Recording and ATP Simulation of Ferroresonance Phenomenon in an SVC of Mexican Electrical System

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***Abstract*—**The Mexican Electrical System has a lot of Static Var Compensators (SVC) distributed in the three main CFE (for its initials in Spanish; Federal Electricity Commission) systems. Four SVCs are located in the 400 kV ring and one in the 230 kV network in the metropolitan area of Mexico City. This SVC-230 kV is located in the *Cerro Gordo* substation and is a fundamental part in supporting the local voltage requirements of the industrial and commercial area. The Cerro Gordo (CRG) substation has nine interconnecting transmission lines, two transformers of 230/85 kV, two transformers of 230/23 kV, and SVC with capacity of 75 inductive and 300 capacitive Mvar. All elements of the substation are connected in one and a half breaker configuration, except the SVC, which is connected in a double breaker arrangement. On June 17, 2013, at 7:46 pm, when it was necessary to de-energize the SVC to modernize its services, workers proceeded to open the switch connected to BUS 2 without problems. Later, when opening the breaker to BUS 1, only the poles of phases "A" and "B" were opened, while the "C" phase remained closed, causing explosion of surge arresters of "A" and "B" phases, producing a series of cascading failures that led to the destruction of the 7^{th} harmonic filter and other damage to the peripheral SVC equipment. Through ATP simulations it was possible to reproduce the events and determine the cause of the surge that occurred in the 230 kV bus, calculating that the energy dissipation capacity exceeded the arrester and verifying the presence of the ferroresonance phenomenon, , which caused the explosion of the "A" and "B" phases. In addition, this document is supported with videos of the explosion through synchronized PMUs recordings, power quality recorders and registers, which were reproduced in the ATP simulator to determine the cause of the failure and the corrective and preventive actions taken, including modifications in the operating logic of breaker failure (50BF) protection.

***Keywords*:** Static Var Compensator SVC, ferroresonance, Alternative Transient Program ATP, surger arrester, Phasor Measurement Unit PMU, Wide Area Measurement System WAMS.

I. INTRODUCTION

The Mexican Electric System consists of three electric systems operating independently. The National Grid is the most complex system, as it integrates the power grids of Mexico and Central America, the load that feeds without Central America is of 40 GW, the backbone of this network is composed of 400 and 230 kV lines. The second is the Baja California Norte Electric System, it feeds a load of 2000 MW and exchanges energy with the US and Canada. The third is the Baja California Sur Electric System with a load of approximately 300 MW (see Fig. 1).

In all three electrical systems, until 2014, 23 SVC with a total capacity of 2830 Mvar inductive and 4840 Mvar capacitive were installed.

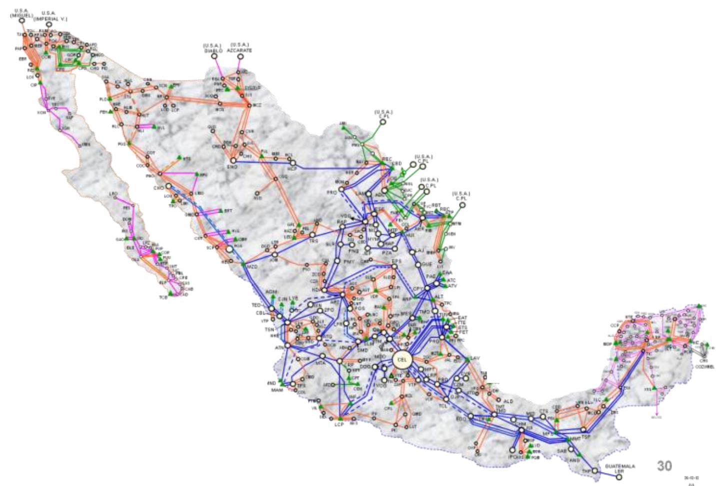

Fig. 1 Mexican Electric System

II. LOCATION AND DESCRIPTION OF THE CERRO GORDO (CRG) SUBSTATION

The metropolitan area of Mexico City has a 25% load of the national grid, the grid of this zone is formed by a double ring of 400 kV and 230 kV. To maintain it permanently integrated with controlled voltages at different system demand conditions, it was necessary to reinforce the network with capacitor banks at levels of low and medium voltage, as well as with Static Var Compensators in ring 400 and 230 kV. The metropolitan area of Mexico City has 5 SVC with a total capacity of 645 Mvar inductive and 1500 Mvar capacitive. The only SVC in the 230 kV grid in this zone is the CRG substation.

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Paper submitted to the International Conference on Power Systems Transients (IPST2015) in Cavtat, Croatia June 15-18, 2015

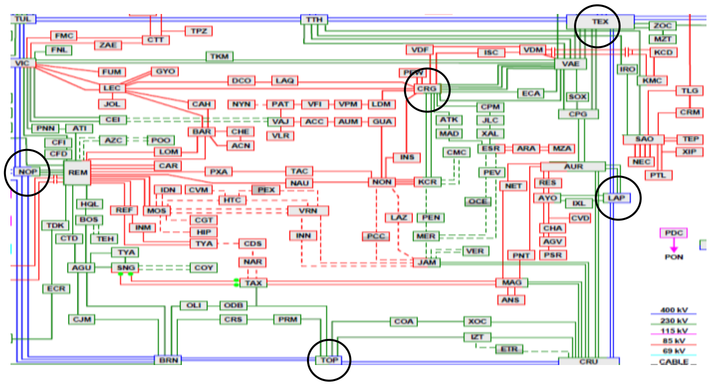

Fig. 2 Network of the metropolitan area of Mexico city, location of SVCs

A. *DESCRIPTION OF THE CRG SUBSTATION*

The CRG substation is composed of the following elements. See fig. 3

- Two 230/85 kV transformers 100 MVA
- Two 230/23 kV transformers 60 MVA
- 9 transmission lines of 230 kV
- 18 lines of 85 kV
- Two grounding transformers of 88.5 MVA (in the 85 kV grid)
- 1 SVC of -75/ 300 Mvar

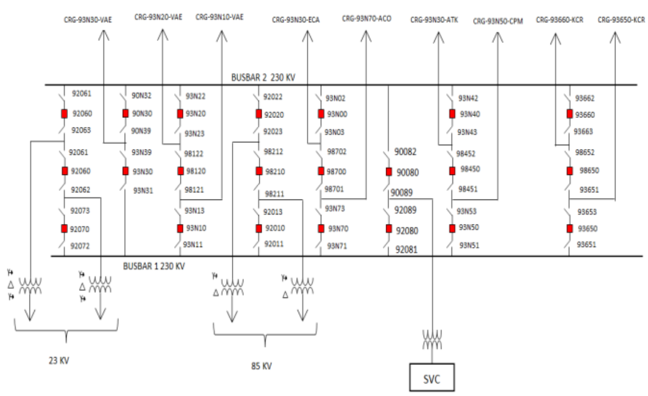

Fig. 3 CRG subestation

B. *SVC description of the CRG substation*

The SVC of CRG substation has a capacity of -75/300 Mvar, is composed of 6 branches. See fig.4

- Thyristor-controlled reactor (TCR) of 135 Mvar
- 2 Thyristor-switched capacitor (TSC) of 120 Mvar each
- 5 harmonic filter 30 Mvar
- 7 harmonic filter 20 Mvar
- 11 harmonic filter 10 Mvar

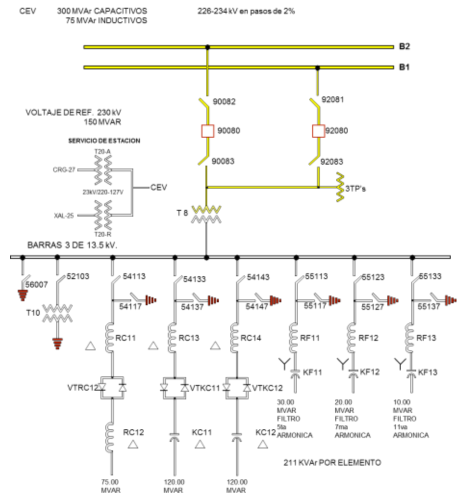

Fig. 4 SVC diagram of CRG

III. DESCRIPTION OF DISTURBANCE

On June 17, 2013, at 7:46 pm, during the process of shutting down the service of the SVC and performing modernization of its services, the 90080 circuit breaker of busbar 2 was opened in normally. During the opening of the circuit breaker 92080, only the poles of the "A" and "B" phases were opened, remaining closed the "C" phase, which triggered a series of events that led to the "destruction" of the 7th harmonic filter, the surge arrester of phase "A" and "B" and other damage to the equipment peripheral to the SVC.

For a description of the sequence of events of the disturbance, there are two types of recordings: one captured by a PMUs of Wide Area Measurement System WAMS CFE [1] with 20 samples per second and recordings from the disturbance recorder.

With the registration of the PMU installed in VAE, substation adjacent to the substation CRG, it was possible to establish the following sequence of events see Fig. 5.

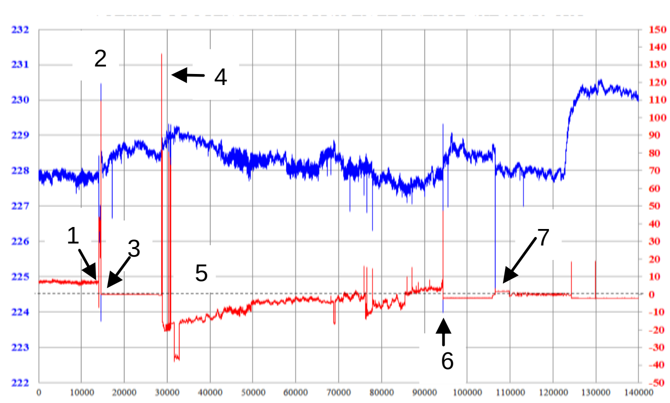

Fig. 5 PMU recording, voltage and reactive power link VAE-93N10-CRG

1. 07: 46: 24.1 h Opening operation of CRG-90080
2. 7:46:44 h Opening of CRG-90082 and substation failure by explosion of surge arresters
3. 7:46:50 h Moment when the Substation had not potential for the operation of backup protection
4.07:58:42 h Energization of CRG substation by transmission line VAE-93N10-CRG.
5. 08:00:07 and 08:00:28 h Arcing in the low side of the SVC
6. 08:54:38 h Opening of switch under load and operation differential protection of busbar 1
7. 09:05:02 h Restoration of substation CRG

Due to failures of the communication channel, the real situation was unknown at the substation, hence, at 7:58 pm the first attempt to restore substation CRG with the closing of the VAE-93N10-CRG line was performed. By having in operation the differential protection transformer with open circuit breakers, it was concluded that there was a problem with one of the SVC circuit breakers. It was erroneously determined that the problem was with the CRG-90080 instead of the 92080.

Due to the above, at 08:54 h opening of the switches 92081 was performed under load, because pole "c" was closed, with the arcing to the metal structure, bus differential protection operate, opening all circuit breakers of busbar 1.

At 9:05:02, finally CRG substation was energized through busbar 2.

The disturbance recorder the SVC, in which the voltage was monitored at high and low sides of the transformer as well as currents in each of the branches, allowing reconstructing the sequence of events from the opening operation of the circuit breaker CRG-92080 until the busbars of 230 kV had no potential. This part of the event was reproduced using the ATP simulator.

IV. SEQUENCE OF EVENTS

The events identified in the recordings are shown in detail in the graphs of Figures 1-6.

1. t=0.46 s Opening phase "A" and "B" of circuit breaker CRG-92080 (see Fig.6)
2. t=1.22 s Conduction in branch TSC (see Figs. 6 and 7)
3. t=1.22 s Zero current in the TCR branch (see Figs.6 and 8)
4. t=2.25 s Zero current in the TSC branch (see Fig. 7)
5. t=1.9 - 4.0 s Surge 2 pu of rated voltage at 230 kV bus of phases “A” and "B". This condition was maintained at approximately 2.1 (see Fig. 6)
7. Failure of the 7th harmonic filter for due to dropped wire guard, recording currents in this branch of 40 kA peak. This fault is extinguished by the failure on the high side in the "C" phase that was the phase feeding circuit (see Fig. 9)
8. Failure in phase "C" in the high side of the transformer with current of 50 kA. this fault was cleared by backup protections (see Fig. 9)

Events 1 through 6 can be identified in a first register. Events 7 and 8 in a second, obtained 30 s after.

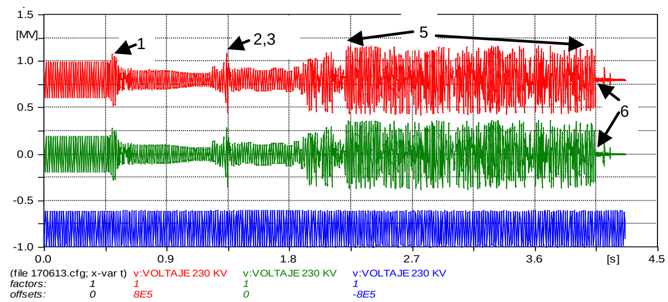

Fig. 6 Voltages on the high side of the SVC (Record 1 07:44:27h)

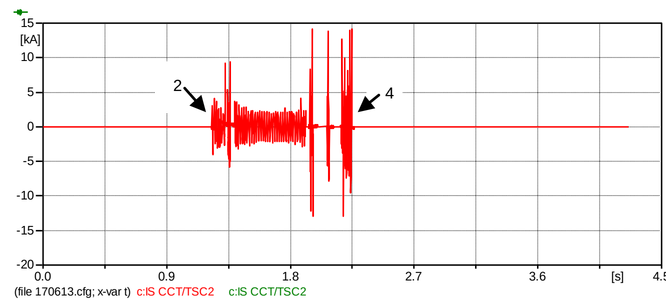

Fig. 7 Currents in TSC branch (Recording 1 07: 44: 27h)

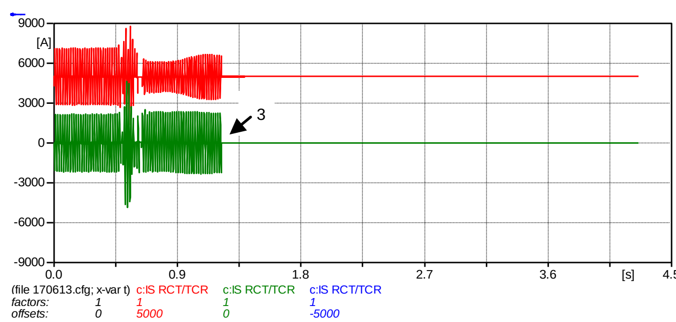

Fig. 8 Currents in TCR branch (Recording 1 07:44:27h)

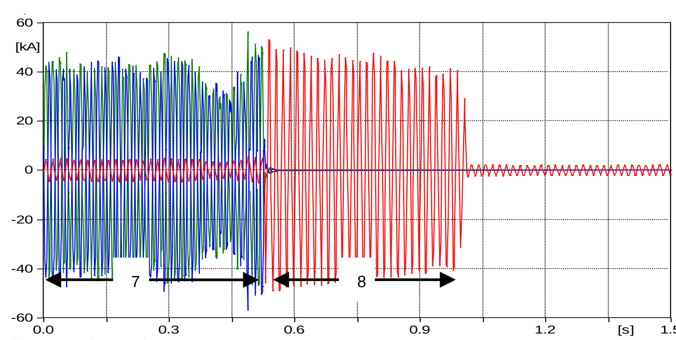

Fig. 9 Current in 7th harmonic filter and phase current "C" high side of the transformer (Recording 2 07: 44: 57h)

V. REPRODUCTION OF RECORDINGS IN THE ATP SIMULATOR

In order to corroborate the sequence of events, the first action was to reproduce the recordings obtained. It was modeled: circuit breaker with gradient capacitors installed on the high side of the transformer 230 / 13.5 kV, the surge arrester at 230 kV busbar and branches of SVC that were operating at the time of the disturbance occurrence. The rest of the network is grouped into an equivalent. See Fig. 10.

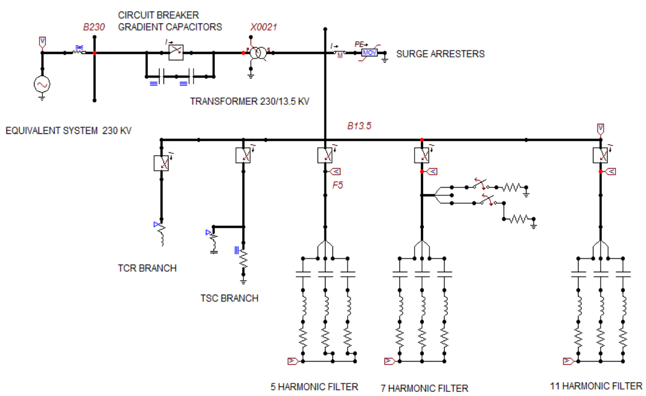

Fig. 10 Electrical network used for ATP simulation

A. INITIAL CONDITIONS (PRE-OPENING CIRCUIT BREAKER)

According to records, the branches that were operating at the time of disconnection of the SVC were: harmonic filters 5, 7 and 11 and the TCR branch.

During the process of disconnecting a SVC [2-3], it takes reactive power in the TCR branch to reach a value close to the sum of reactive power filters, so that the SVC is disconnected from the network with low power in order to avoid voltage variations when switching off.

In the initial conditions, the magnitude of the current at the high side of the transformer of SVC was 50 A. Detailed recording and simulation of current and voltage at the end of 230 kV phase A of SVC are shown in Figures 11 and 12, respectively.

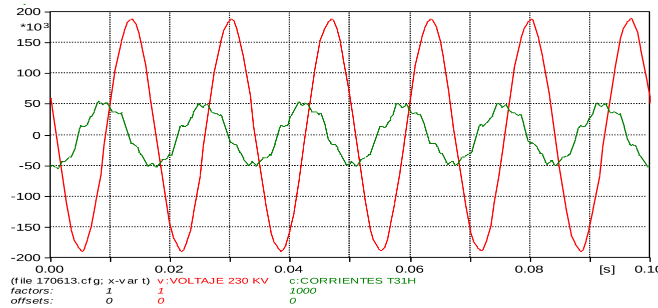

Fig. 11 Voltage and current phase "A" in 230 kV prior to the opening (Recording 1 07: 44: 27h)

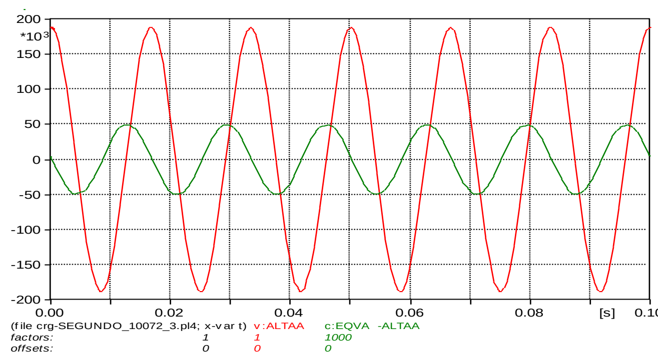

Fig. 12 Voltage and current phase "A" in 230 kVprior to the opening (Simulation)

Figure 13 shows a detailed recording of the current in the TCR branch during initial conditions. This current is measured in the delta arrangement in which reactors are connected. The waveform of the current and its harmonic content depends on the firing angle of the thyristors.

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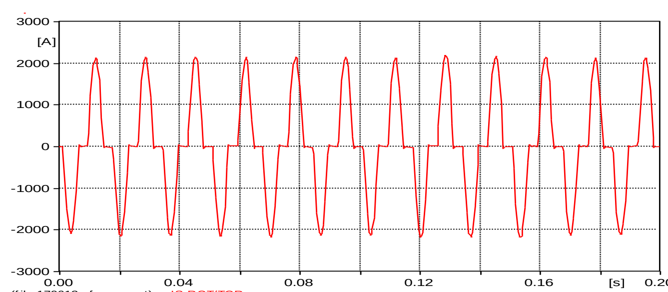

Fig. 13 Detail recording of the current in the TCR branch

According to Fourier analysis of the TCR current, Table 1, this has a fundamental component of 1123 A rms, which corresponds to a reactive power absorption of approximately 45 Mvar that are subtracted from 60 Mvar, the nominal capacity of the filters, this verifies that the SVC was providing to the network 15 Mvar when it was disconnected.

Tabla I
Harmonic content of the current TCR

Harm.	Amplitude	Phase
0	-8.842	0.00E+00
1	1123.2	-161.16
2	10.163	171.24
3	462.14	55.294
4	3.9502	129.09
5	48.396	93.008
6	2.7323	92.869
7	57.762	-52.162
8	2.9286	66.534
9	42.475	-14.588
10	1.7241	21.182
11	6.0258	-167.56
12	2.0439	-18.147
13	22.39	-123.41

VI. ANALYSIS

With the initial conditions adjusted in the model, the sequence of events, 1 to 6, is simulated, achieving the reproduction of the overvoltage in phases "A" and "B" in the 230 kV busbar; see Fig. 14.

In Fig. 15a the waveform of the voltage obtained from the simulation can be observed and Figure 15b corresponds to the recording. Both graphs show mode of chaotic ferroresonance.

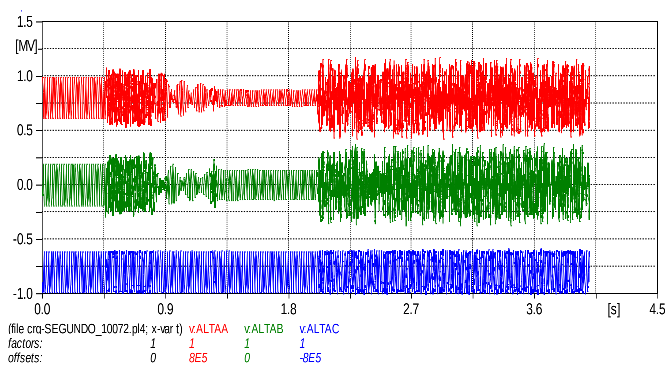

Fig. 14 Voltages obtained in the simulation, 230 kV

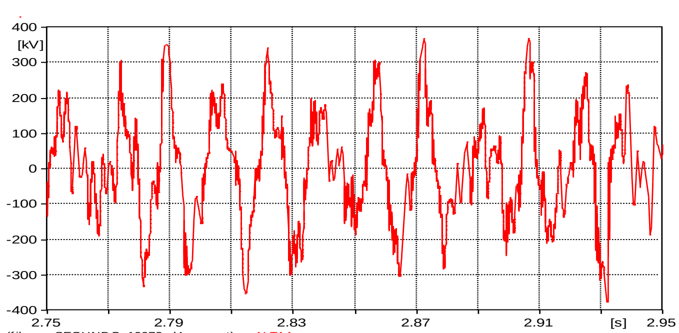

Fig.15a. Details of the simulation voltage of phase "A"

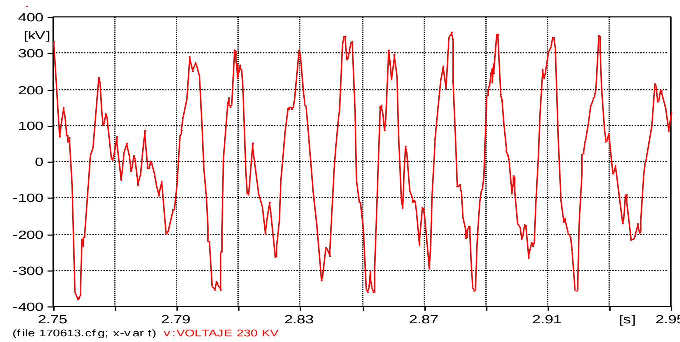

Fig.15b Details of the recording voltage of phase "A"

VII. THEORETICAL SUPPORT

The ferroresonance phenomenon is usually characterized by over-voltage with irregular waveforms and is associated to excitation of a saturable inductance through a capacitance [4-6]. Inductance in a simple resonant circuit is normally an air core and its value does not change. A ferroresonant circuit has a core of ferromagnetic material that varies with voltage, therefore there may be several possible points of operation and some of them may induce ferroresonance.

In Fig. 16, the operating conditions of the SVC is displayed when over-voltages occurred in phases "A" and "B". The saturable inductance of the transformer, Fig. 17, together with the filter capacitors forms the ferroresonant circuit, feeding the circuit through the closed "C" phase.

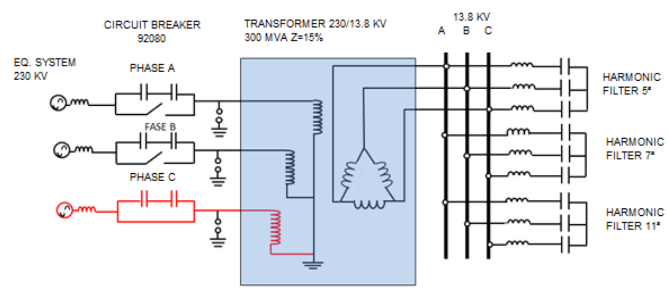

Fig. 16 Ferroresonant circuit

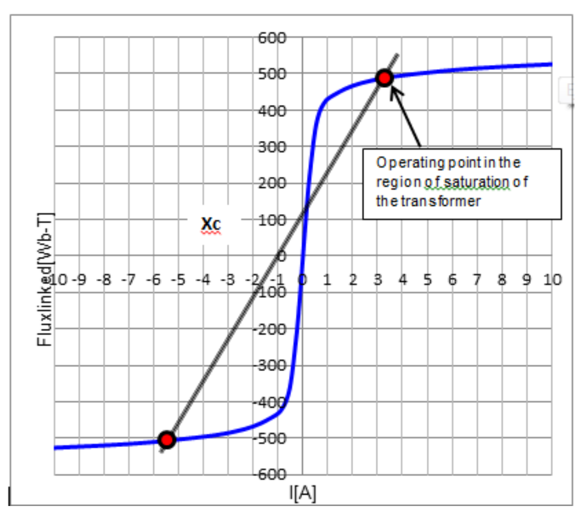

Fig. 17 Transformer saturation curve

The over-voltage that appears for 2 seconds in the "A" and "B" phases on the 230 kV side, causes the surge arresters to exceed their ability to dissipate energy. In this period, according to the simulation, Fig. 18, the dissipated energies reach values of 1.5 MJ, exceeding their maximum capacity of dissipation, which can be estimated at 1.38 MJ

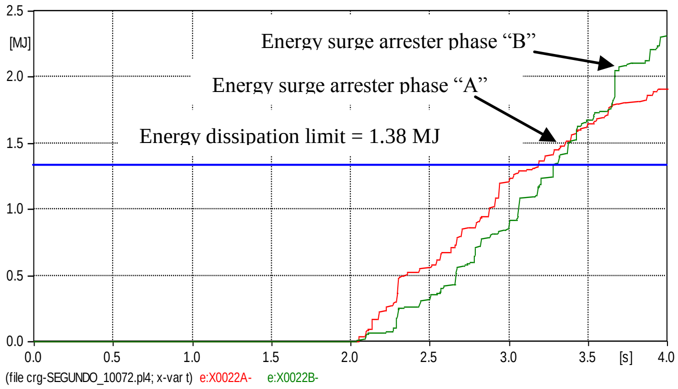

Fig. 18 Dissipated energy in surge arresters

The dissipation of energy expressed in kJ of surge arrester is defined by each manufacturer in tables of the corresponding properties of these sets, and is usually specified as a constant that multiplies the rated voltage arrester. With reference to Table 2 for an arrester with rated voltage of 192 kV, the maximum capacity is 1.38 MJ (192 x 7.2).

TABLE II TABLE II
Data of surge arresters TRANQUELL[7]

RATED VOLTAGE kVrms	ENERGY CAPABILITY (KJ/KV)
2.7 – 4.8	4
54 - 360	*7.2*
396 - 588	13.1

The explosion of the surge arrester caused detachment of the wire guard. The fall of the wire guard caused the failure of the 7^{th} harmonic filter with a duration of 500 ms; this failure was not seen by any protection. The current in the filter was interrupted when failure occured in phase "C" on the high side of the transformer and lost the source that fed the circuit. The failure of the high side of the transformer was cleared by backup protection. The duration of this fault was 450 ms, time corresponding to the distance of zone 2 relays plus the time of opening of the circuit breakers.
It was considered that failure in the high side may be caused by the wire guard or there is also the possibility that it was the product of fire due to the explosion and failure in the filter.

VIII. SCHEME OF BREAKER FAILURE PROTECTION

The CRG substation had not implemented schemes for breaker failure protection 50BF; however, according to the CFE policy the logic for protection in the SVC is based on:

1. Start for operation of some SVC protection
2. Circuit breaker position

Therefore, for these conditions, the operation would not be possible, since the circuit breaker erroneously indicated that the circuit breaker was opened in three phases.
In order to prevent similar events, logic operation of breaker failure protection of the SVC was modified: adjusting the power level detectors on minimum values, monitoring the state of switches to avoid false operations and adding a current unbalance function to detect when one or two poles remain closed

IX. CONCLUSIONS

The phenomenon that is present between the transformer and harmonic filters energizing transformer SVC by the "C" phase was ferroresonance. This phenomenon caused over-voltages in the "A" and "B" phases, causing the explosion of surge arresters to exceed their ability to dissipate energy. The explosion caused the detachment of the wire guard. The fall of the wire guard caused the failure of the 7^{th} harmonic filter and failure in the high side of the transformer.

The ferroresonance phenomenon could have occurred by keeping energized phase in the high side of the transformer, delta winding on the secondary, which allowed keeping energized the secondary and the voltage of a single phase.

The possibility of modifying the logic of operation of the breaker failure protection in SVC arises. The new logic includes an imbalance function, to detect when one or two poles remain closed, and must operate properly even with a wrong indication of circuit breaker position.

It is essential to improve procedures, establishing and standardizing operations to avoid opening switches under load, because the arc is extinguished by operation of differential protection bus causing greater affectation network.

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