_2 + p2C_1$
7.	$Y_{IN} = p^7R_1R_2R_3R_4R_5R_6C_1C_2C_3C_4C_5C_6C_7 + p^6 2R_1R_2R_3R_4R_5C_1C_2C_3C_4C_5C_6 + p^5 2R_1R_2R_3R_4C_1C_2C_3C_4C_5 + p^4 2R_1R_2R_3C_1C_2C_3C_4 + p^3 2R_1R_2C_1C_2C_3 + p^2R_1C_1C_2 + p2C_1$

5. Frequency Filters Using Synthetic Immittance Elements

There was used synthetic immittance element DP shown in Fig. 5 for the realization of low-pass filter of third order. Circuit solution of third order low-pass is shown in Fig. 6.

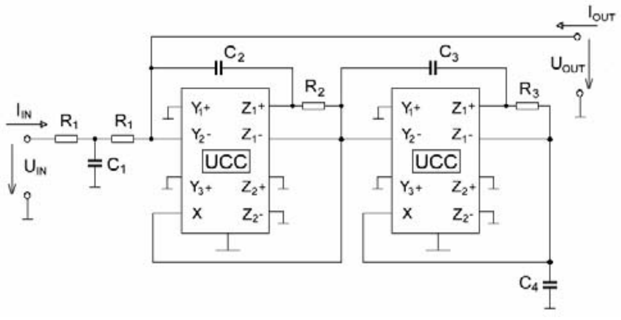

Fig. 6: Third order low-pass using synthetic element with current conveyors.

Two universal current conveyors were used in the final circuit solution of active frequency filter. With its help, ICCII+/- was implemented. There was also used passive low-pass at the input of active filter to smooth the final frequency responses at higher frequencies. Resistor R_1 was divided into two parts, and it creates passive low-pass together with capacitor C_1. Transfer function of active third order low-pass shown in Fig. 6 has form as follows:

$$K_U(p) = \frac{1}{p^3 2R_1R_2R_3C_2C_3C_4 + p^2 4R_1R_2C_2C_3 + p4R_1C_2 + 1} . \qquad (8)$$

Specific values of passive components were calculated with general design relations for active third order low-pass [6]:

$$\frac{c_{33}}{\omega_0^3} = 2R_1R_2R_3C_2C_3C_4 , \qquad (9)$$

$$\frac{c_{32}}{\omega_0^2} = 4R_1R_2C_2C_3 , \qquad (10)$$

$$\frac{c_{31}}{\omega_0} = 4R_1C_2 . \qquad (11)$$

Butterworth approximation was chosen. The coefficients of this approximation for filters of third order have values $c_{31}=c_{32}=2$, $c_{33}=1$ [6]. As already mentioned in the previous text, the values of capacitors are chosen and values of resistors are calculated. The values of passive elements of frequency filter are also based on the chosen value of cut-off frequency 1 MHz and the coefficients of chosen approximation. The forms for calculation of values of resistors (12), (13), (14) are expressed from equations (9), (10), (11):

$$R_1 = \frac{c_{31}}{4\omega_0 C_2} , \qquad (12)$$

$$R_2 = \frac{2c_{32}}{\omega_0 c_{31} C_3} , \qquad (13)$$

$$R_3 = \frac{2c_{33}}{\omega_0 c_{32} C_4} . \qquad (14)$$

Values of resistors are calculated after substituting of specific values. Optimization in PSpice was also used to determine the ideal values of passive elements. The resulting values of the passive elements were determined R_1=2,7 kΩ, R_2=5,6 kΩ, R_3=1,2 kΩ, $C_1=C_2=C_3$=22 pF, C_4=100 pF. The resulting amplitude frequency response and phase response of a real model of third order low-pass is shown in Fig. 7. There are two traces here. First trace is for circuit solution of active low-pass and second trace describes the behavior of circuit solution of active low-pass using also passive low-pass. As can be seen, use of passive low-pass in the circuit structure of third order active low-pass changes the position of cut-off frequency. However, this solution also gives good results at higher frequencies, where the gain increase is reduced. Cut-off frequency of the filter is defined as a decrease of magnitude about 3 dB [6]. Cut-off frequency in this case was chosen 1 MHz. The simulated characteristic shown in Fig. 7 does not exactly match those requirements. The selected cut-off frequency of 1 MHz is defined as a decrease of amplitude frequency response about 4,43 dB.

Such a large deviation can be tolerated. Some of the factors that could cause the deviation are the ideal properties of the used universal current conveyor model and the passive low-pass at the input of active filter.

Also, sensitivity analysis was carrying out. The change of cut-off frequency of active low-pass depends mostly on capacitor C_2. The amplitude frequency response and phase response shown in Fig. 8 describe particular traces depending on the variable tolerance of C_2.

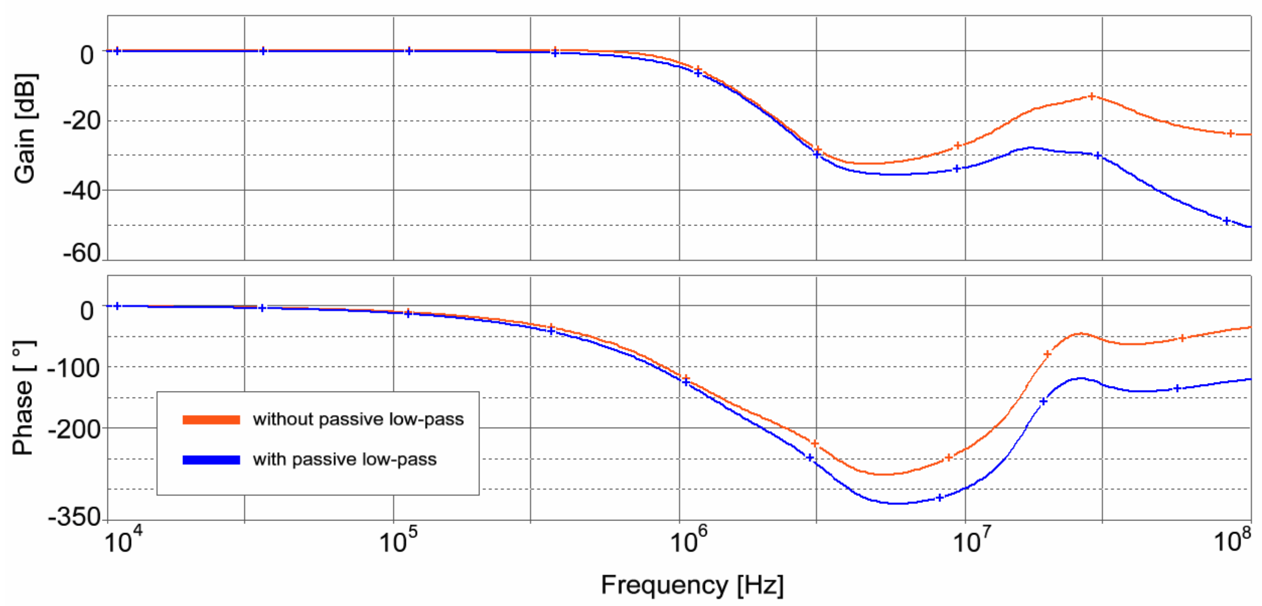

Fig. 7: Amplitude frequency response and phase response of third order low-pass using synthetic element with current conveyors.

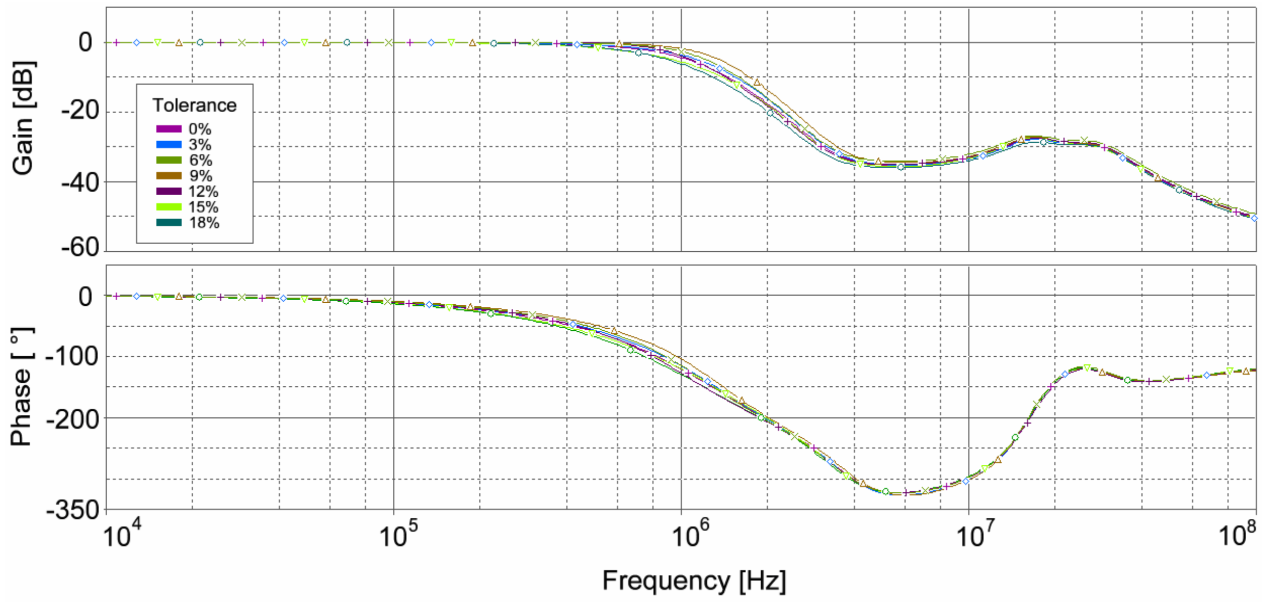

Fig. 8: Monte Carlo analysis of amplitude frequency response and phase response of third order low-pass with passive filter.

6. Conclusion

The paper tries briefly describe the realization of frequency filters with synthetic immittance elements of higher order with current conveyors. Application use of synthetic immittance elements brings a lot of advantages. One of the most important advantages is the easy integrability of the final circuit solution. This is a very important factor especially in electro-industrial production.

It is advantageous to use universal current conveyor in design. UCC is able to substitute all previous generations of current conveyors but its commercial unavailability is a disadvantage and universal current conveyor can be used only as a theoretical element now.

The described theory and the final circuit solution of third order low-pass indicate that the described method produces relatively good results. The article describes only one of total three found synthetic elements. Despite further attempts no other elements were found. It can therefore be assumed to find another solution of synthetic immittance elements with current conveyors is very difficult. However, other solutions of synthetic immittance elements can be found with combinations of different types of current conveyors or with other active elements.

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