

An EMTP-based analysis of the switching shift angle effect during energization/de-energization in the final ferroresonance state

J. A. Corea-Araujo, F. González-Molina, J. A. Martínez-Velasco, J. A. Barrado-Rodrigo, L. Guasch-Pesquer

Abstract—Ferroresonance is one of the most common transient phenomena studied by power system engineers. The unpredictable behavior and hazardous effects associated to ferroresonance have led researchers to determine the main parameters involved in its occurrence. Despite the extensive literature available today, its behavior and characterization still remain widely unknown. This paper analyzes the implication of the switching shift angle in the final ferroresonant state. Bifurcation diagrams are here applied to characterize ferroresonance behavior and to analyze the possible divergence in parametric analysis results due to the switching shift angle effect.

Keywords: Ferroresonance, EMTP-ATP, bifurcation, modeling, transformers, shift angle, energization.

I. INTRODUCTION

FERRORESONANCE is a firmly established term in power systems analysis that is used to denote oscillating overvoltages that usually appear in scenarios involving a non-linear inductance associated with any capacitance source. In general, ferroresonance can occur in any power system that contains transformers, regardless its type or size. Capacitance interaction can be found either in the form of actual capacitor banks or a capacitive coupling [1]. A typical power system can contain series capacitor for line compensation, shunt capacitor banks, underground cables, capacitive coupling, double circuit line, systems grounded via stray capacitance, grading capacitors on circuit breakers, generator surge capacitors, or capacitive coupling internal to transformer. Therefore, the possibilities to obtain a ferroresonant circuit path are endless.

Many conditions prone to initiate ferroresonance on a three-phase system are related to any manner of transformer energization/de-energization [2]. Some typical cases are [3]: load rejection; fault clearing; transformer energized accidentally on one or two phases while the transformer remains unloaded or lightly loaded (below 10-20% rated load); transformer energized through grading capacitance of one or more open circuit breakers; transformer connected to a series

compensated transmission line; voltage transformer connected to an isolated neutral system; capacitor voltage transformer; transformer connected to a de-energized transmission line running in parallel with one or more energized lines; transformers supplied by a long transmission line cable with low short-circuit impedance. For more than a century a very high number of ferroresonance cases has been reported, modeled and studied [4] - [7].

Beside the dangerous transient that can be unfolded, it is worth remarking that all cases are the consequence of a commutation process. In most cases, research focuses in long parametric analysis involving the capacitance effect, the saturable inductance effect, load implication or waveform interpretation.

Nevertheless, there are some research works where oscillations prior to the steady-state ferroresonant condition were very difficult or impossible to be replicated. It has been suggested that this can be due to a random combination of parameters such as switching time or pre-switching voltage [8].

To date a serious study of the implication of the energization/de-energization shift angle into the final ferroresonant state cannot be easily found. This work tries to illustrate such implication by providing a case study aimed at understanding the ferroresonance behavior and presenting an alternative method to more accurately reproduce real ferroresonance cases [8], [9].

The document is organized as follows. A complete system description is presented in Section II. Modeling guidelines for switching shift angle analysis are presented in Section III. A case study is presented in Section IV. A parametric analysis extension is presented in Section V. Conclusion and foreseen works are discussed in Section VI.

II. TEST SYSTEM DESCRIPTION

The test system studied in this work contains the principal elements for a classical ferroresonance parametric analysis [3], see Fig. 1. In this study, the shift angle of the switch S1 for the energization/de-energization will be the priority.

The system zone presented in Fig. 1 interconnects a transmission system to a distribution network by means of a substation transformer. The parameters of the power system components are detailed below.

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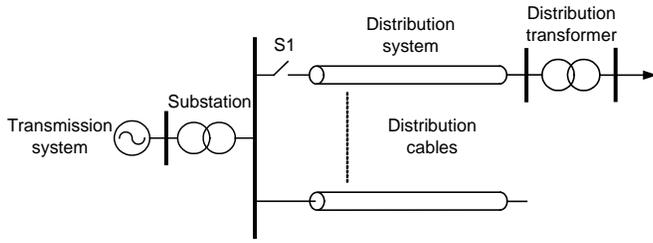


Fig. 1. Diagram of the system under study.

A. High Voltage Transmission System

The HV transmission system is represented by a 110 kV, 1500 MVA power source with $X/R = 10$, $X_0/X_1 = 1.1$, and a 110/25 kV, 35 MVA, 12%, Yd11, triplex core substation transformer grounded through a zig-zag reactance with 75 Ω per phase. The transformer characteristics are as follows:

- No load test (positive sequence, MV side): $V_0 = 100\%$; $I_0 = 0.296\%$; $W_0 = 18.112$ kW.
- Short circuit test (positive sequence, HV side): $V_{sh} = 12\%$; $I_{sh} = 83.34\%$; $W_{sh} = 348.263$ kW.

B. Medium Voltage Distribution System

The MV distribution system is represented by two of the main components involved in the ferroresonance phenomenon, a distribution insulated cable and a distribution transformer.

The main characteristics of the underground cable are (see Fig. 2): 18/30 kV, Al RHV, 3x(1x240 mm).

The distribution transformer is a 25/0.4 kV, 1 MVA, 6%, Dyn11, three-legged stacked core, with internal characteristics given by:

- Short-circuit test (positive sequence, MV side): $V_{sh} = 6\%$; $I_{sh} = 100\%$; $W_{sh} = 12$ kW.
- No load test (homopolar sequence, LV side): $V_h = 100\%$; $I_h = 0.5\%$; $W_h = 1.8$ kW.
- Saturation curves (legs & yokes) are shown in Fig. 3.

The study has been performed using EMTP-ATP [10]. Considering the system configuration and data, ATP built-in components (LCC for cables and the hybrid model for transformers) are accurate enough for analyzing the ferroresonant behavior of the system and for estimating the shift angle effect. The system modeled in ATPDraw is shown in Fig. 4.

III. SHIFTING ANGLE REPRESENTATION

The angle of the supply voltage at the moment of the commutation is rarely known during the energization/de-energization of a transformer while performing a ferroresonance analysis. This has been normally due to the fact that this parameter is unknown or not considered important. In any case, the set up for switches in simulation software is given in time values not in degrees, leading to the common mistake of thinking in seconds and not in the amount of volts.

Fig. 5 shows a normal sinusoidal signal over the shifting angle. Since any angle value corresponds to a different instantaneous value of the voltage signal, it is easy to understand that for different values of voltage, the transformer has different saturation points.

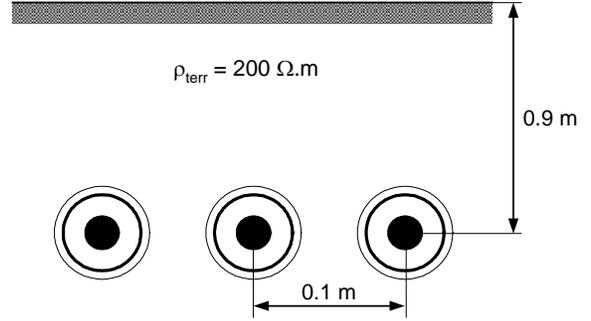


Fig. 2. Underground cable configuration.

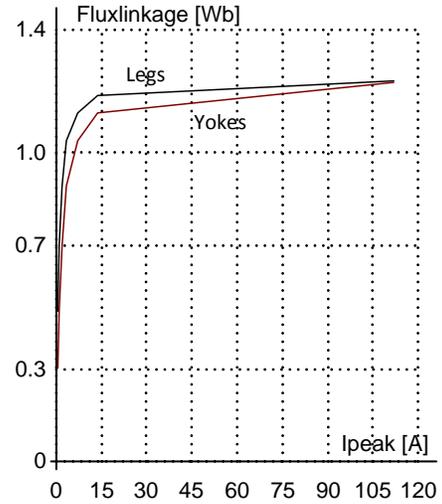


Fig. 3. Saturation curve of the distribution transformer.

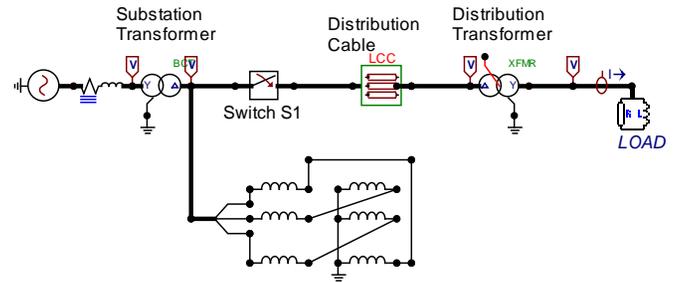


Fig. 4. ATPDraw network model of the test system.

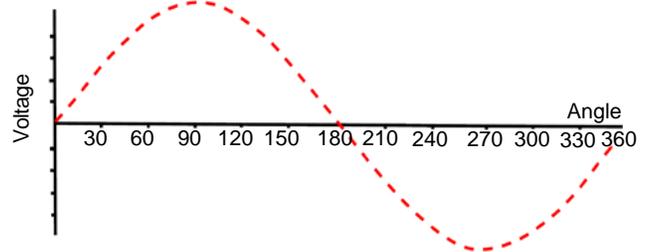


Fig. 5. Sinusoidal signal.

The saturation curve is the cornerstone in the appearance of ferroresonance. There are previous works dealing with the impact of ferroresonance behavior due to source phase angle [11], [12], but yet not explaining its dynamical and overall influence.

In order to calculate any possible angle for the sinusoidal

signal, assume that:

$$v = \sqrt{2} \cdot V_{rms} \cdot \sin \omega t \quad (1)$$

Since ωt represents the angle in this case, it is allowed to assume:

$$\theta = \sin \omega t \quad (2)$$

$$t = \frac{\theta}{2\pi f} \quad (3)$$

By using this simple expression, it is possible to have the time for any studied angle. However, it is recommended to leave at least one duty cycle before setting the switch. Since the period of a cycle is equal to the inverse of the frequency, this value will be equal to 0.02 s for 50 Hz signals and 0.01667 s for 60 Hz.

The shift angle time then can be defined as:

$$t_{shf} = k + \frac{\theta}{2\pi f} \quad (4)$$

where θ is the angle or set of angles under study, k is the period of one duty cycle in seconds and f is the power system frequency.

This analysis could seem too simple, but it grows in relevance due to the great development in computational software. Current EMTF-like software allows users to edit variable parameters in which a simple value such the open/close time of a switch can respond to an elaborated equation. For that reason, it is simple to obtain the whole behavior of a signal under the phase shift effect by implementing the expression (4).

IV. CASE STUDY

The basis of the proposed analysis relies on two principal premises:

- A power system is prone to ferroresonance when a transformer is energized/de-energized accidentally on one or two phases while the transformer remains unloaded or lightly loaded (below 10-20% rated load).
- The switching time (shift angle) of the energized/de-energized action can be undetermined but it affects the final state of the ferroresonance signal.

Consider the test system configuration shown in Fig. 4. Ferroresonance will be induced into the distribution transformer by accidentally opening the phase A pole of the switch S1 connected to the primary side while the transformer remains lightly loaded; the other two phases remain closed.

Two operating conditions are taken into consideration: 0.1%, and 2% of the transformer load. For both cases the shift angle will be varied in order to see whether there is any change in the state of ferroresonance. Only the de-energization part is performed assuming that the energization action will be affected in the same manner.

A. De-energizing a 0.1% Loaded Transformer

Taking into account that the full load for the distribution transformer is 1 MVA, the load applied will be around 1 kW. Initially, it is important to know the shape of ferroresonance under such operating conditions. Figs. 6, 7 and 8 show the

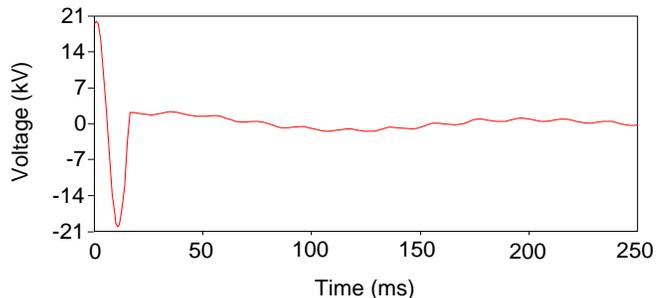


Fig. 6. Ferroresonance signal for a 0° shift angle - 0.1% load.

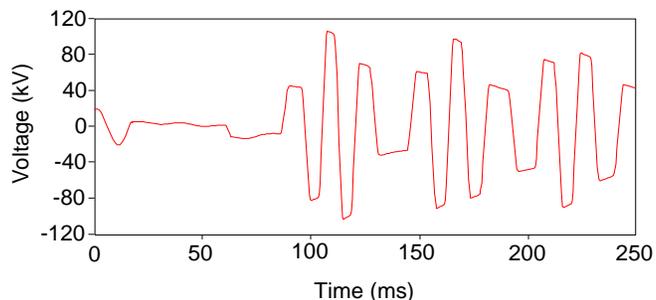


Fig. 7. Ferroresonance signal for a 15° shift angle - 0.1% load.

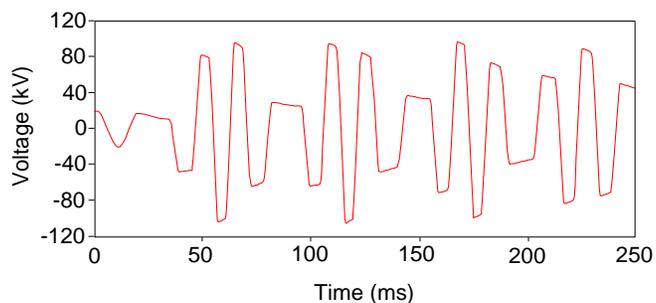


Fig. 8. Ferroresonance signal for a 60° shift angle - 0.1% load.

behavior of the ferroresonant voltage on the phase A for three different angles. It can be easily seen that, apart from the high values of the voltage, the switching shift angle has a major implication, not only in the final overall behavior of the signal but also in the initial transient between the normal stable state and the ferroresonance state.

The whole influence of the shift angle for the ferroresonance condition in a 0.1% loaded transformer can be resumed using a bifurcation diagram as shown in Fig. 9 [13], [14]. The diagram presents three important states: damped zones in which the voltage drops to almost 0.1 p.u., dangerous chaotic zones with voltage peaks up to 4.5 p.u., and repeatedly quasi-periodic zones oscillating between 2.5 and 3 p.u. values.

B. De-energizing a 2% Loaded Transformer

Once it has been seen that the shift angle can affect the behavior of ferroresonance, it is necessary to assure that assumption. For that purpose, the load of the transformer is increased to 5 kW. The shape of ferroresonance at different shift angles with the new operating condition is shown in Figs. 10, 11 and 12.

The pattern shown by the new plots is similar to the situation with 0.1% load, which means again that the shift

angle has a direct implication on the way ferroresonance is going to be unfolded. However, from the bifurcation diagram shown in Fig.13, it is evident that now there are more damped areas than in the previous case (see Fig. 9).

V. PARAMETRIC ANALYSIS

The previous section has proved that the switching shift angle is a parameter to be taken into account in ferroresonance studies. To extend the results shown in this paper, a parametric analysis aimed at exploring the effect of the load has been performed and repeated for different values of the shift angles. The resulting effect is important because besides the load, there are no other critical parameter changes (capacitance or saturation) in the power system.

- The result shown in Fig. 14 follows the typical shape in which ferroresonance theory is described [15]; that is, ferroresonance has a significant attenuation, normally referred to as damping, when the load increases in the secondary side of the transformer.
- The dynamic of the diagram shown in Fig. 15 goes from chaotic mode to a damped signal. The importance of the shift angle becomes here more evident and realistic. In contrast with the results from Fig. 14, the dangerous behavior remains even if the load reaches more than the 5% of the nominal value.
- The result shown in Fig. 16 confirms that the possibility of obtaining a misleading response in a parametric analysis can be high if the shift angle is not well defined. That is, the dynamic behavior of ferroresonance can be misrepresented.

VI. CONCLUSIONS

This paper has shown that in addition to the parameters usually considered in ferroresonance analysis (i.e., series capacitance, transformer core non-linear reactance, load), it is important to consider the shift angle of the voltage source with which the commutation action is performed. There are some cases in which a long transient is established between the steady state voltage signal and the ferroresonant final state.

It has been proved that the veracity of a parametric analysis involving any system value related to load or capacitances, among others, can be significantly affected just by changing the set up in the switch event, so much of the responsibility of the transient relies on the shift angle. In order to obtain the most precise representation of such cases, some effort should be addressed to approach the correct moment of the energization/de-energization event.

VII. ACKNOWLEDGMENT

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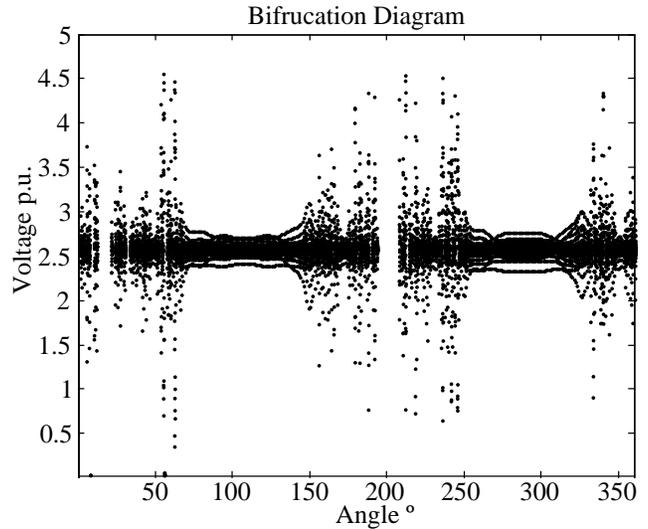


Fig. 9. Bifurcation diagram for 0.1% load connected.

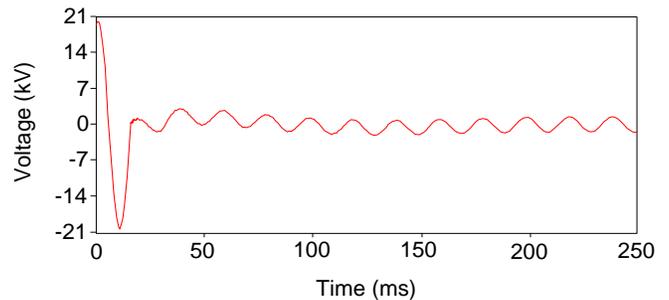


Fig. 10. Ferroresonance signal for a 0° shift angle - 2% load.

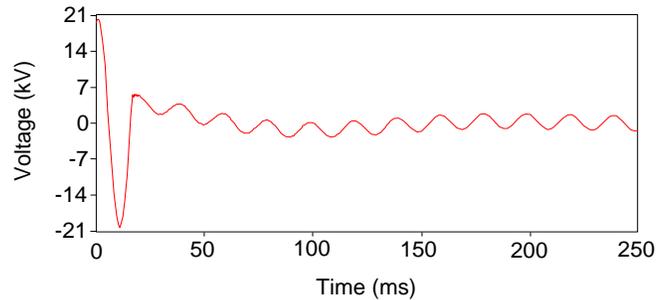


Fig. 11. Ferroresonance signal for a 15° shift angle - 2% load.

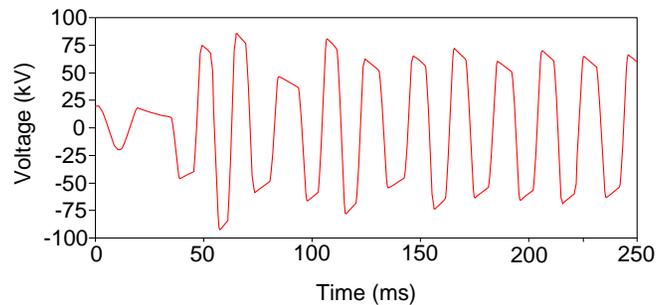


Fig. 12. Ferroresonance signal for a 60° shift angle - 2% load.

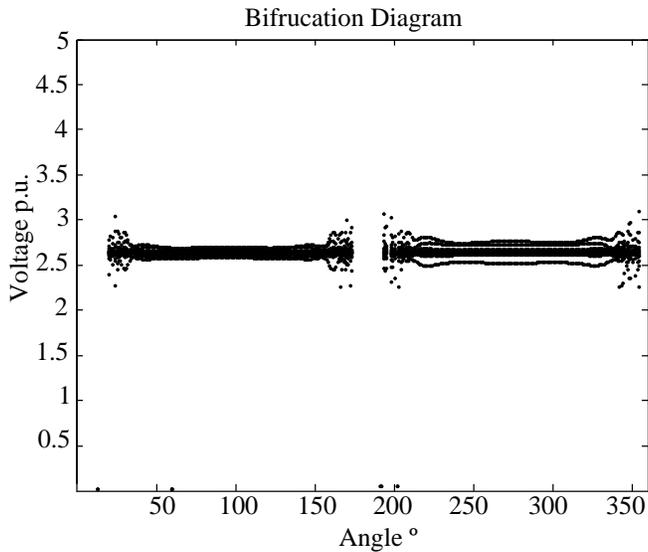


Fig. 13. Bifurcation diagram for 2% load connected.

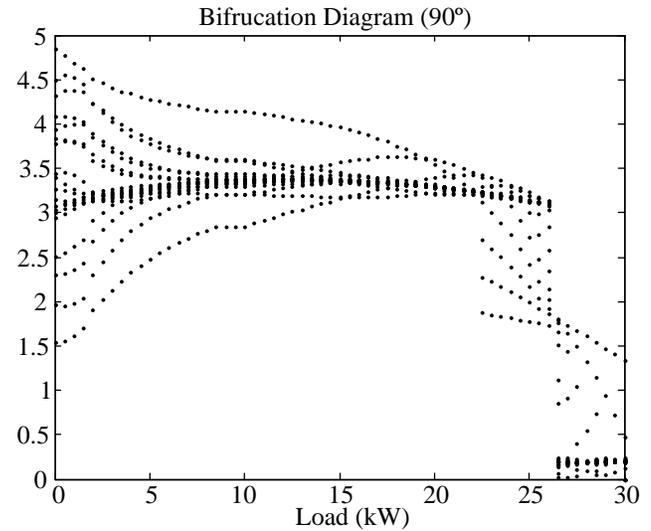


Fig. 16. Bifurcation diagram for 90° shift angle.

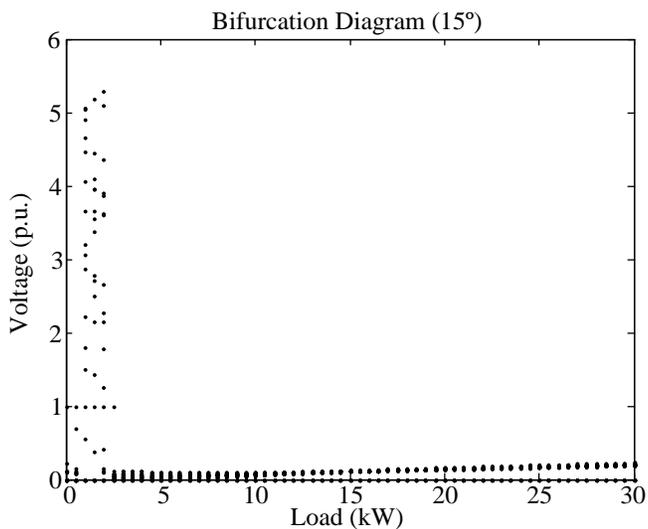


Fig. 14. Bifurcation diagram for 15° shift angle.

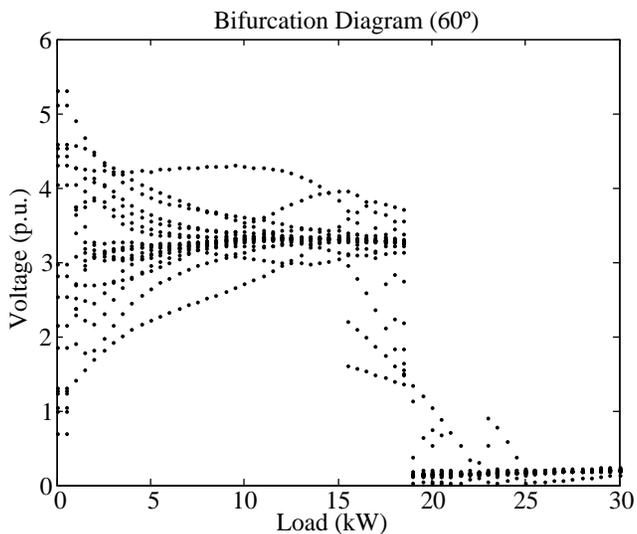


Fig. 15. Bifurcation diagram for 60° shift angle.

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