UNIVERSIDAD TÉCNICA COTOPAXI

FACULTAD DE CIENCIAS DE LA INGENIERÍA Y APLICADAS

CARRERA DE ELECTRICIDAD

“ANÁLISIS TRANSITORIO EN LA LÍNEA DE TRANSMISIÓN TRINITARIA 138 kV”

PROYECTO DE INVESTIGACIÓN PREVIO A LA OBTENCIÓN DEL TÍTULO DE INGENIERO ELCTRICO

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Latacunga, 28 julio 2025

DECLARACIÓN DE AUTORÍA

Yo Roche Galarza Cristhian Sebastian declaro ser autor del proyecto de titulación "ANÁLISIS TRANSITORIO EN LA LÍNEA DE TRANSMISIÓN TRINITARIA 138 KV", siendo la Ing. Castillo Jessica Nataly, Mgtr. Tutora del presente trabajo de titulación; y eximo expresamente a la Universidad Técnica de Cotopaxi y a sus representantes legales de posibles reclamos o acciones legales.

Además, certifico que las ideas, conceptos, procedimientos y resultados vertidos en el presente trabajo de titulación, son de mi exclusiva responsabilidad.

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AVAL DEL TUTOR DEL PROYECTO DE INVESTIGACIÓN

En calidad de Tutor del Trabajo de Investigación sobre el título: “**ANÁLISIS TRANSITORIO EN LA LÍNEA DE TRANSMISIÓN TRINITARIA 138 KV**”, propuesto por el o la estudiante **Cristhian Sebastian Roche Galarza y Placencia Guartatanga Mauricio Xavier** de la Carrera de **ELECTRICIDAD** considero que dicho proyecto de titulación cumple con los requerimientos metodológicos y aportes científico-técnicos suficientes para ser sometidos al tribunal de lectores.

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AVAL DE APROBACIÓN DE LECTORES

Cumpliendo con el Reglamento de Titulación de la Universidad Técnica de Cotopaxi, en calidad de Lectores de Tribunal de Proyecto de Investigación con el Título **“ANÁLISIS TRANSITORIO EN LA LÍNEA DE TRANSMISIÓN TRINITARIA 138 kV”**, propuesto por los estudiantes **CRISTHIAN SEBASTIAN ROCHE GALARZA** y **MAURICIO XAVIER PLACENCIA GUARTATANGA** de la Carrera de Electricidad, me permito indicar que los estudiantes han concluido todas las observaciones y realizado las correcciones señaladas por el Tribunal de Lectores, por lo cual presentamos el Aval de aprobación del Proyecto de Titulación correspondiente a la modalidad proyecto de investigación en virtud de lo cual los postulantes pueden presentarse a la Defensa de su Proyecto de Titulación.

Particular que pongo en su conocimiento para los fines legales pertinentes.

Atentamente,

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Transient Analysis On The 138 kV Trinitaria Transmission Line

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Abstract. The study examined the behavior of a capacitor bank coupled to a 138 kV transmission line in three key scenarios: energization, ground faults and capacitor opening. The energization of the capacitor bank resulted in a maximum inrush current of 1,295 kA with an oscillation frequency of 832.64 Hz, which ratifies the need for synchronized switching to prevent overvoltages, in line with the IEEE 1036-2010 standard and previous CENACE studies. In ground faults, the use of choke reactors was effective, significantly reducing current and frequency peaks by increasing inductance, in accordance with EEQ and IEC 60071-1. During the opening of the bank, it was verified that the zero-crossing control decreases the voltage peaks (from 273.87 kV to 250.71 kV), which protects sensitive equipment against transients, as established by IEEE 1159-2009. In all cases, the results remained within the limits accepted by the IEC 60071-2 standard, validating the effectiveness of the strategies applied for the safe operation of the high voltage electrical system.

Keywords: First Keyword, Second Keyword, Third Keyword.

1 Introduction

The study of electrical networks is key to ensure that the network works properly and without risks. Nowadays, there are programs that help to visualize how the network will behave in different cases, which makes it easier to analyze and improve it [1], [2], [3]. In the National Interconnected System of Ecuador, capacitor banks are very important to maintain stable voltage and control reactive power in 138 Kv transmission lines [4], [5]. However, getting these devices to intervene at the right time can be a challenge, especially with regard to reactive power delivery and disconnection, since transient currents, sudden frequency changes and overvoltages can be generated during these processes, which could jeopardize the stability of the network and damage its components [6], [7], [8]. To analyze the system in these cases, the ATP Draw program, which simulates how the network behaves in electromagnetic terms, will be used [9], [10]. This study will focus on how the capacitor banks act in the 138 kV bus in three different scenarios: when they are turned on for the first time, when there are faults near the bank and when the capacitor bank is disconnected [11], [12], [13].

2 Methodology

For the following case study, a 138 kV network model was built which refers to the Trinitaria-Esclusas-Caraguay transmission system. The ATP Draw program will be used to simulate three different scenarios to evaluate the electromagnetic impact of capacitor groups on the 138 kV Esclusas line.

- *Presence of faults near capacitor Banks.*
- *Capacitor bank shutdown under normal load conditions*
- *Subsequent paragraphs, however, are indented.*

As a starting point, the necessary technical data are collected, including the configuration of the transmission network with a length of 7.4 km, using a pair of ACAR 750 MCM 18/19 type conductors, as well as different electrical characteristics of the capacitor groups and other important components of the system, as shown in Table 1.

Table 1. Conductor Characteristics of the 138 kV Transmission Line.

Gauge (AWG o kcmil)	**Cross section (mm²)**	**Conductor Diameter (mm)**	**Total Weight (kg/km)**	**Breaking Load (kg)**	**Resistance DC to 20 °C (Ω/km)**	**Current capacity (A)**
750 AWG o Kcmil	387,63 mm²	25.81mm	1066.29 kg/km	8846,46 kg	0.0831 Ω/km	839 A

2.1 Transformers

In order to correctly simulate the transformer within the 138 kV system, it was key to consider the electrical parameters to show its function in transitory moments. Next, the data for the 225 MVA transformer, with three windings (primary, secondary and tertiary) is defined. This includes voltage, resistance and inductance values. This information is vital for the analysis of electromagnetic events through simulations in ATP Draw.

2.2 Capacitor bank

In the National Grid, capacitor banks operate at different voltages, 138 kV being one of the most important. In the ATP Draw program, these banks are modeled in microfarads (μF) and calculated with the following equation 1:

$$C_Y = \frac{Q_{Mvar}}{(V_{rms\ l-l})^2 \cdot 2\pi \cdot f} \tag{1}$$

2.3 Additional Configurations

The maximum time stop, called Tmax, changes between 0.003 and 2 seconds, depending on the event under consideration, which affects the visual outputs of the simulation. The Xopt and Copt values were set to a frequency of 60 Hz.

3 Result

The system under study will be subjected to switching events in the existing capacitor banks of the interconnected NIS based on the following scenarios:

- *First-pass energization in capacitors.*
- *Ground faults in the vicinity of capacitor bank.*
- *Capacitor bank opening.*

In each scenario, standardized strategies will be used to reduce or treat the changes in current oscillations, and also to determine the current and voltage magnitudes. As shown in Table 2 for the analysis of high voltages, the case-peak form will be used which is established in the IEC 60071-2 standard; this standard establishes that only the phase with the highest phase-to-ground overvoltage in each maneuver will be taken into account. The voltages before the maneuvers will be seen according to the lack of plus or minus 5% of the normal voltage allowed by the INS.

Table 2. Comparison of voltages with and without compensation at the 138 kV bus.

Busbar	**Voltages without capacitive compensation (kV)**	**Voltages with capacitive compensation (kV)**
Esclusas - 138 kV	137.79 kV	144,75 V

4 First-pass energization in capacitors.

Fig. 1 shows the first evaluation scenario, the breaker closing time for energiz-ing the first capacitor bank on the 138 kV Esclusas busbar, considering a three-pole closing with closing maneuver time at T=30 ms. That the run time selected voltage in phase A is minimum and in Phase B is maximum, this difference is more noticeable in the peak energizing current in Phases B and C are higher compared to phase A. As for the energizing current shown in Fig. 2, a high value of 1.295 kA is recorded, and an oscillation frequency of 832.64 Hz. Thus, obtaining the value of the shock waves at 1.0574 kAkHz. The results of current and oscillation frequency are shown in Table 7.

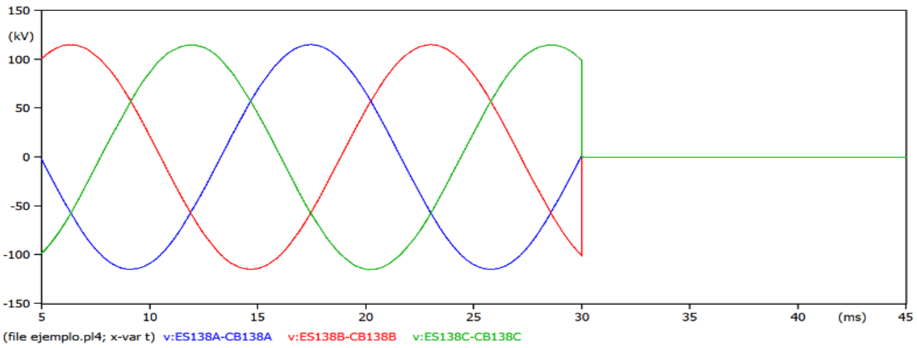

Fig. 1. Diagram of the Trinitaria-Esclusas-Caraguay transmission system in ATP Draw.

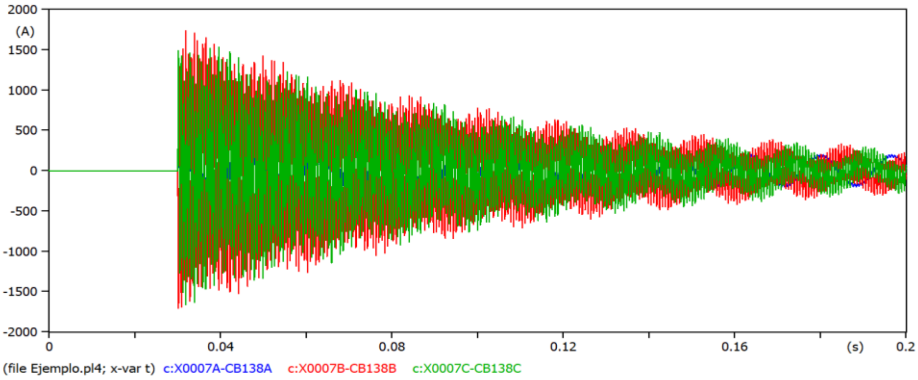

Fig. 2. Breaker inrush current, T-lock=30ms.

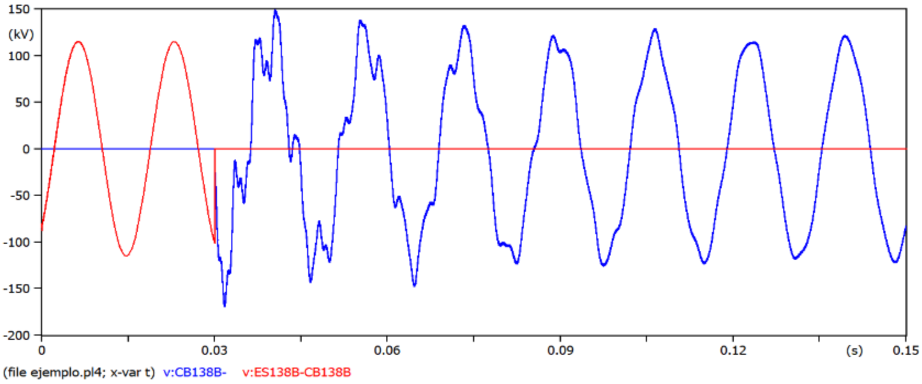

Fig. 3. Voltage on the switch vs. voltage on the capacitor phase B.

Immediately after the circuit breaker closes, overvoltages are present at the capacitor bank terminals, obtaining the inrush current, transient stabilization time, peak voltage at the bank terminals and oscillation frequency data for each type of maneuver evaluated in Table 3.

Table 3. Transient overvoltage parameters in the capacitor bank energization.

Type of closing maneuver	Energizing Current Inrush (A)	Transient stabilization time(s)	Peak Voltage at Bench Terminals (kV	Oscillation Frequency (Hz)
No control	1805 A	0.118 s	430.85kV	1499.40Hz
Reintegration resistances	377.9 A	0.0928 s	125.1 kV	722.8 Hz
Synchronized knob at minimum voltage	367.2 A	0.1213 s	130.82 kV	162.5 Hz

4.1 Ground faults in the vicinity of capacitor banks

The single-phase fault will be executed on the Esclusas 138kV busbar, at t=0.03 s and based on the breaker specifications (44 ms opening time) the breaker opening maneuver will be performed at t= 0.054 s. Table 4 presents the results obtained by simulating ground faults in the vicinity of a capacitor bank operating at 138 kV, evaluating the impact of different inductance values on the choke reactors.

Table 4. Results of ground fault near a 138 kV capacitor bank.

mH Shock Reactor	Peak current Icc A	Switch A Peak Current Icc	Hz Oscillation Frequencies	Shock Wave kAkHz
0.001	25	1512.3	1562.20	23.61
1	25	192.5	1298.70	0.259
2.65	25	165.3	1277.63	0.211
3.97	25	163.2	1265.82	0.206

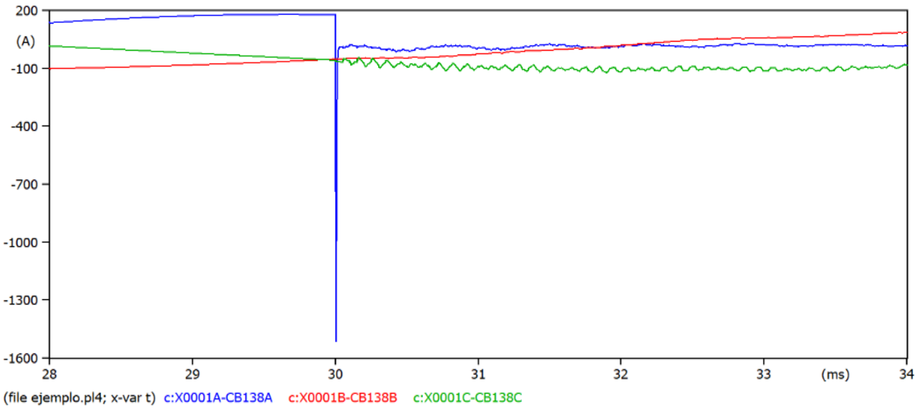

Fig. 4. Comparison of output current with different configurations.

Compared to the current value of the case with the lowest surge inductance, 1.51 kA is obtained. As for the oscillation frequency, the class 0 breaker, according to its sensitivity to high frequencies of 20 kHz, adequately withstands the most crit-ical case evaluated in Fig. 4.

Fig. 5 shows the behavior of these transient waves during capacitor disconnec-tion, evaluating parameters such as oscillation frequency, peak voltage reached and zero crossing control.

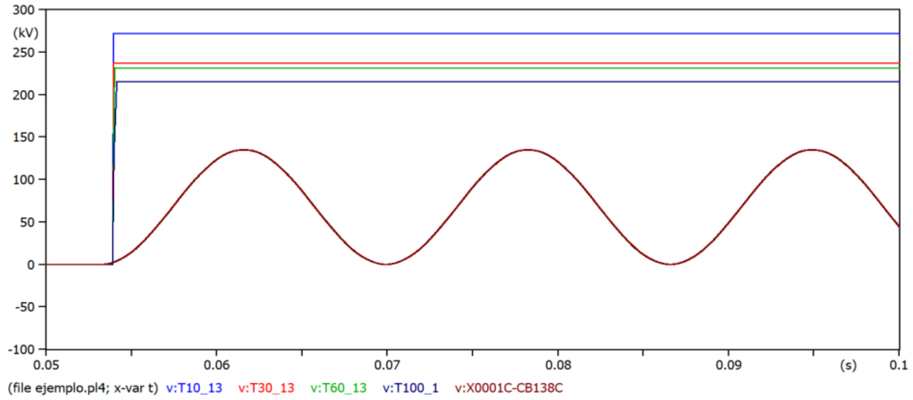

Fig. 5. Surge waves in the opening of capacitor banks.

4.2 Opening of capacitor bank.

The opening of the first step occurs at T=85 ms, where Fig. 6 shows extreme oscillations in the order of 5.06 kHz, producing the most severe case during the connection of 138 kV capacitor banks

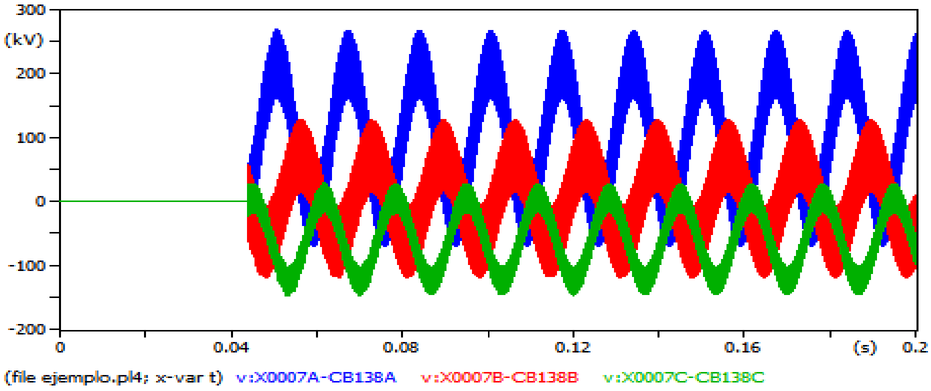

Fig. 6. Variation of the oscillation frequency depending on the voltage level.

Fig. 7 illustrates the behavior of voltage and current during the opening of a capacitor bank using the co-current zero-crossing control technique.

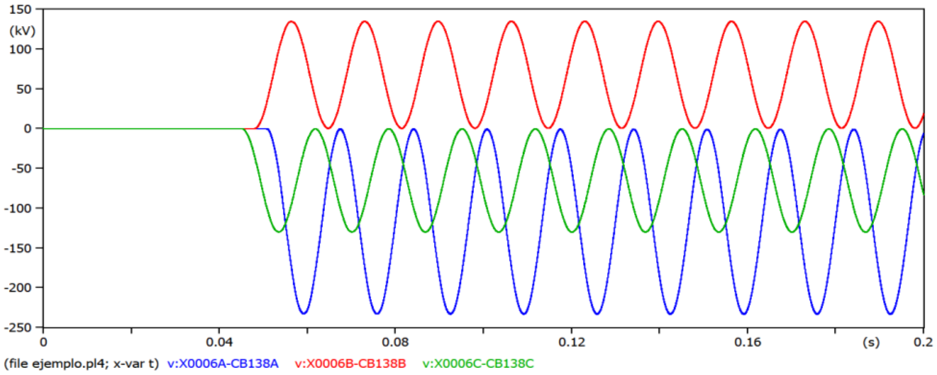

Fig. 7. Voltage - Current in the cut-off with current zero crossing control.

Table 5 presents the results obtained during the first step of opening a capacitor bank in a 138 kV system in the two scenarios.

Table 5. Results of the first capacitive opening step on the switch.

Scenario	**Maximum Opening Voltage Vrms l-l Kv**	**Oscillation Frequency Hz**
No opening control	273.87	50. 69
Zero crossing control	250.71	61.17

At the moment of disconnecting the capacitor banks of the 138 kV System, Fig-ure 8 shows the design that a breaker must have to match the recovery speed between contacts and the transient voltages that appear after opening.

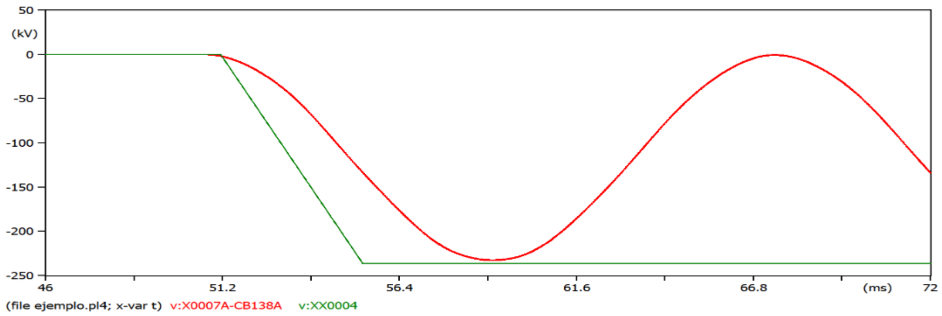

Fig. 8. Dielectric strength curves versus opening process.

4.3 Comparison with previous studies and regulations.

The findings on the 138 kV line are consistent with previous studies on capacitor bank activation in high voltage environments. The simulations suggest that the use of synchronized switching, together with choke reactors, successfully keeps the overvoltage within the limits set by IEC 60071-2, which requires the operat-ing voltage to be maintained between 105% and 110% of the nominal value.

1. Capacitor Bank Initial Stage Activation.

As can be seen in Fig. 2, a transient oscillation of 1.0574 kAkHz was rec-orded at the moment of the three-pole closing of the breaker, corresponding to a maximum inrush current of 1.295 kA and an oscillation frequency of 832.64 Hz.

This value, although within permissible limits, represents an important eval-uation situation, where the occurrence of oscillations can compromise the stability of the equipment and the integrity of the circuit breakers if the in-stant of closing is not adequately controlled [13].

Previous studies at 138 kV level conducted by CENACE Ecuador in 2021 found that the non-synchronized start-up of capacitor banks at 138 kV level caused transient overvoltages reaching a maximum of 1. 12 pu, while syn-chronized operation kept overvoltages below 1. 05 pu, demonstrating the success of this method [14].

Standards: IEEE 1036-2010 recognizes synchronized operation as an effec-tive practice to alleviate oscillation and overvoltage problems in medium and high voltage systems [15].

2. Ground Faults Near Capacitor Bank

As can be seen in Table 5, at lower inductance (0.001 mH), high current peaks (1562.20 A) and high oscillation frequencies (23.61 kHz) are generated. However, by increasing the inductance to 3.97 mH, these values decrease notably (1265.82 A and 0.206 kAkHz), significantly improving the system response to faults.

Previous studies at the 138 kV level by Empresa Eléctrica Quito in 2022 indicated that choke reactors incorporated into capacitor banks can decrease transient spikes by up to 65% during near ground faults [16].

Standards: IEC 60071-1 (2021) states that limiting devices should be implemented when temporary overvoltages exceed 120% of rated voltage, which can occur during such incidents [17].

3. Opening of the Capacitor Bank

During the opening of the first step of the capacitor bank at 138 kV (T = 85 ms), critical oscillations of up to 5.06 kHz were presented in Fig. 6 In the uncontrolled scenario, a voltage of 273.87 kV and a frequency of 50.69 Hz were reached, while with zero-crossing control the voltage was reduced to 250.71 kV, although the frequency increased to 61.17 Hz. This shows that zero-crossing control is effective in mitigating voltage spikes at disconnection.

Previous studies by Maldonado indicated that frequencies higher than 4.5 kHz arose in 138 kV networks during capacitor bank disconnections, suggesting the implementation of non-synchronized circuit breakers to reduce these effects.

Standards: IEEE 1159-2009 dictates that transient mitigation measures must be used to prevent damage to electronically connected devices on the network.[18].

5 Conclusion

Simulations carried out on the 138 kV line show that the energization, fault, and disconnection of capacitor banks generate significant transient phenomena that can compromise system stability if not properly managed. During energization, an inrush current of 1,295 kA and a frequency of 832.64 Hz were recorded. These values, while acceptable, highlight the need for synchronized switching to avoid overvoltages, as supported by IEEE standard 1036-2010 and CENACE studies (2021). In the case of ground faults, the use of choke reactors was found to considerably reduce current and frequency, in accordance with technical re-ports such as EEQ (2022) and the provisions of IEC standard 60071-1. Finally, during disconnection, the zero-crossing control managed to reduce voltage peaks from 273.87 kV to 250.71 kV, albeit with a slight increase in frequency, confirm-ing its effectiveness in mitigating transients according to IEEE standard 1159-2009. Overall, these results confirm that the implementation of synchronized switching techniques and mitigation devices, such as reactors, is essential to keep overvoltages within the range permitted by IEC 60071-2 (105-110% of nominal value) and ensure the protection of the electrical system.

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