Autotransformer Inadvertent Energization Through Circuit Breakers Gradient Capacitors

E. Martínez M.,   E. Godoy A.,   R. Ruelas T.

***Abstract*- This paper discusses the commissioning experience with a 400/230/34.5 kV (primary/secondary/tertiary) auto transformer (AT) in the electrical substation Choacahui, located in the Northwest of the Mexican Electrical System MES. The analyzed case was the energization of an AT when was closing disconnectors with primary and secondary breakers opened. In these conditions, was detected a 20% of the nominal voltage at secondary AT. In this work, reproduction of measurements was performed with the ATP program. A voltage divisor was found among the equivalent system in the electric substation, the gradient capacitors in the AT breakers, and the AT impedance. Once the cause was found, simulations were performed to verify the occurrence of inadvertent energization for the connection of busbars, short and long transmission lines, reactors etc. Finally, a discussion is presented about limiting the use of gradient capacitors in power transformer circuit breakers with similar characteristics to avoid possible injuries to the substation operating personnel.**

***Keywords*: Inadvertent energization; gradient capacitors, Alternative Transient Program ATP.**

I. INTRODUCTION

When a new substation or a section of it is synchronized to the power system, there is always the risk of affecting the stability of the electrical system. It is very important to mention that, at the time of closing the switch powering a new element to the system, all design features and quality of the work of construction of the substation must be matched to the operating conditions of the given electrical power system. In that moment voltage, frequency or angular stability conditions can be altered, which defines commissioning success and this process can take just a few milliseconds. This was the Choacahui substation case, which originally was operated at 230 kV in the Northwest of MES. See fig. 1.

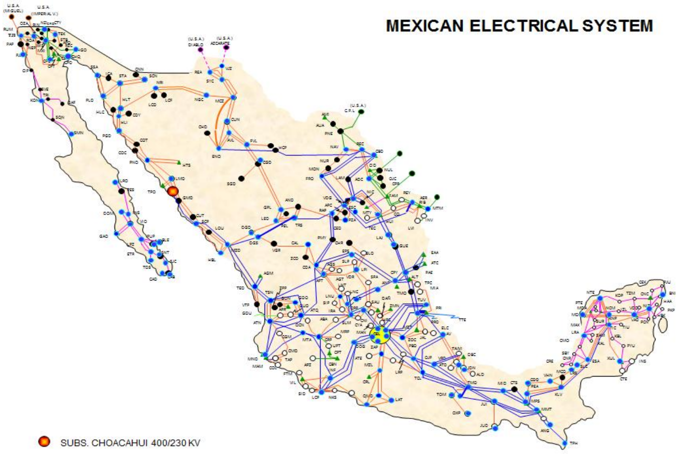

Fig.1 Mexican electrical system diagram

The 400 kV busbar was energized from the adjacent substation through a 400 kV and 247.61 km transmission line, and the disconnectors were closed (breakers in primary and secondary autotransformer, side remained open). A noise and vibrations were detected in the AT one-phase 3x125 MVA´s. There was disturbance recorder operation in the AT secondary side that measured 45 kV. See fig. 2

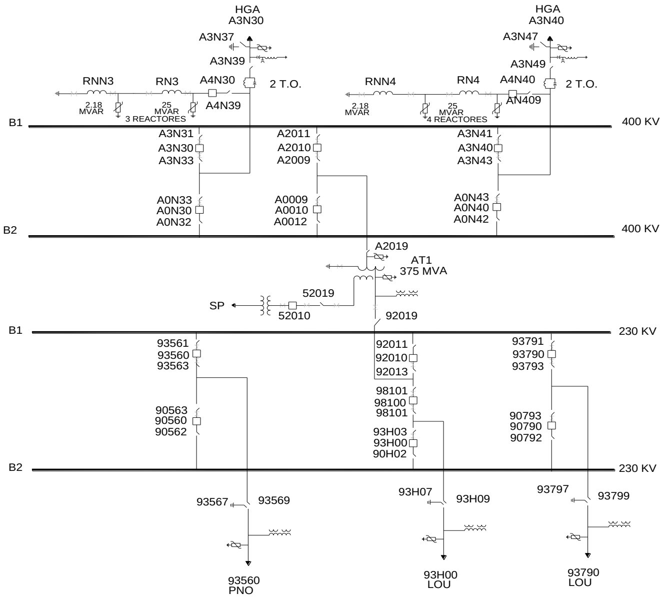

Fig. 2 400 kV Choacahui substation one-phase diagram

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II. 400 KV CHOACAHUI SUBSTATION ENERGIZATION

On April 21, 2012 at 18:36:23 h the 400 kV busbar was energized for the first time in the Choacahui substation (CHO) through HGA-A3N40-CHO circuit. The 400 kV section arrangement corresponds to double busbar and double breaker and 1 ½ circuit breaker scheme for 230 kV section, see fig 2. When 400 kV disconnectors (A02011, A2019, A0012 and A0019) were closed, an abnormal noise of vibration was presented at the transformer. The records obtained correspond to CHO-A3N40-HGA voltage and auto-transformer currents from the 400 kV side. See fig. 3 and 4.

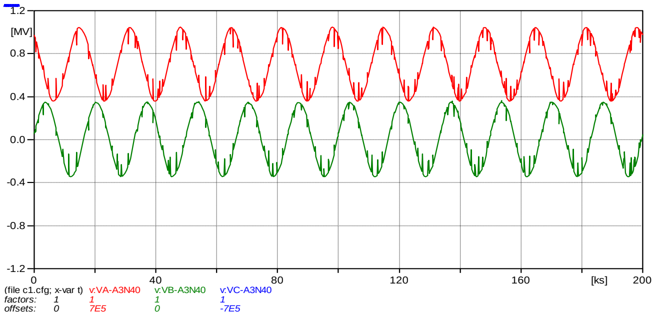


Fig. 3 CHO voltage records of CHO-A3N40-HGA line

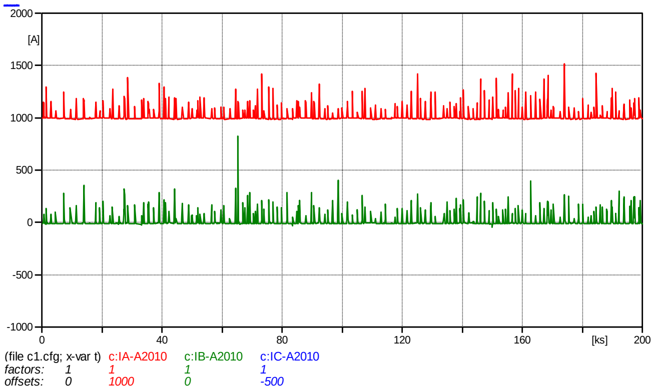


Fig. 4 Current records in A2010 (400 kV) breaker

The voltage was distorted by notches. Notches are due to electrical arching because of closing disconnectors. The current through the open breaker is shown in fig. 4. Both graphs (fig. 3 and 4) indicate abnormal conditions in breakers when disconnectors were closed.

III. INADVERTENT ENERGIZATION PHENOMENON

During the April 21, 2012 event, it was not possible to record the auto-transformer's voltage. However, in an instantaneous measurement, 45 kV was detected in the secondary auto-transformer. Thus, disconnectors were opened the auto-transformer commissioning and suspended due to unsafe conditions. About the causes of this event, there were many theories and questions:

1. Damage in the breaker's main chambers.
2. Damage in the gradient capacitors.
3. Ferroresonance [1], [2].
4. Inadequate ground connections in the substation.

Fig. 5 shows a 400 kV AT air insulated switchgear (AIS) circuit breaker. It has two chambers with gradient capacitors and without preinsertion resistance.

Fig. 5 400 kV breaker in Choacahui substation

The 400 kV gradient capacitor breakers were sent to the laboratory to be checked. Capacitances measurement, dissipation factor, alternate voltage endurance, partial dischargers measurement, capacitance and dissipation factor were tested according to their corresponding standard [3]. No damage or error was found.

To determine the type of phenomenon that occurred, simulations with ATP were made. Each substation equipment was modeled [4], see fig. 6. The equivalent electrical system was modeled as well as: the 400 kV lines (247.61 km each), 400 kV busbar substation, 400 kV inductive voltage transformers, 400 kV circuit breakers with their gradient capacitors (2000 pF each chamber), 400/230/34.5 kV AT, 230 kV busbar substation, 230 kV inductive voltage transformers and equipment connected at the tertiary (34.5 kV) see fig 6.

IV. MEASUREMENTS REPRODUCTION WITH ATP

The first simulated event was closure of the disconnector. which could take place in several seconds, depending on the disconnector type. It is characterized by intermittent current electrical arching until closing. This event was simulated with instantaneous energization of the auto-transformer through gradient capacitor breakers. The results obtained were very close to measurements.

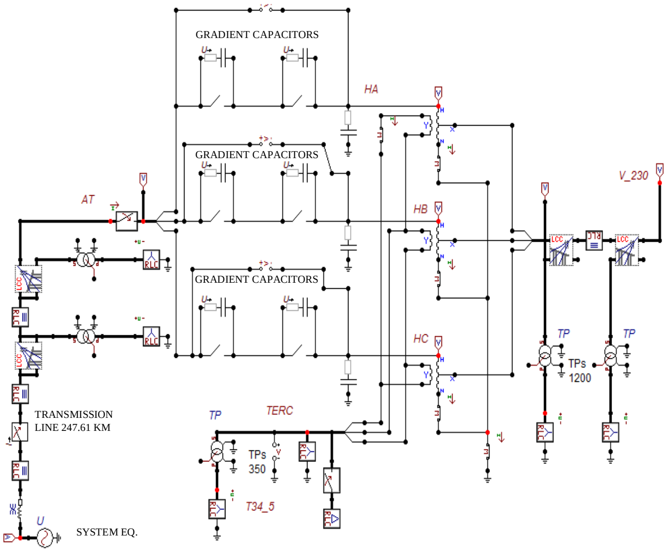


Fig.6 ATDraw diagram

Fig. 7 shows a diagram with measurement points. According to the simulation the auto-transformer is energized in 400 kV through the gradient capacitors and reaches 63.28 kV (VH). The 230 kV voltage reaches 36.5 kV (VL). It also shows the voltage through the gradient capacitor (VE-VH), which is slightly higher than the source nominal voltage (VS). The graphs of these values are shown in fig. 8.

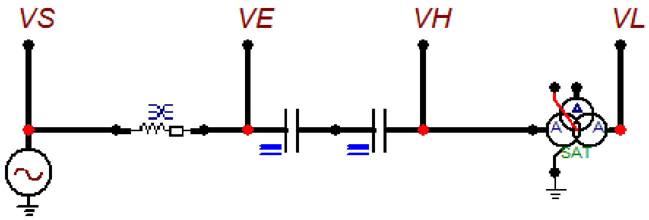


Fig.7 Measurement during simulations

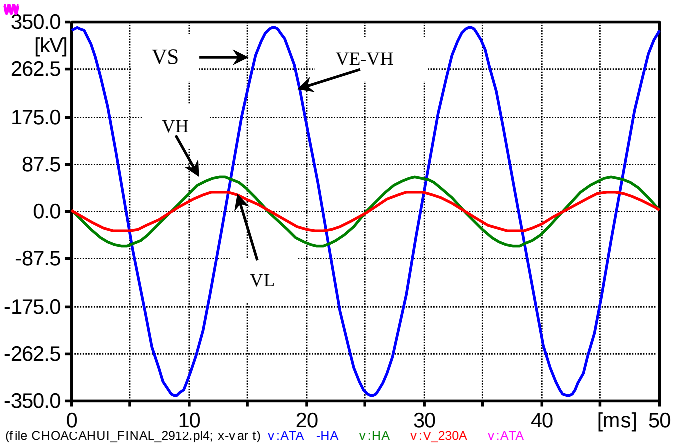


Fig. 8 Voltage obtained from steady state simulation

Several cases with different capacitance values (800 to 2000 pF) were simulated and it was found that the voltage values in the AT decrease with a lower capacitance, but they do not disappear.

To establish why the protection schemes did not operate, a three-phase fault in the 400 kV auto-transformer was simulated and it was found that the capacitance was so small that it represented a very high capacitive reactance; therefore, the fault current was limited.

Through simulations, it was determined that with gradient capacitors energization a reduced voltage appears and this voltage is not hazardous for operating personnel or equipment.

On May 1st, 2012 the CHO substation was energized by a 400 kV autotransformer. Voltages of 230 kV and currents of 400 kV were recorded. See fig. 9 y 10.

Fig. 9 shows reduced voltage from 0 to almost 0.15 s, when the circuit breaker was opened. Then it was closed and there was almost the nominal voltage with a distorted wave due to inrush, when the auto-transformer was energized. Inrush current is shown in fig.10.

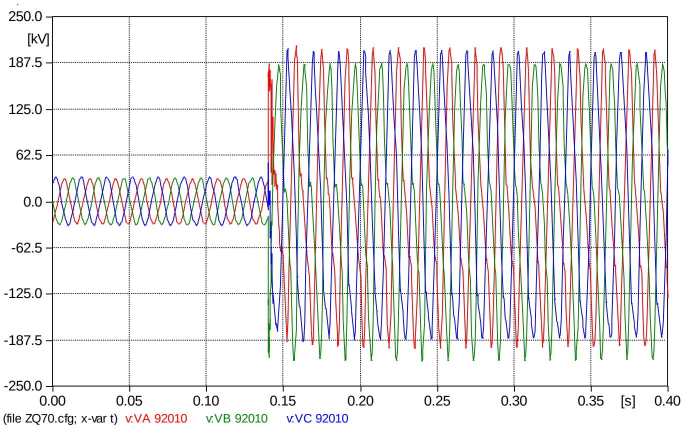


Fig. 9 Voltages in AT secondary side (230 kV) during energization

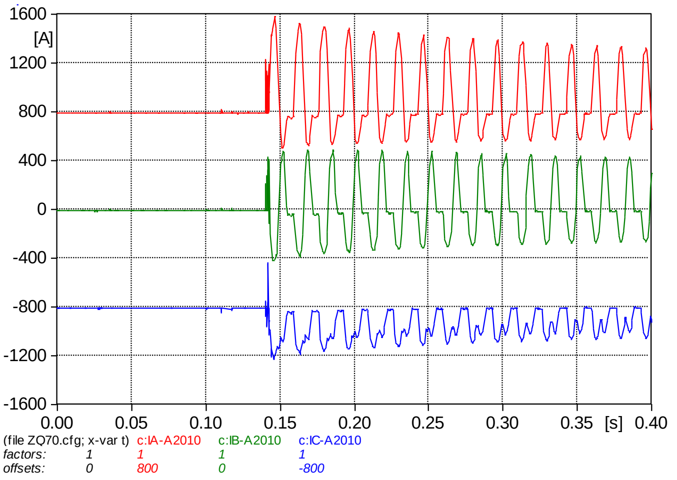


Fig.10 Currents in AT primary side (400 kV) during energization

To attain reliability in the simulations, the measurements were reproduced with the ATP program using the electrical network shown in fig. 6. Similar results were obtained, see fig. 11 and 12.

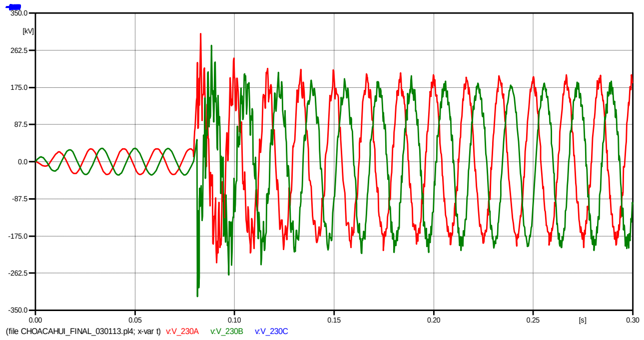


Fig. 11 Voltages simulated in AT secondary side (230 kV) during energization

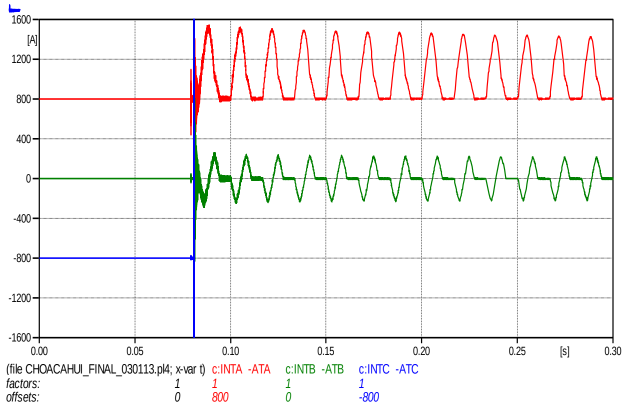


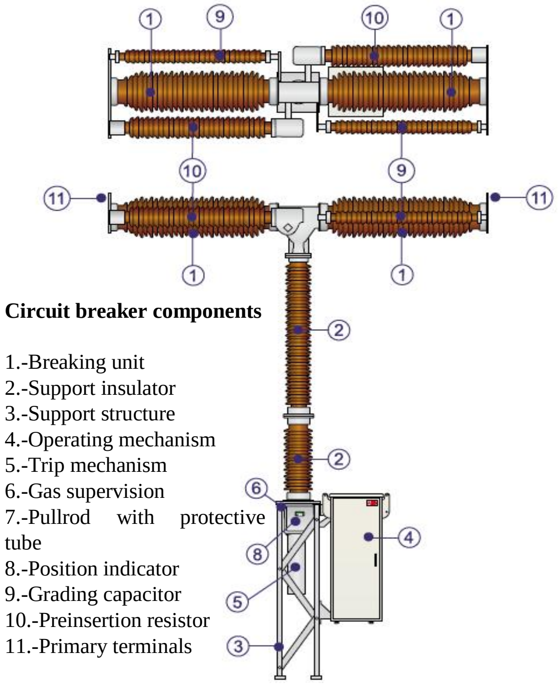
Fig.12 Currents simulated in AT primary side (400 kV) during energization

V. TECHNICAL DISCUSSION

In the Mexican electrical system there are about 1150 circuit breakers and 97% of them have gradient capacitors. In this work, it was necessary to know if the breakers used in CHO were suitable for the auto-transformer. To know this, it was necessary to analyze gradient capacitors performance to determine:

1. If the breaker's chambers or the gradient capacitors pose any hazard at energization.
2. If the breakers lifetime is degraded when gradient capacitors are used.
3. If the interrupting capacity is affected when gradient capacitors are used.

Gradient capacitors are equipment for high-voltage circuit breakers used to control the voltage distribution across the breaker's chambers when they are composed of several units [5]. These capacitors are in parallel in each breaker chamber. Fig. 13 shows two-chamber circuit breaker components with gradient capacitors and pre-insertion resistors [6]. In CHO, the circuit breakers do not have pre-insertion resistors because they are used for the AT connection/disconnection.



Circuit breaker components

1.-Breaking unit
2.-Support insulator
3.-Support structure
4.-Operating mechanism
5.-Trip mechanism
6.-Gas supervision
7.-Pullrod with protective tube
8.-Position indicator
9.-Grading capacitor
10.-Preinsertion resistor
11.-Primary terminals

Fig. 13 Circuit breaker components

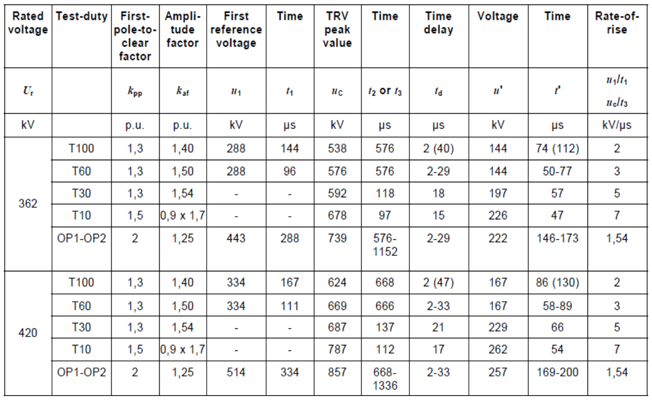
Another gradient capacitor function is to modify the transient recovery voltage slope of the breaker, mainly when a very quick increase of the voltage is originated, endangering the recovery capability of the SF6. As occurs in failures of too short lines.

Some manufacturers mention that gradient capacitors provide increase in the interrupting capacity. However, interrupting capacity is not only the maximum current magnitude that the breaker achieves to open successfully. It includes several situations, like avoiding restrikes through their contacts. This situation could be unsuccessful with a high rate-of-rise- TRV [6].

Initially, capacitance values from the gradient capacitors were selected to ensure voltage distribution into the breakers chamber with a maximum difference above 5%. These differences could be due to contamination and variation in chambers manufacturing. It is common to find values less than 1000 pF in 400kV breakers.

During breakers design it is hard to comply with the standard requirements respect to the maximum values of rate-of-rise TRV, it is necessary to increase the capacitances of the gradient capacitors to 2000 pF per chamber, with the drawback of causing phenomena like the one occurring in CHO. Table 1 depicts the values set for 420 kV breakers by the IEC 62271-100 standard [7].

Table 1. Standard values of prospective transient recovery voltage [7]



Rated voltage	Test-duty	First-pole-to-clear factor	Ampli-tude factor	First reference voltage	Time	TRV peak value	Time	Time delay	Voltage	Time	Rate-of-rise
U_r		k_{pp}	k_{af}	u_1	t_1	u_c	t_2 or t_3	t_d	u'	t'	u_1/t_1 u_c/t_3
kV		p.u.	p.u.	kV	µs	kV	µs	µs	kV	µs	kV/µs
362	T100	1,3	1,40	288	144	538	576	2 (40)	144	74 (112)	2
	T60	1,3	1,50	288	96	576	576	2-29	144	50-77	3
	T30	1,3	1,54	-	-	592	118	18	197	57	5
	T10	1,5	0,9 x 1,7	-	-	678	97	15	226	47	7
	OP1-OP2	2	1,25	443	288	739	576-1152	2-29	222	146-173	1,54
420	T100	1,3	1,40	334	167	624	668	2 (47)	167	86 (130)	2
	T60	1,3	1,50	334	111	669	666	2-33	167	58-89	3
	T30	1,3	1,54	-	-	687	137	21	229	66	5
	T10	1,5	0,9 x 1,7	-	-	787	112	17	262	54	7
	OP1-OP2	2	1,25	514	334	857	668-1336	2-33	257	169-200	1,54

As these phenomena affect the electrical system, oversizing the gradient capacitors can affect the breaker, because a breaker with large capacitances is not able to prevent reignition. Therefore, conductors damage is bigger because the load acquired by the capacitor is applied to the contacts surface, causing SF6 contamination.

Despite the benefits of using gradient capacitors in breakers, there are disadvantages like the presence of ferroresonance and inadvertent energization. It is necessary to take into account if advantages are bigger than disadvantages, because the circuit breaker is an equipment that should not contribute to failures that might endanger other system elements.

VI. BREAKER APPLICATION ANALYSIS IN SEVERAL ELECTRICAL SYSTEM EQUIPMENTS

In order to verify the behavior of the two-chamber breakers with 2000 pF gradient capacitors at energization, several simulations were conducted with the ATP program, using typical parameters of several 400 kV equipment systems, such as transmission lines, reactors and transformers. In the graphs shown below, current and energizing voltage are presented with the following sequence: At 0.01 s the equipment is energized through the gradient capacitors, at 0.10 s occurs the full voltage energization with bypassing capacitors, and, finally, at 0.2 s occurs opening of the breaker preserving the gradient capacitors.

A. *Short line energization*

In fig. 14 and 15 voltage and current are shown for a 5 km line in vertical configuration, double 1113 MCM conductor per phase. The input impedance of the line is 47.2 kOhms with the remote end open when it is energized through gradient capacitors developing a voltage of 5.7 kVp. At 0.1 s the breaker is closed with the gradient capacitors bypassed, a high current is presented with a transient characteristic frequency in capacitors, then the line’s capacitive current is established.

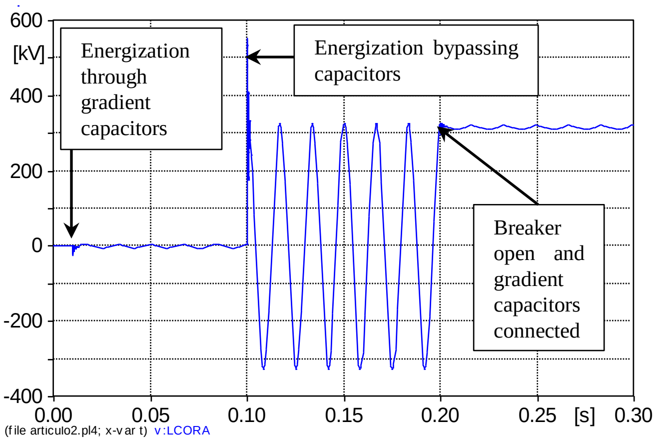


Fig. 14 Sending end voltage for a short transmission line

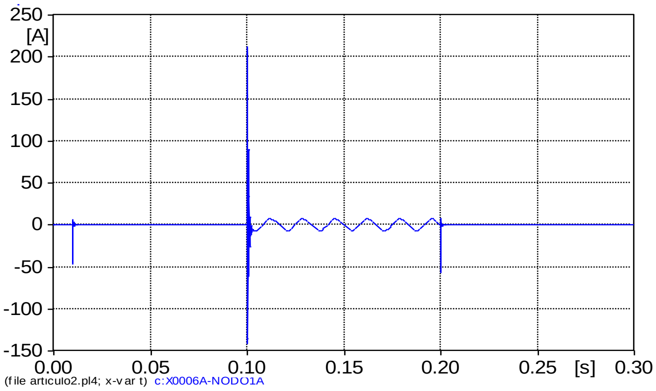


Fig. 15 Current during a short transmission line energization

B. *Long line energization*

For a 150 km long line, with similar characteristics to the short line, the steady state voltage developed when is energized through the gradient capacitors is lower than 0.2 kV, determining an 1.6 kOhms input impedance

In fig 16 y 17, the voltage and current behavior are shown.

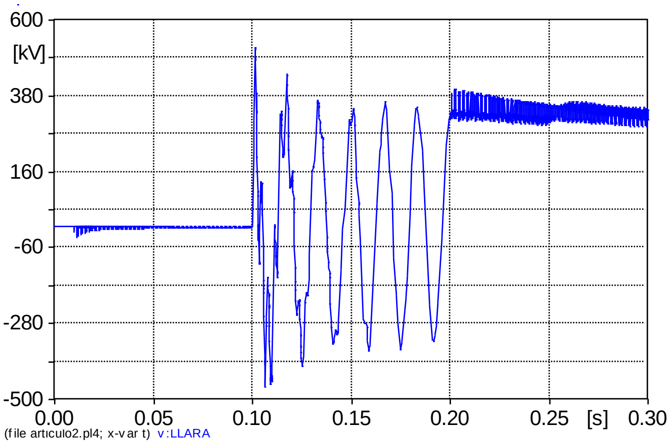


Fig. 16 Sending end voltage for a long transmission line

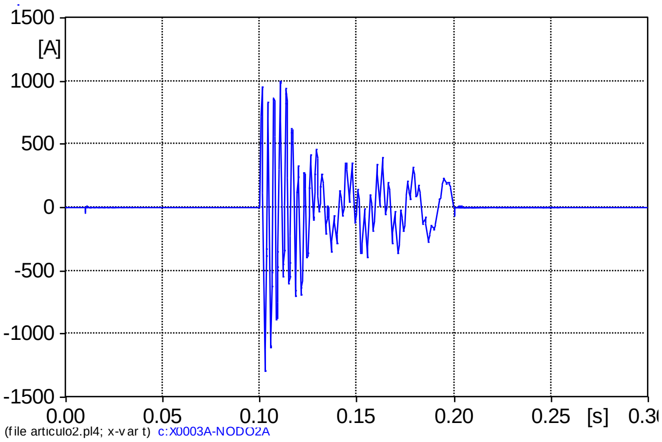


Fig. 17 Current during a long transmission line energization

C. Short and long buses energization

In order to simulate short and long buses, sections of 70 and 200 m, respectively, and Inductive Voltage Transformers (IVT) were included. For short buses the voltage is 168 kV and 2800 kOhms of impedance, and 88.5 kV with 27 kOhms impedance for long buses. The characteristic elements are the high voltage magnitude that occurs when energized through the capacitors and a possible ferroresonance that occurs because the IVT saturated inductance and the busbar capacitance.

The coupling sources through the gradient capacitor produce this inadvertent energization phenomenon, which is independent of busbar longitude. This can be observed in the final waveform of voltage graphs shown in fig. 18 and 19.

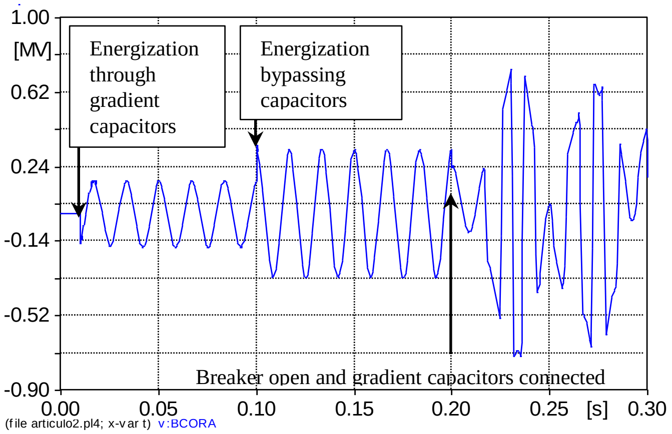


Fig.18 Voltage during a short busbar energization

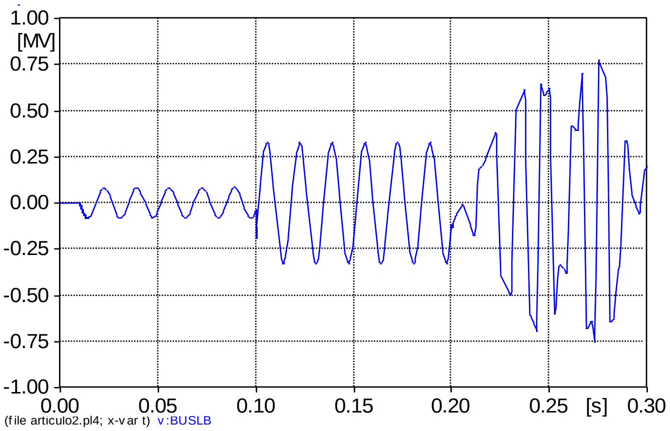


Fig.19 Voltage during a long busbar energization

D. Reactors energization

The energization of a single-phase 25 MVAR's reactor is common in the 400 kV Mexican electric system. Hence, a simulation with a reactor connected to a 400 kV busbar was made and energization occurred through a gradient capacitors breaker, it was found that the resonance frequency was above 2.1 kHz. This phenomenon also appeared while the breaker opened the circuit, preserving the gradient capacitors. See fig. 20.

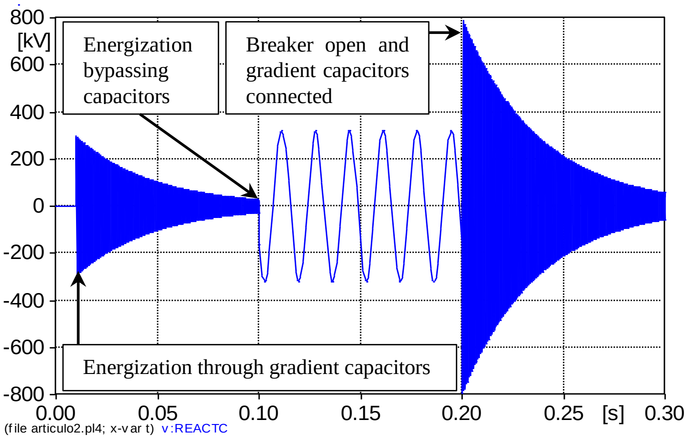


Fig. 20 Voltage during a Reactor energization

E. Power transformer energization

When a 400/115 kV transformer is energized, 120 kV are presented on the primary side, see fig. 21. At full energizing voltage, in 0.1 s an inrush current is presented. See fig. 22.

In fig. 23 both capacitor voltages (blue color) and voltage source phase-ground are shown (red color). The voltage presented in the gradient capacitors was 40 kV, higher than the source voltage, causing over-voltage through the capacitors. This means that due to the impedance characteristics of the transformer, it is possible to obtain, in a high voltage terminal, a larger voltage than in the autotransformer case. See fig. 8

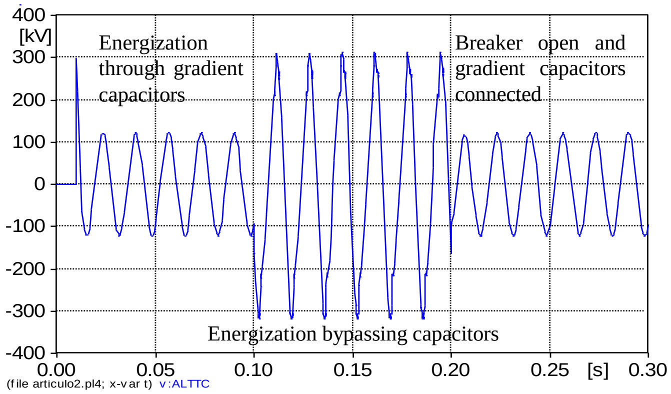


Fig. 21 Primary voltage during 400/115 kV transformer energization

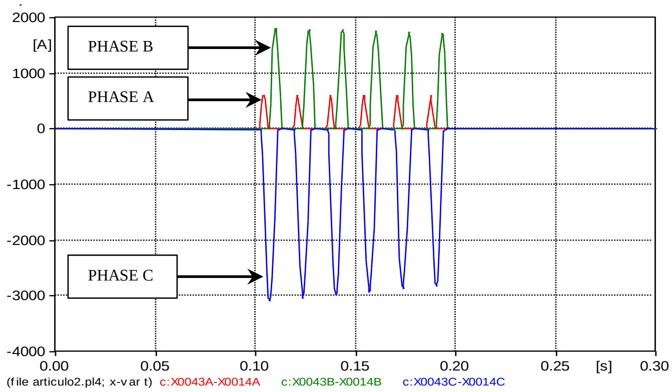


Fig. 22 Transformer current

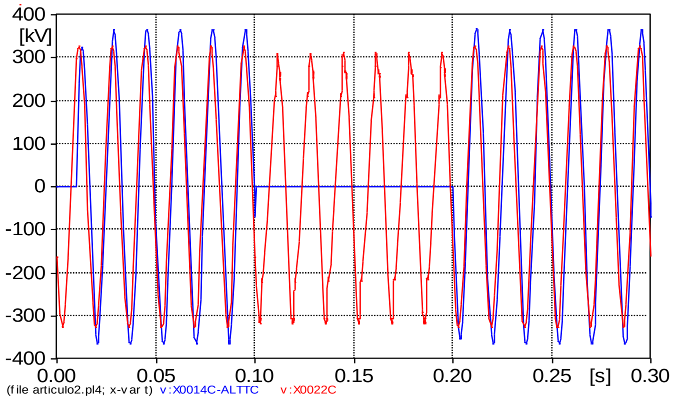


Fig. 23 Voltage through gradient capacitors

VII. CONCLUSIONS

In this analysis, it was possible to find that the gradient capacitors associated to extinction chambers cause voltage in the primary auto-transformer (H), because the gradient capacitors circuit is closed through auto-transformer windings and an excitation current is generated in the magnetic cores, generating enough magnetic field to induce a voltage to the other two windings (secondary and tertiary X, T).

Based on simulations, it is concluded that using double-chamber breakers and gradient capacitors for power transformers connection/disconnection is the least appropriate selection; besides, a previous study is required to determine potential risks to personnel and equipment during commissioning.

According to manufacturer's specifications, operating breakers without gradient capacitors degrade the interrupting capacity above 45%; however, this concept is just for double-chamber breakers originally designed with gradient capacitors and is not applicable to increase the interrupting capacity of a breaker with one or several chambers by adding gradient capacitors.

VIII. REFERENCES

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