Evaluation of the Effect of Advanced Core Settings of the Hybrid Transformer Model on the Harmonic Content of Inrush Currents

J. R. M. S. Souza, C. S. Pereira Filho, A. De Conti

Abstract-- **Power transformers are important elements that find widespread use in electric power systems. However, their modeling for transient studies is challenging for involving nonlinear and frequency-dependent phenomena. Recently, some accurate transformer models have been implemented using of the duality principle, such as the Hybrid model (XFMR) available in ATPDraw. The use of this principle improves significantly the core representation, which is particularly desirable for transformer energization studies. However, there are some advanced settings defined by the user that could affect the simulation results. The aim of this paper is to present a parametric study to evaluate the effect of these advanced core settings on the harmonic content of the inrush current during transformer energization. The results of this analysis could assist protective relay engineers in the setting of inrush detection functions based on the harmonic content, which are typically used in transformer differential relays.**

***Keywords*: Power transformer, differential protection, time domain analysis, hybrid model, ATP.**

I. Introduction

POWER transformers are important elements that find widespread use in electric power systems. However, their modeling for transient studies is challenging for involving nonlinear and frequency-dependent phenomena. Difficulties also arise due to the lack of general information about design criteria used by manufacturers. In an attempt to provide more accurate transformer models for low-frequency transient studies, many efforts have been made in the last decade or so. Most of the proposed models are based on the duality principle, in which the electric circuit elements are obtained from a magnetic circuit based on the physical parameters of the transformer, such as core dimensions and topology [1-2].

ATPDraw has a transformer model based on the duality principle that is called Hybrid or XFMR model [3-4]. In this model the transformer core is placed in a separated winding and its representation depends on the core topology, which could be triplex (independent cores), stacked core (with three or five legs) and shell core. This more detailed core representation is important to study inrush currents that flow during transformer energization.

To use the XFMR model, some advanced settings related to core representation must be defined by the user. However, the user generally has little information about the transformer construction. This leads to uncertainties with respect to the characteristics of inrush current waveforms obtained in transformer switching studies using the XFMR model. In this paper, a parametric study is performed to evaluate the effect of these advanced core settings on the harmonic content of the inrush current. The results of this analysis could assist protective relay engineers in the setting of inrush detection functions based on the harmonic content, which are typically used in transformer differential relays.

In [5] the authors presented a parametric study of the effect of the transformer core topology the relative dimension of their components in the harmonic content of inrush currents. The same methodology is also used in this study, but now to investigate the effect of the advanced core settings of the hybrid transformer model on the harmonic content of inrush currents. So, hundreds of simulations involving the switching of a three phase power transformer modeled by the Hybrid Model were performed using the statistic switches available at ATP. The inrush currents were treated by an algorithm implemented in MODELS that calculates the fundamental component and the rate of second and fourth harmonic using cosine filters. The maximum value of these quantities obtained for each simulation was recorded and exported to Scilab, where a script was written to present two types of plots: one showing the maximum second harmonic content against the maximum fundamental component and another one showing the maximum fourth harmonic content against the maximum fundamental component. This procedure was performed considering the variation of four advanced settings: the function used to fit the excitation curve (the original Frolich equation or the modified one), the quantity of points represented in the saturation region, the type of element used to represent the nonlinearity (pseudo-nonlinear, true-nonlinear and hysteresis), and the use of a final slope.

This paper is organized as follows. Section 2 presents the core representation in the ATPDraw XFMR model. Section 3 presents the methodology used to perform this parametric study. Section 4 shows the analysis of the effect of the advanced

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core settings of XFMR model on the harmonic content of the inrush currents. Section 5 presents a discussion of the obtained results. Finally, section 6 presents the conclusions.

II. Core Representation in hybrid model

The XFMR model is the most recent transformer model available at ATPDraw. It has several improvements compared with its predecessors. For instance, by using the duality principle, the XFMR model is capable to represent the transformer core more properly than the BCTRAN or saturable models. In the duality principle, the electric equivalent circuit of the equipment is obtained from its magnetic circuit, which is built based on physical parameters, such as core topology and the dimensions of its parts. The elements related to the transformer core representation depend on these parameters and are placed into a separated winding specifically created for this purpose. For instance, Figure 1 shows the equivalent circuit of a 3-leg stacked core transformer [3,6].

To define the nonlinear inductances shown in Figure 1 the user must define some settings that could affect the simulation results. For instance, to make the extrapolation of the magnetization curve, the XFMR model uses the fitting of the Frolich Equation. However, the user could choose between two variations of this equation: the original form, given in (1), and the modified one given in (2).

$$\lambda = \frac{i}{a + b \cdot |i|} \tag{1}$$

$$\lambda = \frac{i}{a + b \cdot |i| + c \cdot \sqrt{i}} \tag{2}$$

Besides the equation used in the fitting of the magnetization curve, the user could choose the element used to model the nonlinear inductances. The ATP program has three different types of elements that could be used to do this: pseudo-nonlinear (98), true-nonlinear (93) and hysteresis (96). All three elements could be used to model the transformer core parts at hybrid model.

The user must also define the number of points used to describe the magnetization (saturation) curve. It is expected that a more detailed description of this curve will provide more accurate inrush currents during transformer energization.

The Frolich equation used in the XFRM model implemented in ATPDraw could include an additional linear term. The aim of this term is to represent more properly the final slope inductance L_a. The user has three possible choices for this inductance: to choose a specific value, to perform an estimation according described in [7] or neglected it.

The aim of this paper is to evaluate their effect in the harmonic content of the inrush current during transformer energizations.

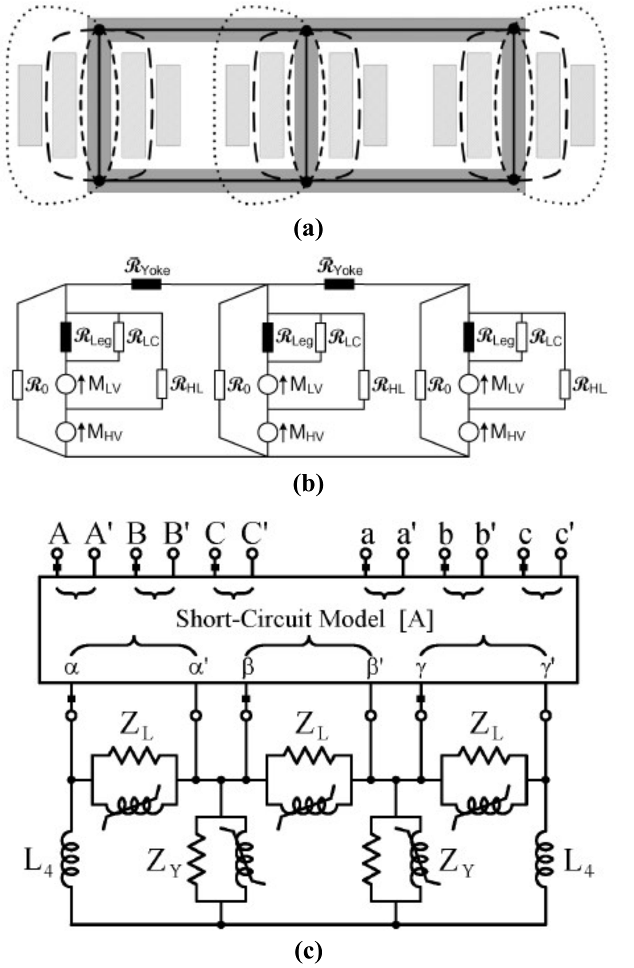

Fig. 1. 3-leg stacked core transformer representation: (a) physical structure [6], (b) magnetic equivalent circuit [6] and (c) dual electric equivalent circuit [3].

III. Methodology Used in This Study

As mentioned previously, the parametric study presented in this paper follows the same methodology used in reference [5]. So, a set of 200 simulations dealing with the no-load energization of a triplex core three-phase transformer was performed using ATPDraw according to the circuit shown in Fig. 2. In all cases the energization was performed at the high voltage winding (primary).

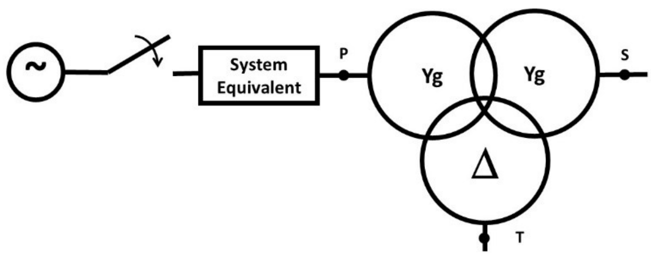

Fig. 2. Circuit used in simulations.

The transformer parameters, which are listed in Tables I-III, were obtained from the test report of an actual transformer.

TABLE I – TRANSFORMER PARAMETERS

	Primary	Secondary	Tertiary
V (kV)	138	34.5	13.8
S (MVA)	18	18	18
Connection	Yg	Yg	D
Phase Shift (°)	-	0	30

TABLE II – SHORT-CIRCUIT TEST RESULTS

	Impedance (%)	Power Base (MVA)	Loss (kW)
P – S	4.28	18	34.47
P – T	7.46	18	39.95
S – T	2.50	18	31.03

TABLE III – OPEN CIRCUIT TEST RESULTS (PERFORMED AT TERTIARY)

Voltage (%)	80	85	90	95	100	105	110
Loss (kW)	15.825	17.945	21.292	24.752	28.906	32.126	46.788
Current (%)	0.117	0.128	0.151	0.189	0.295	0.638	2.378

The system equivalent seen from the transformer primary winding was modeled with a balanced three-phase voltage source behind an RL coupled element represented in symmetrical components. The values of the positive and zero sequence resistance and reactance used in this study are presented in Table IV.

TABLE IV – SYSTEM EQUIVALENT

	R(Ω)	X(Ω)
Positive Sequence	0.826	5.728
Zero Sequence	0.703	5.245

A MODELS code was written to evaluate the value of the fundamental, second and fourth harmonic components of the inrush currents. This code uses a cosine filter and a rectangular window with a single 60 Hz cycle length and 64 points per cycle. The peak values obtained for phase A after each simulation were presented as sets of points relating the second and fourth harmonics to the fundamental component. These plots were generated by Scilab routines, and a regression to polynomial curves was also performed, such as in [5].

IV. RESULTS

As demonstrated in [5], the harmonic content of the inrush current can be approximated by (3) and (4).

$$i_n(\alpha)=\frac{I_m}{\pi}\cdot\left(\begin{array}{l}\frac{1}{n+1}\cdot\sin[(n+1)\cdot\alpha]+\frac{1}{n-1}\cdot\sin[(n-1)\cdot\alpha]+\\ +2\cdot\cos(\alpha)\cdot\frac{1}{n}\cdot\sin(n\cdot\alpha)\end{array}\right),n>1 \quad (3)$$

$$i_1(\alpha)=\frac{I_m}{\pi}\cdot\left[\alpha-\frac{1}{2}\cdot\sin(2\cdot\alpha)\right],n=1 \quad (4)$$

In (3) and (4), α is the width of the current pulses of the inrush currents, in radians, n is the harmonic order, and Im is the maximum possible value of the inrush current, which is reached if α=π radians.

Based on (3) and (4), two plots can be used to show the expected relationship between the fundamental component of the inrush current and the second and fourth harmonic components. These plots are shown in Fig. 3 [5]. Fig. 4 also shows the points obtained during the simulations performed with the base case using the methodology previously described in section III. A linear blocking characteristic was also included in both plots of Fig. 4. Several manufactures use the second and fourth harmonic content ratio to block their differential relays during a transformer energization. Thus, the points located above the blocking characteristic represent cases in which the differential relay could operate incorrectly.

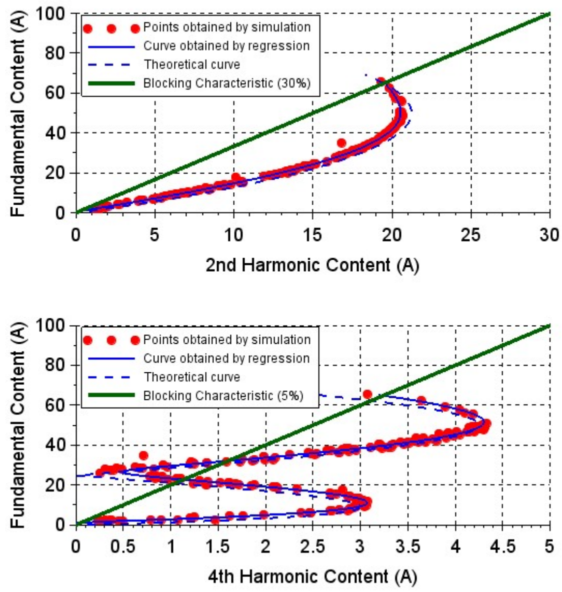

Fig. 3. Second and fourth harmonic characteristics of inrush currents.

A. *Type of Frolich equation*

The first parameter investigated in this study is the type of the Frolich equation used. Fig. 4 shows the magnetization curve obtained by ATP SATURTION routine and in both mentioned situations and the.

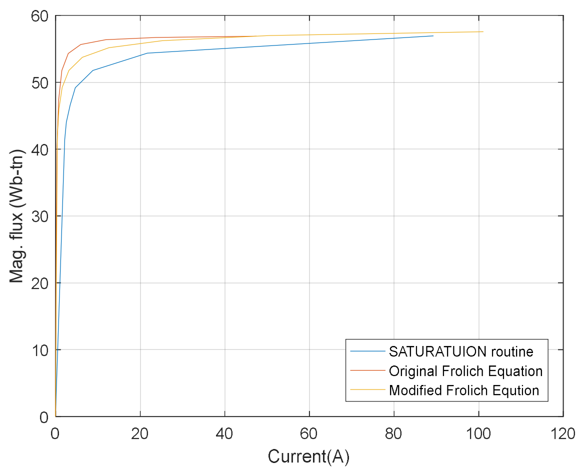

Fig. 4. Magnetization curves obtained by varying the type of Frolich equation

The plots of second and fourth harmonic against the fundamental component of the calculated inrush currents obtained by varying the type of Frolich equation are presented in Fig. 5.

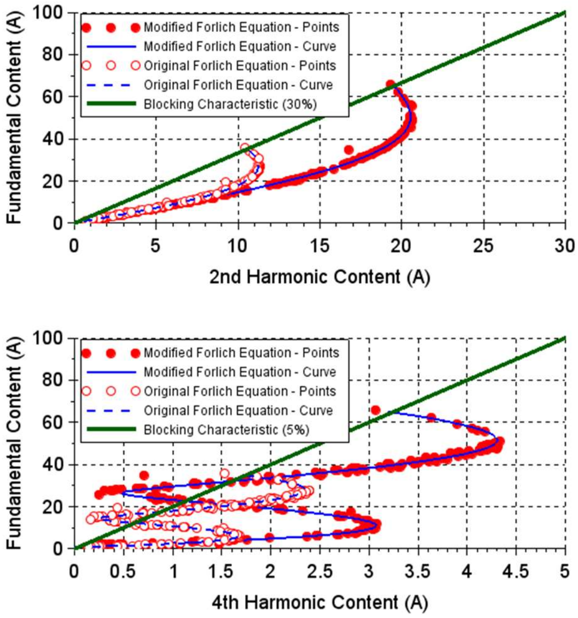

Fig. 5. Second and fourth harmonic characteristics of inrush currents obtained by varying the type of Frolich equation

These plots show that using the modified Frolich version increases the value of the fundamental, second and fourth harmonics. It is reasonable because, for the same magnetic flux, the modified Frolich equation drives to higher current values than the original one, as shown in Fig. 4. However, the observed rise seems to occur at the same rate. Therefore, since inrush detection algorithms use the ratio of those harmonic components, the type of Frolich equation seems not to affect their behavior significantly

However, the fundamental component value is also important for other functions implemented at transformer relays, such as differential and overcurrent functions. So, using the modified Frolich equation seems the best choice because it drives to a more conservative solution.

B. Number of points at saturation curve

Another parameter tested in this study is the number of points used in the saturation curve. The first point is placed at peak value of the magnetic flux at nominal voltage. The following points are placed alternately in the saturation region and in the linear region of the curve. Fig. 6 shows the magnetization curve obtained varying the number of points from 2 to 7. The plots of second harmonic component against fundamental component obtained by varying the number of points of the saturation curve are presented in Fig. 7.

These plots presented in Fig. 7 show that when the number of points increases from an odd to an even amount, the values of fundamental, second and fourth harmonics also increase. It happens the slope of the last section of the magnetization curve decreases if the number of points increases, as shown in Fig. 6. However, this increase occurs almost in the same rate. Similarly as observed by varying the type of Frolich equation, it thus seems that increasing the number of points used in the saturation curve is not likely to significantly the behavior of inrush detection algorithms based in harmonic content. However, using a higher number of points seems the best choice to perform an analysis of the operation of differential relays because it drives to a more conservative solution taking into account the absolute value of the fundamental component of the currents.

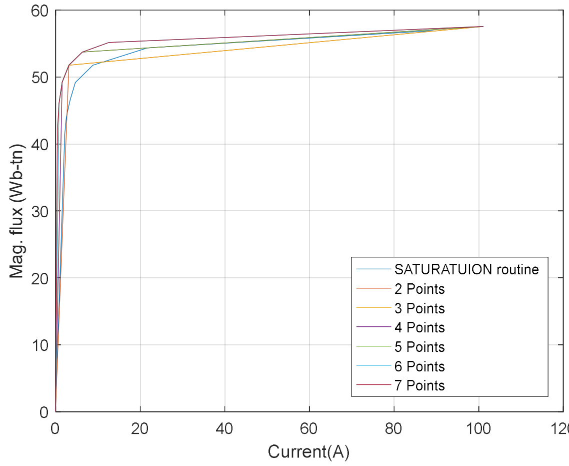

Fig. 6. Magnetization curves obtained by varying the number of points used in the saturation region.

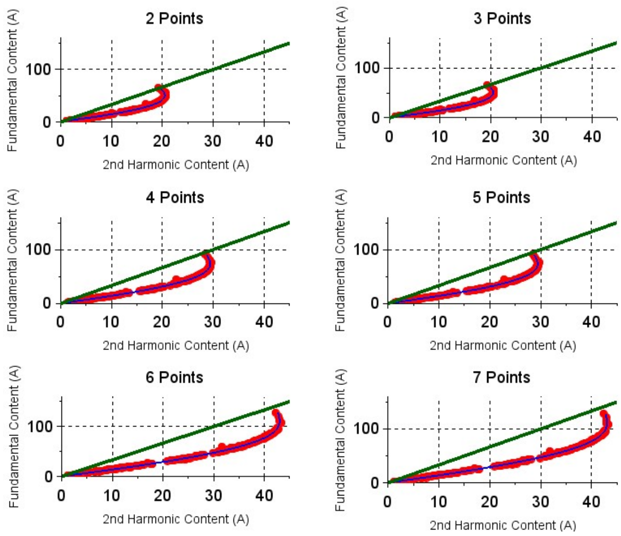

Fig. 7. Second harmonic characteristics of inrush currents obtained by varying the number of points used in the saturation region.

C. Element used to model nonlinear inductances

As mentioned, ATP has three types of elements that can be used to model nonlinear inductances in the context of the XFMR model: pseudo-nonlinear (98), true-nonlinear (93) and hysteretic (96) inductors. The plots of second harmonic against fundamental component and fourth harmonic component against fundamental component obtained for these three elements are presented in Fig. 8. It can be seen in this Fig. 8 that changing the element used to model the nonlinear inductances of the transformer core parts does not affect significantly the analyzed harmonic components. It happens because the type of element used does not affect the magnetization curve.

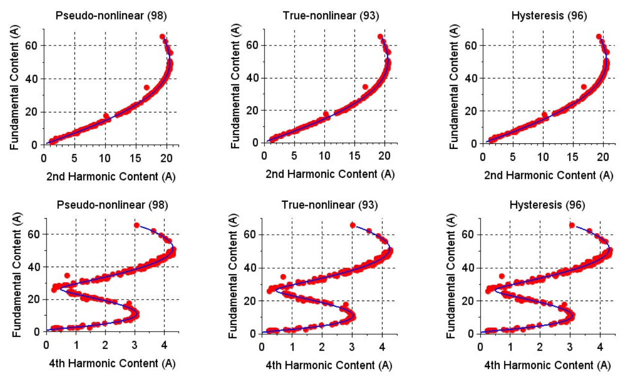

Fig. 8. Second and fourth harmonic characteristic of inrush currents obtained varying the type of elements used to model nonlinear inductances for transformer core parts.

D. Final slope

The magnetization curve obtained for three different options of final slope La (neglecting La, using the predefined value of 0.10 mH and using an estimated value) are presented in Fig. 9. The plots of second and fourth harmonic components against fundamental component obtained for each situation are presented in Fig. 10.

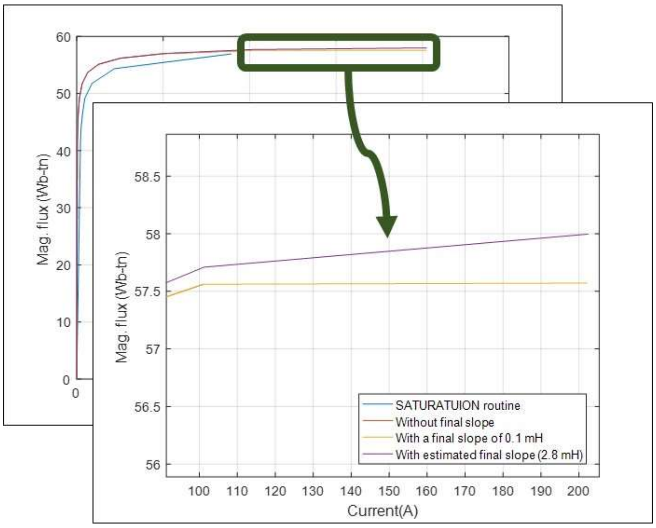

Fig. 9. Magnetization curves obtained by varying the value of the saturated core inductance L_a.

It is seen in Fig. 10 that, if an estimated value of La is used, the value of all harmonic components associated with the calculated inrush currents becomes very small. This happens because the estimated value for La (2.82 mH) is higher than the predefined value of La (0.10 mH). However, if the predefined value of La is used, these harmonic components reach the highest values. As a consequence, this choice seems the most conservative in terms of the absolute value of the harmonic components. However, the ratios of these components seem to remain the same, similarly as with the type of Frolich equation and the number of points in saturation curve.

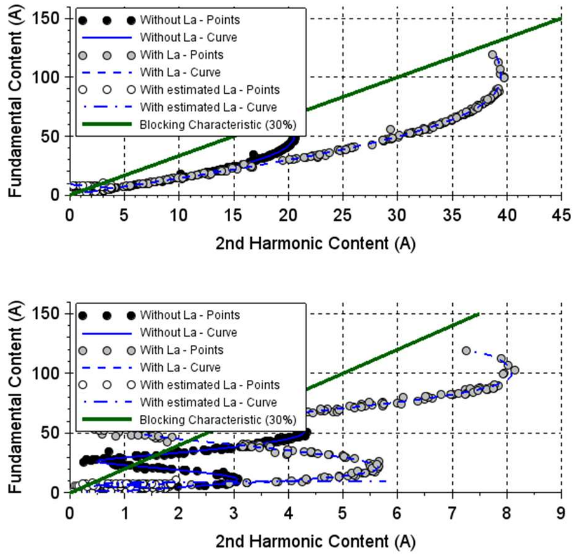

Fig. 10. Second and fourth harmonic characteristics of inrush currents obtained by varying the value of the saturated core inductance L_a.

V. Conclusions

This paper presents an analysis of the effect of advanced core settings of the XFMR model available in ATPDraw on the harmonic content of transformer inrush currents. It is shown that changing the considered settings does not significantly affect the harmonic content of the calculated inrush currents and hence the setting of inrush detection functions that are present in transformer protective relays. This can be explained by the fact that according with equations (3) and (4) the ratio of any pair of harmonic component of inrush current depends only on the order of these components and the pulse width α. By the way, the pulse width α depends basically only on the location of the knee point. Thus, because the four parameters analyzed in this study does not affect significantly the location of the knee point they do not affect the ratio of any harmonic component of the inrush current.

However, the fundamental component value is also important for many other protection functions also implemented in differential relays. Therefore, if the XFMR model were used to perform a transient analysis to assist a protective relay engineer during a transformer protective relay setting, it is important to choose properly the type of Frolich equation, the number of points in the saturation region and the value of the La inductance, as also shown in this paper.

In future studies, the considered method of analysis could be used to evaluate the effect of other parameters, such as residual flux, in the behavior of inrush detection functions. Furthermore, it could be also used to study and validate novel techniques for detection of inrush currents.

VI. References

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