Undesired Trip of a 230 kV Transmission Line due to 500 kV/450 MVA Autotransformer Energization

J. F. Piñeros, J. A. Vélez, J. M. Salas, O. Monroy, M. T. Gutiérrez, F. Montaño

Abstract-- **This work presents the analysis of an event which caused the disconnection of two 230 kV transmission lines due to the energization of a 500/120/11.4 kV 450/450/1.66 MVA autotransformer in the Colombian Power System on May 9th 2014. An EMTP/ATP model was used to clarify the transient phenomena observed and DIgSILENT Power Factory was used to get network frequency response. Simulation results explained how power system topology and switching an autotransformer led to an undesired trip of a directional overcurrent relay (ANSI 67N).**

Keywords: **Defense plans, disturbance analysis, protection systems, bulk power system reliability, inrush current, sympathetic inrush, transformer energization.**

I. Introduction

Several switching maneuvers over high voltage transformers are not a common practice. Growth of power system increases the probability of energization maneuvers in high voltage transformers. It's well known that large transformers (>100 MVA) energization could be a problem depending upon the behavior of the inrush current which is influenced by power system topology and transformers core design [2][3][4][7].

This work presents the analysis of an event which tripped two 230 kV lines during the energization of a 500/120/11.4 kV 450/450/1.66 MVA autotransformer in Colombian Power System on May 9th 2014 [1].

Tripped line bay's currents showed high harmonic content (3rd, 6th, and 7th) with low damping leading to overcurrent protection of near transmission lines (67N) to trip. Observed waveforms suggested an inductive saturation as the root cause of the phenomena. Line bay's neutral current presented also very low damping and peak values higher than 200 A after 2 seconds of the autotransformer switching.

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J. F. Piñeros and J. A. Vélez are with XM S.A. E.S.P. (jpineros@xm.com.co, jvelez@xm.com.co).

J. M. Salas and O. Monroy are with CODENSA S.A. E.S.P. – Colombia, (jsalasd@endesacolombia.com.co, omonroy@endesacolombia.com.co).

M. T. Gutiérrez and F. Montaño are with Empresa de Energía de Bogotá S.A. E.S.P. (EEB) Utility – Colombia, (tgutierrez@eeb.com.co, fmontano@eeb.com.co).

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For a better understanding of the disturbance, EMTP/ATP was used to recreate the observed transient phenomena with a simplified model. The purpose of this is to know if the energization of the autotransformer could cause the waveforms observed.

Taking into account the amount of harmonics in the neutral current, DIgSILENT Power Factory simulation software was used to carry out a frequency response network impedance analysis. It was done trying to find an explanation about this content of harmonics.

Considering the event facts, such as network topology is continuously changing due to maintenances and new projects, the impact of switching maneuvers of high voltage inductive equipment must be studied in detail with several real scenarios. Moreover, these studies should be updated considering each new system topology conditions as required. This work is proposed as an initial point to identify system long-term actions from the perspective of the system operator when large transformers energization represent potential risks for the reliability of the system.

II. Network and Initial Disturbance Description

A. System Summary

Colombian Power system is composed by voltage levels of 500 and 230 kV. Fig. 1 summarizes a section of Bogotá 230 kV Area with Sub B and Sub N substations. Sub B is connected to the 500 kV system through two 450 MVA Autotransformers, which also connect this substation to 230 kV and 115 kV systems. Table I presents Autotransformers electrical parameters.

Sub N 230 kV has three 230/115 kV 168 MVA power transformers and 75 MVAR capacitive compensation connected to 115 kV.

Sub B and Sub N 230 kV substations are connected with a double circuit transmission lines. Table II shown the electrical parameters of the lines connected to Sub B 230 kV substation.

TABLE I
SUB B AUTOTRANSFORMERS PARAMETERS

ATR	Power [MVA]			Impedance [%]			Base
	HV	MV	LV	HM	HL	ML	[MVA]
500/230/34.5 kV (ATR 1)	450	450	150	11.45	44.01	30.78	450
500/120/11.4 kV (ATR 2)	450	450	1.66	11.4	101.79	88.91	

according to the measurements).

Bay 2 tripped with 190 A_{rms} and peak values around 372 A, high third harmonic component was observed (57.8% according to the measurements)

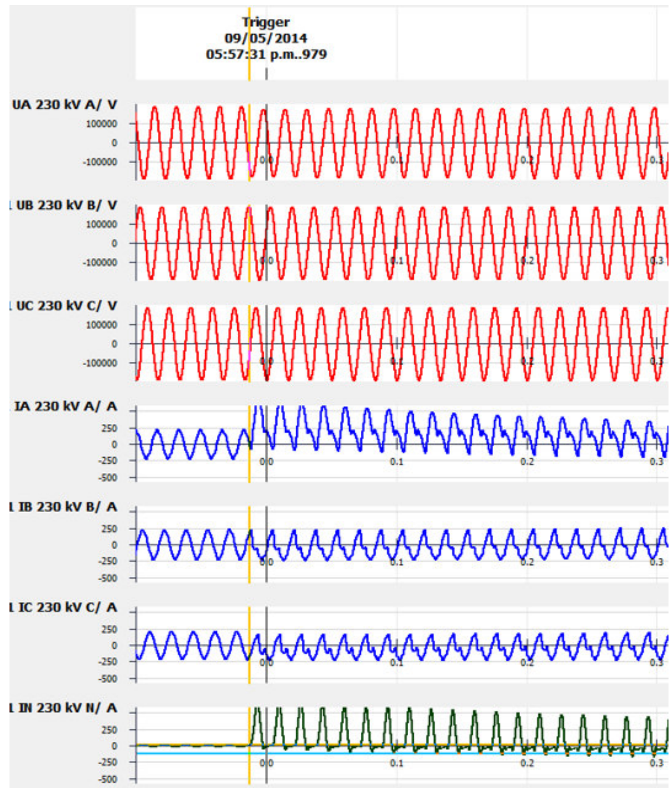

Fig. 2. Fault Record LB1 to Sub N in Sub B 230 kV Substation at the initial instant ATR 2 450 MVA energization in Sub B 500 kV [1]

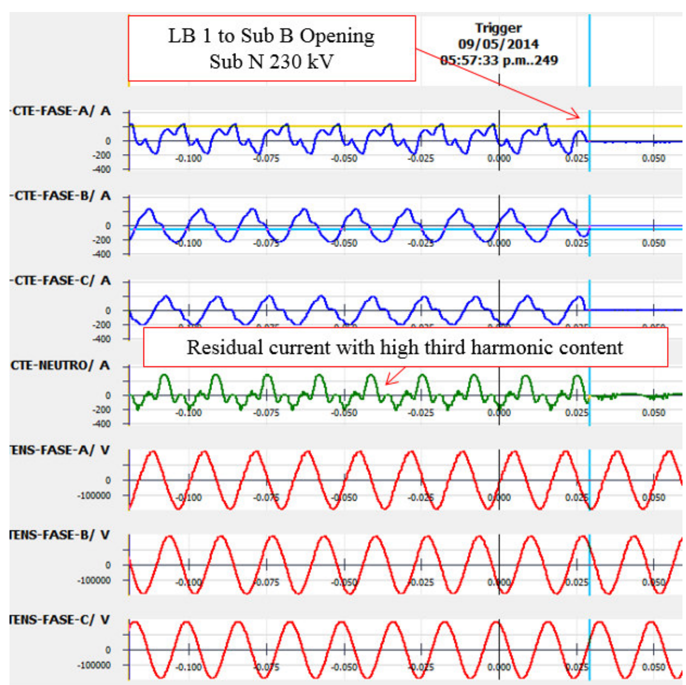

Fig. 3. Fault Record LB1 to Sub B opening in Sub N 230 kV Substation [1]

TABLE II
SUB B 230 KV LINE PARAMETERS

Line	R1	X1	R0	X0	Length
	[Ω/km]	[Ω/km]	[Ω/km]	[Ω/km]	[km]
Sub B – Sub N	0.0477	0.3691	0.1909	0.9508	5.7
Sub B – Sub D	0.0482	0.3841	0.2305	0.9706	19.88

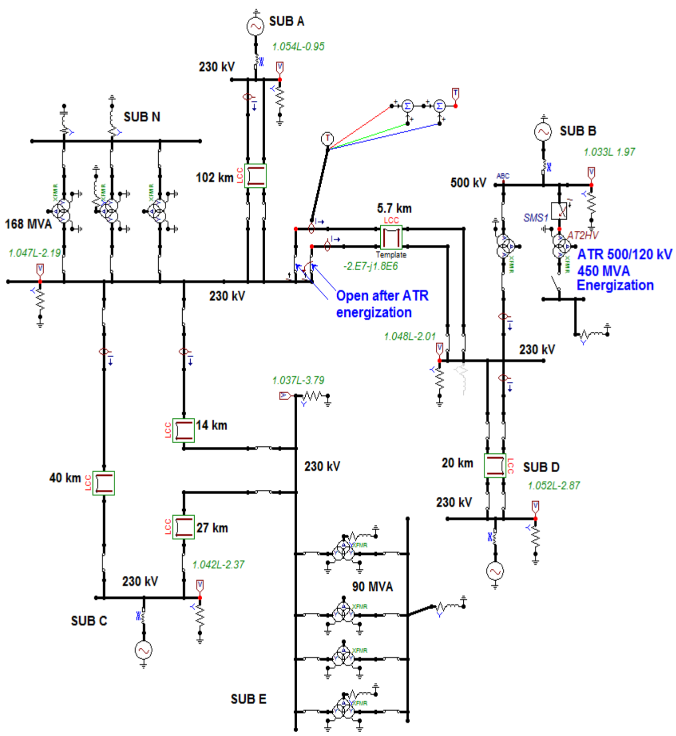

Fig. 1. Event Network Topology and Description - ATPDraw

B. Disturbance description

On May 9th 2014 ATR 2 in Sub B substation, had a maintenance-scheduled job to change its phase B unit. The work had been programmed to start at 05:30 hours but it was raining and the work started at 09:55 hours.

At 17:41 hours the System Operator ask to the connection of ATR 2 due to system conditions. At 17:57:31.996 hours the Utility closes the 500 kV ATR 2 breaker.

After 1575 and 3148 ms of ATR 2 energization, line bays 1 and 2 to Sub B in Sub N substation trip by directional earth overcurrent protection (ANSI 67N) operation. In Sub B 230 kV substation not protection operation were observed. Overcurrent relays that operated were analog devices. ATR 2 had a synchronized switching relay that was in service at the time of the energization.

Before the line bays disconnection in substation Sub N 230 kV, both circuits to Sub B were carrying 58 MW each one to Sub N.

Bay 1 tripped with 135 A_{rms} and peak values around 300 A, high third harmonic component was observed (79.5%

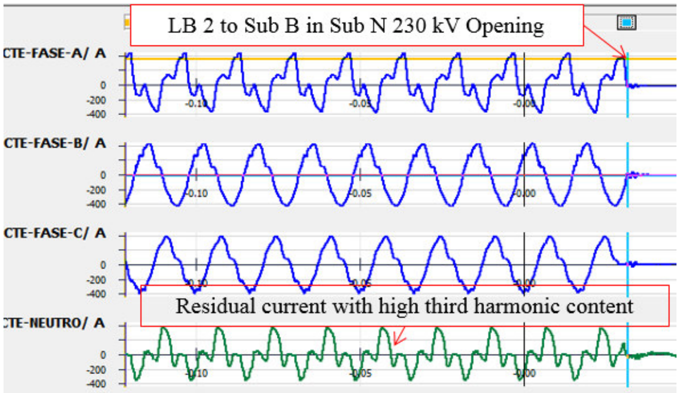

Fig. 4. Fault Record LB2 to Sub B opening in Sub N 230 kV Substation [1]

C. Initial Analysis

At the moment of the event, both System Operator and Utility did not relate bay line trips with Sub B ATR 2 energization because not relay operations were observed. Initial efforts led to verify the performance of the relays operated and the measurement devices due to the distortions observed. All verifications indicate that all those devices were working properly.

After system maneuvers verification, the ATR 2 energization was suspected as the root cause of the trip, although, it wasn't so clear how it could happen because normally highly mesh power systems present high damping and the trips occurs after 1.5 seconds of the energization.
Fig. 5 shown inrush current at ATR 2 energization by 500 kV side.

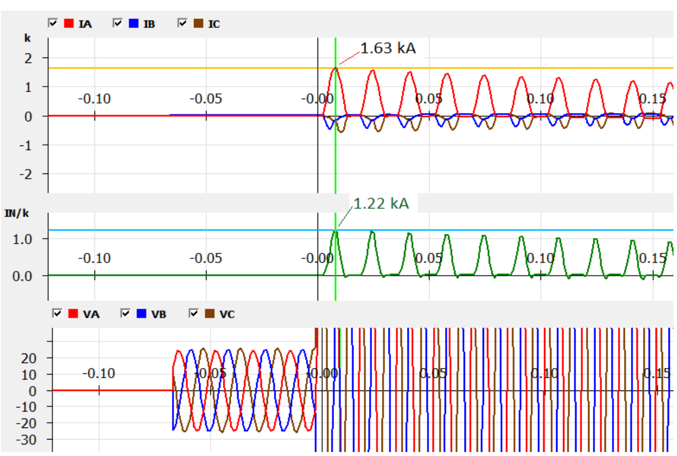

Fig. 5. Fault Record - Inrush 500 kV ATR 2 Bay at the Energization [1]

III. Further Analysis

A. EMTP/ATP Simulations

To understand how the event occur a simplified model was built in ATPDraw. The model was focus on determine if neutral current waveform observed at Sub N 230 kV substation when line bays were tripped under ATR 2 energization. The model considered the ATR impedances as reported by the utility with a typical magnetization curve. Hybrid model option in ATPDraw was used because real data was unavailable. Transmission line parameters were represented with typical data trying to approximate reported impedance values. The line model selected was Bergeron setup at 60 Hz. The network was reduced as shown in Fig. 1 and network equivalents used are given in Table III.

TABLE III
Network Equivalents

Substation	R1 [Ω]	X1 [Ω]	R0 [Ω]	X0 [Ω]
Sub B 500 kV	8.58	100.89	96.22	246.4
Sub D 230 kV	3.06	15.38	1.33	11.76
Sub C 230 kV	0.96	8.23	1.07	7.26
Sub A 230 kV	1.38	11.74	3.91	16.57

According to the records of the 500 kV ATR 2 energization record, the sequence looks like a three phase energization and Phase A did not follow the pre-established sequence of energization which recommends close this phase after 4.2 ms from zero crossing of the reference voltage and 8.3 ms after close phases B and C.

Fig. 6. to Fig. 13. shown the results of the simulations.

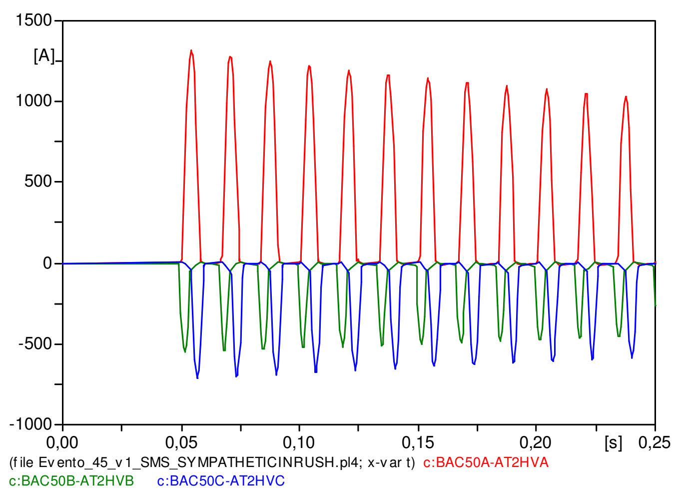

Fig. 6. Inrush 500 kV ATR 2 Energization – EMTP/ATP simulation

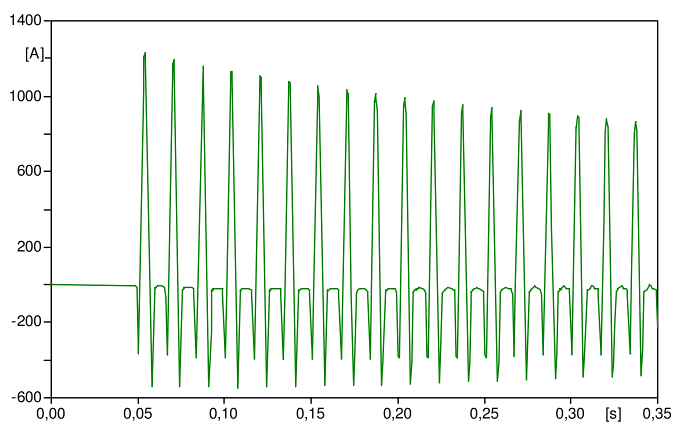

Fig. 7. Neutral current at 500 kV ATR 2 Energization – EMTP/ATP simulation

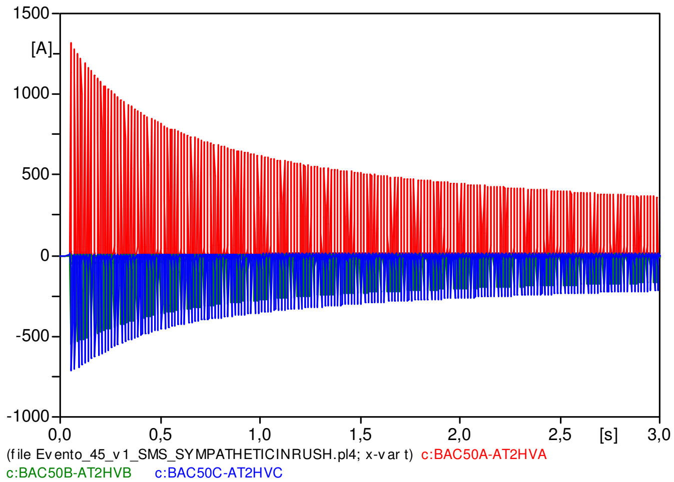

Fig. 8. Inrush 500 kV ATR 2 Energization – EMTP/ATP simulation – damping detail

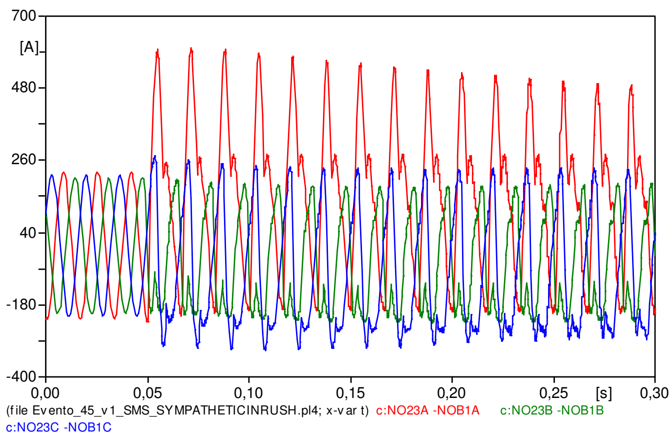

Fig. 9. LB1 Sub B in Sub N 230 kV Substation at the ATR 2 450 MVA energization in Sub B – EMTP/ATP simulation

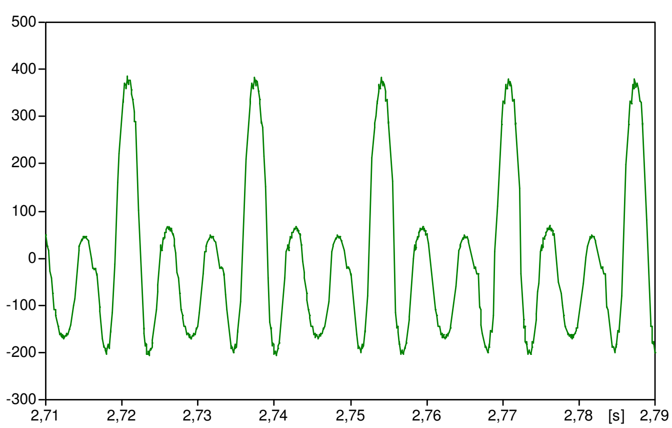

Fig. 10. Sub N 230 kV Circuit 2 to Sub B – neutral current EMTP/ATP simulation

Results obtained of the EMTP/ATP allowed to conclude that ATR 2 Energization in Sub B substation caused neutral current conditions to trip bays 1 and 2 to Sub B in Sub N 230 kV substation.

Although the active power flow was inversed in tripped line bays, directionality conditions appears leading overcurrent relays to trip. This fact can be explained considering that under this topology the system had a better path (lower impedance) through Sub N and Sub D substations, but Sub N is electrically closer. Transformers in Sub N 230 kV substation shown a sympathetic inrush response with the ATR 2 450 MVA energization in Sub B 500 kV allowing the relays to see neutral inrush current in forward direction [4].

Sub N 230 kV 168 MVA Transformers inrush responses caused low damping of the ATR 2 450 MVA energization phenomena. Zero sequence impedance showed low value because of the influence of tertiary delta windings and the low transmission lines zero sequence impedances. Fig. 11. to Fig. 13. Shown the simulation results for one of the Sub N 230 kV 168 MVA transformers. Sympathetic inrush response was observed in simulations with long duration.

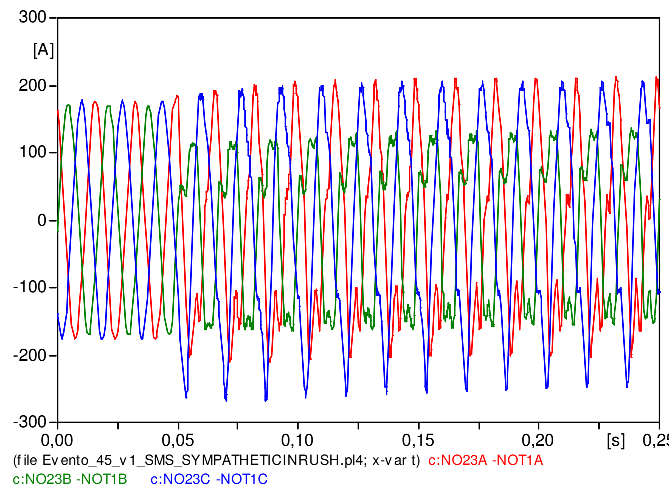

Fig. 11. Sub N 230 kV 168 MVA Transformer Initial Sympathetic Inrush response at ATR 2 450MVA energization in Sub B substation.

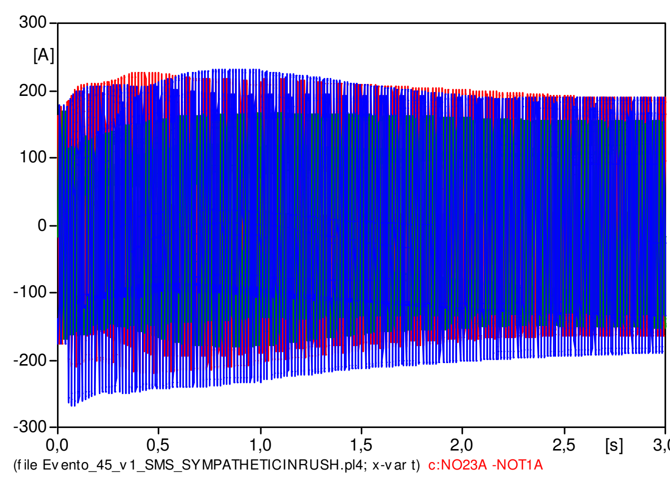

Fig. 12. Sub N 230 kV 168 MVA Transformer Sympathetic Inrush response at ATR 2 450MVA energization in Sub B 500 kV substation.

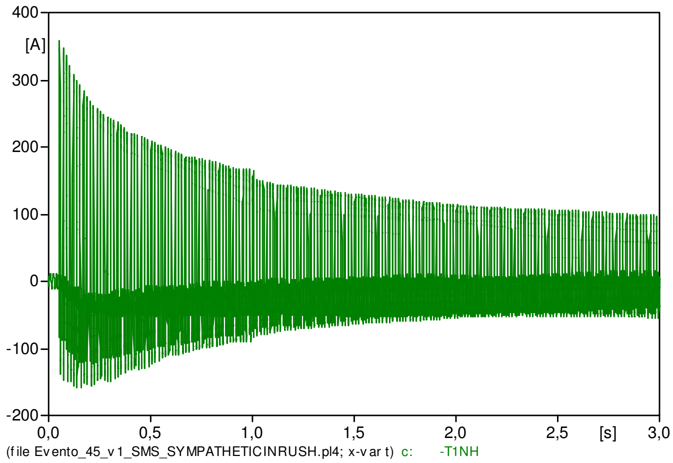

Fig. 13. Sub N 230 kV 168 MVA Transformer Neutral HV current - Sympathetic Inrush response at ATR 2 450MVA energization in Sub B 500 kV substation.

It's important to note that ATR 1 brought a nonlinear coil in series between 500 kV and 230 kV in Sub B. The system topology was unfavorable to damping inrush phenomena due to the amount of transformers at 230 kV system. It created a collective sympathetic inrush response that held up high neutral current in 230 kV line bays. ATR 1 in Sub B substation presented series and parallel sympathetic inrush response while transformers in Sub N 230 kV substation presented parallel sympathetic inrush response [4]. Fig. 14 illustrates this point.

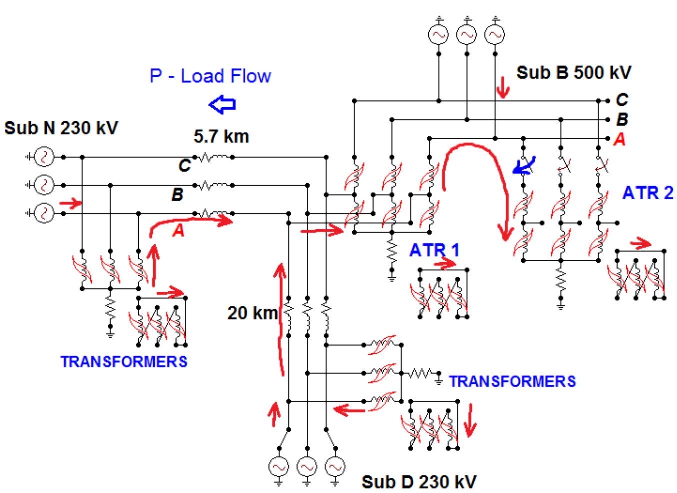

Fig. 14. Simplified schema – explanation sympathetic inrush series and parallel response of zone transformers at ATR 2 450 MVA energization in Sub B 500 kV substation.

B. System Frequency Response

According to the fault records the power system showed low damping at third harmonic. Fault record harmonic data suggest not only third harmonic component was present. Fig 15 shows the harmonic content in neutral current in line 2 to Sub B in Sub N substation (approximately due to errors by current transformer ratio).

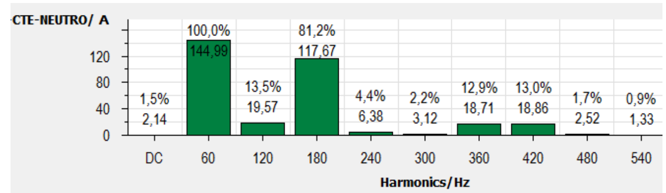

Fig. 15. Sub N 230 kV Circuit 2 to Sub B – neutral current harmonic content

115 kV network around Sub B and Sub N substations has several capacitive compensations, some of them are tuned at 7th harmonic. This fact explains the component found in the waveforms. High third harmonic is due mainly to sympathetic inrush response. Sixth harmonic level observed in the records required a zero sequence impedance frequency response review. DIgSILENT Power Factory was used with the whole network of the Colombian power system to generate zero sequence impedance frequency response (this impedance sweep takes only linear impedance part of power transformers). Fig. 16. Shows the result. First key point is the low resistance at third harmonic which presented low damping to inrush currents. Second key point is the series resonance at sixth harmonic.

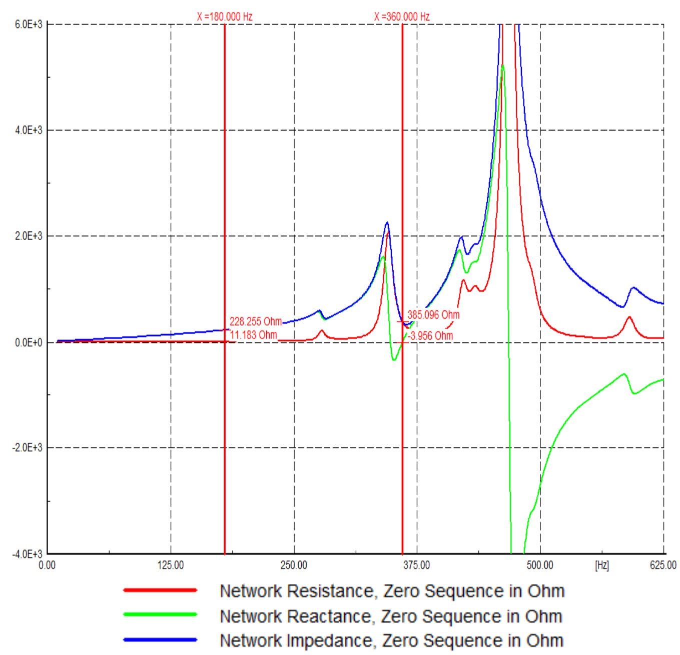

Fig. 16. Sub B 500 kV power system zero sequence impedance frequency response

IV. Findings and Short-Term Actions

According to event information and simulations some key points are given regarding operation, design and remedial actions to avoid this kind of undesired trips.

A. Operational findings

- Neutral current fundamental component was 145 A at the moment at bay 2 trips in Sub N 230 kV to Sub B. The Utility informed that ANSI 67N relays was picked up in 120 A, this value was not appropriate at that place in the power system.

- Network topology at the moment of the event had poor conditions to damping inrush currents. It is because the 500 kV system offers high impedance in contrast with 230 kV system with double circuit lines with low zero sequence impedances and several large transformers in 230 kV Substations that created a collective sympathetic (series and parallel) inrush response to the ATR2 450 MVA energization in Sub B 500 kV substation.
- The ATR 2 450 MVA energization in Sub B 500 kV substation was done with critical system conditions – at the beginning of a peak load period.

B. Design issues

- Simulation was done with typical magnetization curve without residual flux. Real curve has a lower slope with a different residual flux value at the moment of energization because of initial peak simulation was lower. It is important for new large autotransformers to avoid high inrush currents and sympathetic inrush response.
- Relays near to large autotransformers require filtering capability.
- Synchronized switching relays should have redundancy schemes with self-healing features before executing energization sequence of large autotransformers to avoid high inrush current and long sympathetic inrush response, windings efforts and harmonics injection.
- ATR 2 tertiary winding has an atypical rated power (1.66 MVA) in comparison with traditional practice (1/3 of main winding rated power). Energization of this ATR considering 1/3 winding rated power shows ATR neutral current is reduced from 100% to 71%. It was noticed that this parameter influences sixth harmonic observed series resonance.

C. Remedial actions taken

- Overcurrent relays ANSI 67N pickup, were setting-up in 135 A in Sub N 230 kV substation by the Utility.
- ATR 2 synchronized switching relays in Sub B substation was replaced due to a failure in one of their components.

V. Lessons Learned and Next Steps

Based on this event following lessons were learned:

- This event shown that synchronized switching relays are important to reduce the risk of undesired trips protection overcurrent relays during the energization of large autotransformer.
- Synchronized switching relays are not guaranty of low inrush at large Autotransformer energization, since those devices can fail. The power system must be prepared for this kind of contingencies.
- Large Autotransformer energization must be studied in detail before maneuvers in order to verify system behavior. These studies should take into account harmonic injection and sympathetic inrush response when large transformers are close due to the generation of low damping paths. Additionally, the studies must evaluate correct pickup values in overcurrent relays in neighborhood to the element to be energized. Special attention in neutral currents is required.
- Large inductive equipment energization studies must be updated as required because power system changing its conditions. Always near protection relays should be taken into account.
- According to this event neutral pickup overcurrent protection near to autotransformers must be selected considering worst scenario to autotransformer energization without synchronized switching. Recommended pickup current to the relays tripped at the event can be too high considering one circuit contingency. Pickup increases must take care the protections dependability.
- In order to not reduce protection dependability by increment overcurrent relays pickup settings, special schemes can be implemented as possible, for example ANSI 67N in directional comparison.

Risk identification studies in the Colombian power system are in progress to avoid future undesired trips.

VI. Conclusions

Large Autotransformers energization can cause undesired trips in overcurrent protection relays of transmission lines.
Inrush current flow and its damping depends of the topology of the network at energization instant. Studies have to be developed and updated as required for different energization maneuvers because power system has a dynamic behavior. These studies should verify overcurrent protection relays pickups to avoid undesired trips while large autotransformer energization. Special attention is required to sympathetic inrush response of neighbor transformers. Synchronized switching relays must not be considering in this studies unless redundant schemes are available.

Selection criteria of rated power of autotransformers tertiary winding requires a further investigation to determine its influence in inrush current peak values and its damping according to the topology at the connection point in the power system.

VII. Acknowledgment

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