Ferroresonance in a 115 kV Network Due to a Single Line Fault

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***Abstract*-- This paper presents an analysis of the ferroresonance in a 115 kV network between a faulted line and a high voltage power transformer winding.**

An EMTP/ATP simulation was used to understand why 2.0 p.u. voltage appears in a 115 kV substation during an event. This substation was connected to a transmission line that experienced a phase to ground fault and was powered by medium voltage motors through a 110/13.2 kV 1.5 MVA Dyn0 power transformer.

The analysis of this phenomena shows that actions may need to be taken at substations with medium voltage power sources and high voltage disconnection (island) risk with Dyn power transformers in order to avoid overvoltages after power system disconnections. An overvoltage simple protection logic is proposed to reduce the risk of damages to substation equipment caused by ferroresonance.

***Keywords*: Disturbance analysis, protection systems, bulk power system reliability improvements, ferroresonance.**

I. Introduction

The Ferroresonance phenomena generates high overvoltages which normally are destructive due to low currents. In most cases the phenomena occurs in medium voltage networks that do not have the appropriate overvoltage protection [5][6].

This work presents a ferroresonance phenomenon analysis in a 115 kV substation during a single phase to ground fault in a transmission line that experienced trip omission of the protection relay and that was powered by medium voltage temporary power sources (motors).

A value of 2.0 p.u. voltage was observed in a 115 kV substation connected to a faulted line and powered by medium voltage motors. The phenomenon stopped without any protection actions having taken place. An EMTP/ATP model was created to understand why 115 kV bus voltage reached 2.0 pu that had a waveform suggesting surge arresters were in operation.

In high voltage substations, this event presents a real risk of ferroresonance with the following situations occur simultaneously: when protection schemes are conventional, when the network has a low shortcircuit and when medium voltage sources power high voltage faulted lines through Dyn transformers that have been disconnected from the power system.

In order to avoid energy and insulation stresses on the substation equipment of high voltage substations with a risk of ferroresonance, special protection logic is proposed and tested. This protection scheme accounts for the fact that conventional overvoltage protection function takes 1 second or more to command a trip, and this time may be too long to save the integrity of surge arresters and the life of the equipment insulation.

II. Network and Initial Disturbance Description

A. System Summary

Colombia Power system includes 115 kV substations and transmission lines that connect in order to power regional transmission systems (STR). Figure 1 shows a section of a STR system with the following 115 kV substations: Sub B, Sub S and Sub Q. Sub B substation has two generation units and Sub S and Sub Q substations are load substation.

One load of substation Sub S is a 400 HP motor used in mining and it is connected to 13.2 kV medium voltage network through Dyn0 1.5 MVA 110/13.2 kV transformer.

Sub Q can be powered with another power system substation which is not shown in Figure 1. The total length of these transmission lines is more than 150 km and its power source has a low short circuit.

Substations Sub B, Sub S and Sub Q are connected through single circuit transmission lines. The load flow was from Sub B to Sub Q substation. Table I shows transmission lines electrical parameters for all transmission lines connected to Sub S 115 kV substation.

TABLE I
SUB S 115 KV PARAMETERS OF CONNECTED LINES

Line	R1 [Ω/km]	X1 [Ω/km]	R0 [Ω/km]	X0 [Ω/km]	Length [km]
Sub B – Sub S	0.1208	0.4735	0.2885	1.6888	28.55
Sub S – Sub Q	0.1830	0.4701	0.4865	1.5830	69.52

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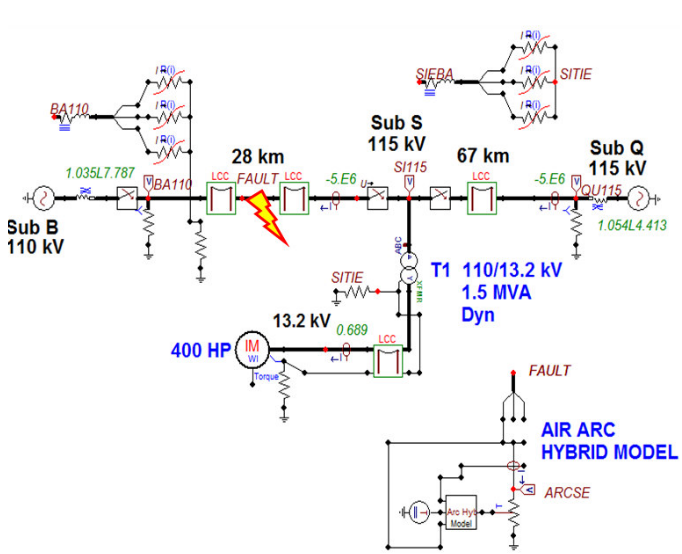


Fig. 1. Event Network Topology - ATPDraw

B. Disturbance description

On June 8th 2014 at 18:48:30.392 hours, a single phase to ground fault occurred in the phase C of Sub B - Sub S 115 kV transmission line. Protection systems at Sub B 115 kV substation detected the fault in zone 1 and tripped the line bay to Sub S, the line bay breaker opened in less than 100 ms.

Line bay to Sub B in Sub S substation didn't open to clear the fault in the protected element. The distance relay only picked up zone 4. The overcurrent ANSI 67N function picked up and its timer element was activated but not trip was commanded. This line bay experienced an overvoltage of 2.0 p.u. in the A and B phases over several cycles. Fig 2. Shows the fault record of the line bay to Sub B in Sub S substation.

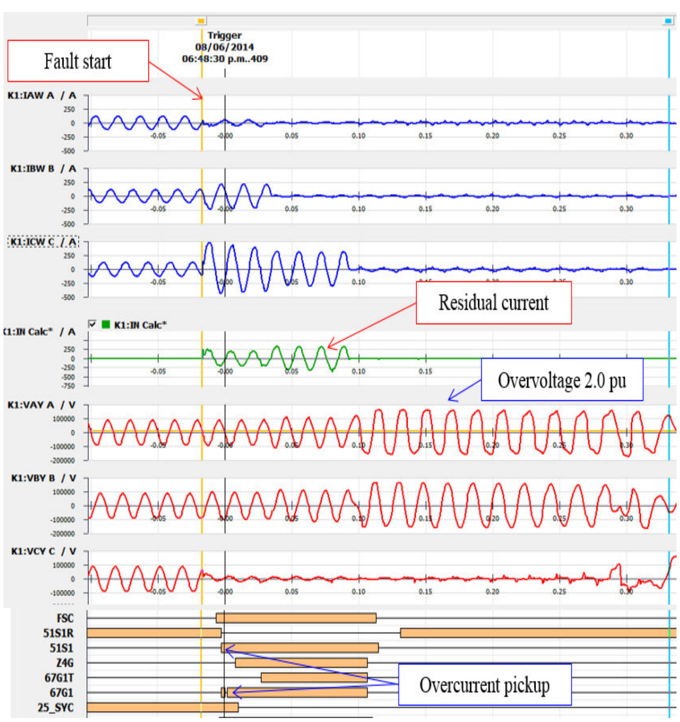


Fig. 2. Fault Record Line Bay to Sub B in Sub S 115 kV substation [1]

Line bay to Sub Q in Sub S substation opened after 112 ms. At the event time the Utility didn't inform the trip cause. No fault records were available. Fault records in line bay to Sub S in Sub Q substation indicates that this trip was undesired because the transmission line Sub S – Sub Q 115 kV didn't have fault according to Fig. 3, this figure reveals low short circuit current from Sub Q to Sub S substation.

A. Initial Analysis

At the time of the event, Operators did not notice the overvoltage at the Sub S 115 kV substation. A potential transformer problem was suspected, but a fault record at the Sub B 110 kV substation had the same overvoltages.

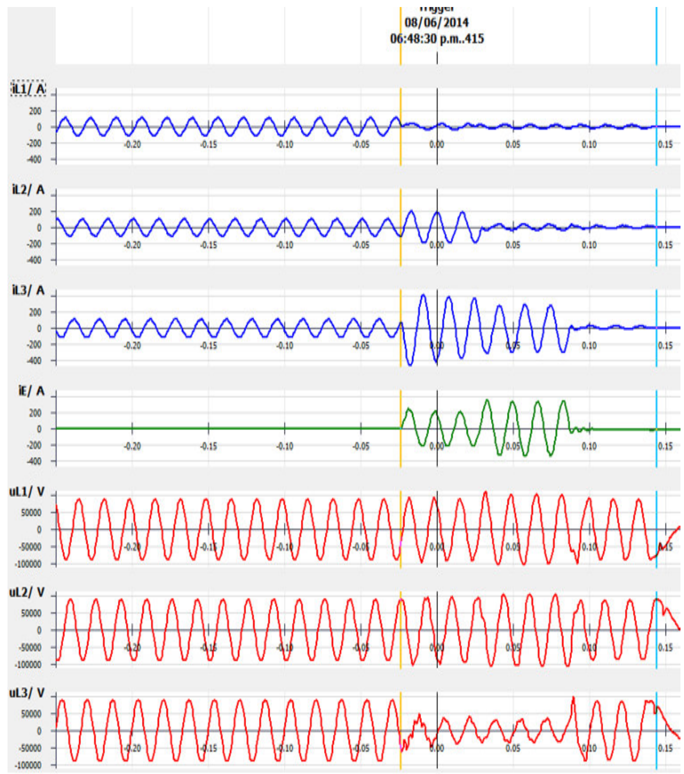


Fig. 3. Fault Record Line Bay to Sub S in Sub Q 115 kV substation [1]

According to available data after the event, the analysis was:

1. The Sub B – Sub S 115 kV transmission line presented a phase to ground fault in phase C.
2. The protection system in line bay to Sub S in Sub B 115 kV substation worked correctly and tripped it.
3. The protection system in line bay to sub B in Sub S 115 kV substation presented a trip omission.
4. The line bays of transmission line Sub S – Sub Q 115 kV presented an undesired trip without fault in the protected element.
5. Sub S 115 kV substation was isolated from power system by a correct trip in Sub B 110 kV substation and undesired bays trips of the Sub S – Sub Q 115 kV transmission line.
6. Overvoltages and currents in Sub S 115 kV substation

line bay to Sub B, revealed an inductive angle difference and saturation behavior in the current waveform.

7. Although the waveform could suggest that ferroresonance occurred it was not clear why the phenomena disappeared and how it was powered. The faulted phase showed evidence of secondary arc extinction behavior. Fig. 4. Illustrates these observations.

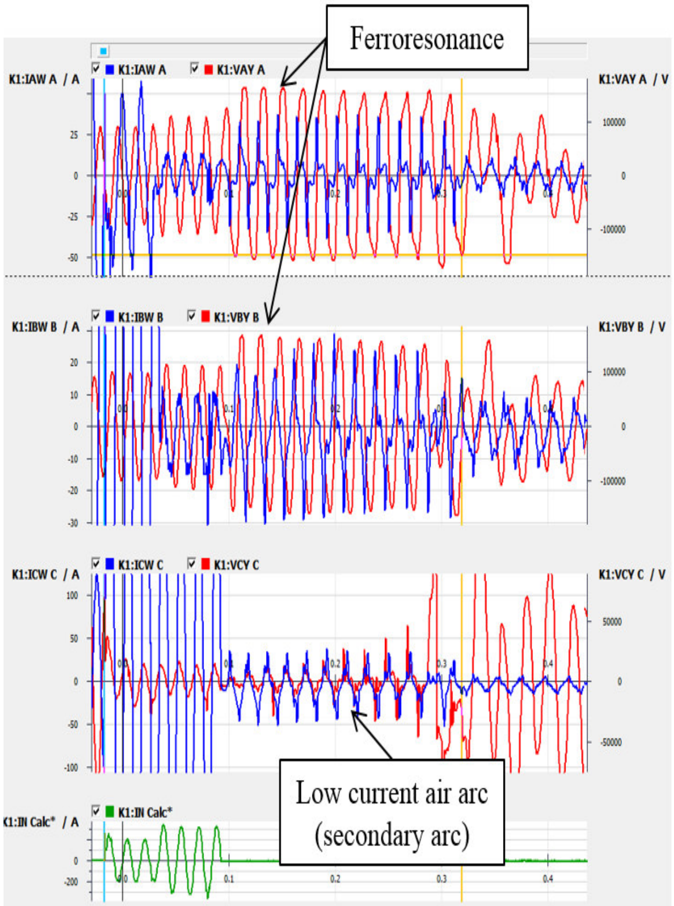


Fig. 4. Fault Record Line Bay to Sub B in Sub S 115 kV substation, ferroresonance evidence [1]

III. Further Analysis

A. EMTP/ATP Simulations

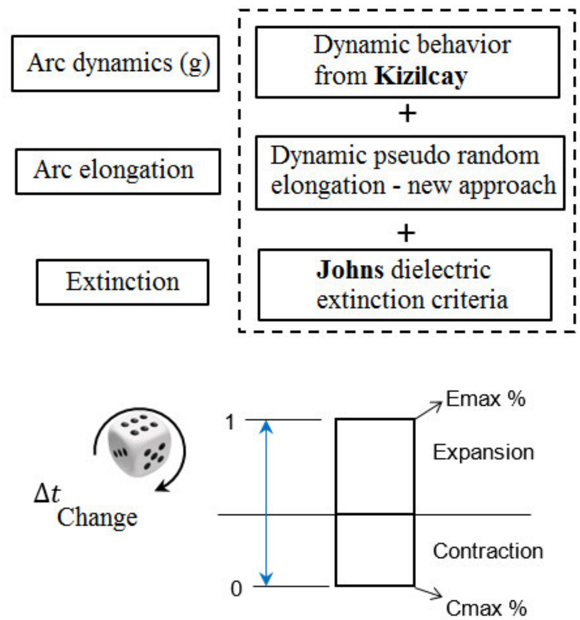
To understand how the event occur a simplified model was built in ATPDraw [11]. The model was focus on determining if overvoltages waveforms and currents observed in the line bay to Sub B in Sub S 115 kV substation correspond to ferroresonance phenomena: on clarifying how it was possible; and on identifying the extinction mechanism.

The model considered the transformer impedances as reported by the utility with a typical magnetization curve. Hybrid model option in ATPDraw was used due to real data was unavailable [12][13]. Transmission line parameters were represented with typical data in an effort to make an approximation of the reported impedance values. The line model selected was Bergeron setup at 60 Hz [8][9]. The network was reduced as shown in Fig. 1 and network equivalents used are given in Table II.

TABLE II
Network Equivalents

Substation	R1 [Ω]	X1 [Ω]	R0 [Ω]	X0 [Ω]
Sub B 110 kV	3.6	15.32	1.806	20.62
Sub Q 115 kV	57.83	76.43	150.3	149.92

The Utility reported a lightning stroke as the line single phase fault cause. After the isolation of Sub S 115 kV substation from the power system, the fault records showed phase C signals low current air arc behavior. A secondary arc hybrid model was used to simulate this behavior to understand how the phenomenon extinction occurred. This hybrid model incorporates the best parts from Johns' and Kizilcay's models [3][4]. The basic elements of the model are described in [2]. Fig. 5 summarizes how this model is design.



$$l_{arc} = l_{arc} + \left[rnd(\ ) \times \left(E_{\max} + C_{\max} \right) - C_{\max} \right] \times l_{arc}$$

Fig. 5. Description of Secondary hybrid arc model used to simulate phase C fault

The Delta t change elongation time was setup to 0.25 ms, Emax was setup to 3.15 % and Cmax to 3%.
The complete model was programmed in MODELS in ATP with Type 91 controlled resistor [8][11].

To simulate the 400 HP motor in medium voltage network in Sub S 13.2 kV network, the universal induction machine with manufacturer's data input model in ATPDraw was used with typical parameters because this information was unavailable [11].

For motor start stabilization, the line Phase C fault was started at t=200 ms.

Fig. 6. to Fig. 10. show the simulation's results.

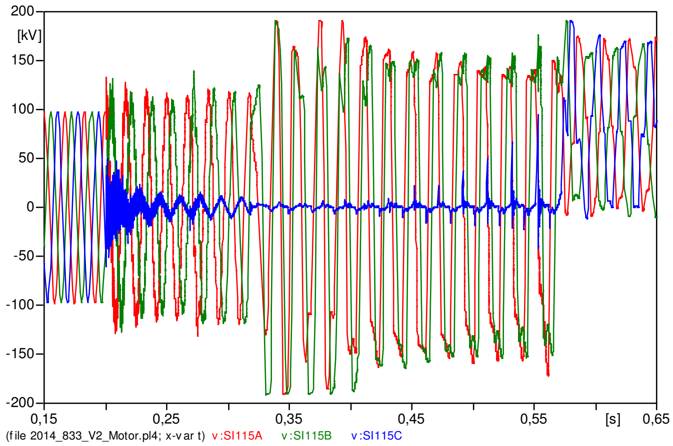


Fig. 6. Line Bay to Sub B in Sub S 115 kV substation Voltage– EMTP/ATP simulation

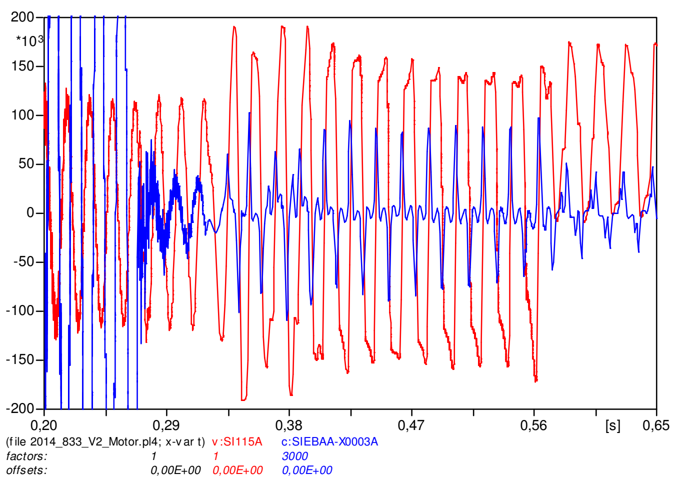


Fig. 7. Line Bay to Sub B in Sub S 115 kV substation Voltage and current phase A – EMTP/ATP simulation

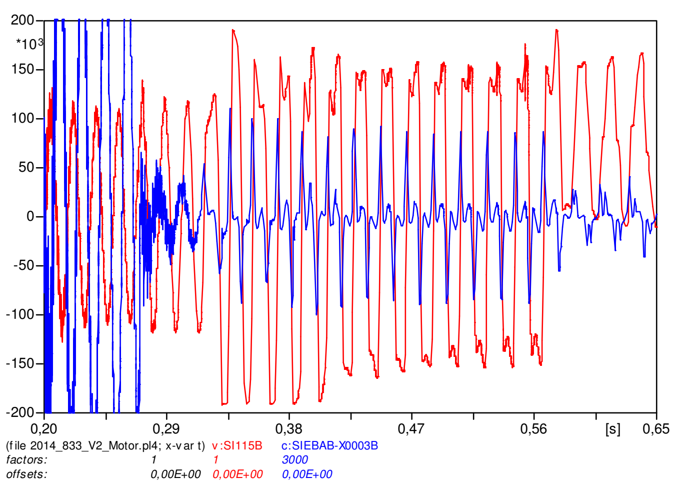


Fig. 8. Line Bay to Sub B in Sub S 115 kV substation Voltage and current phase B – EMTP/ATP simulation

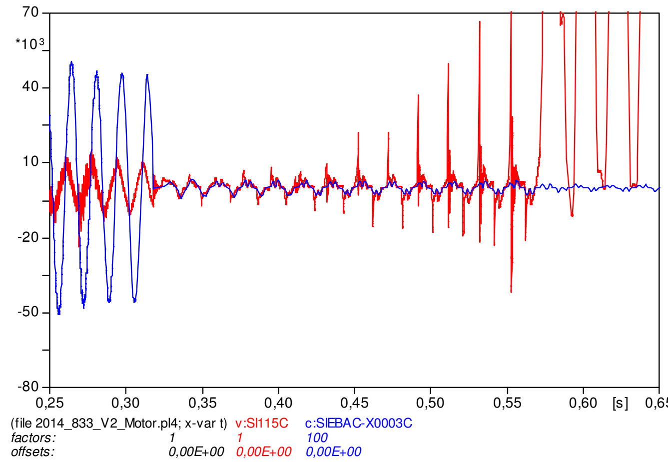


Fig. 9. Line Bay to Sub B in Sub S 115 kV substation Voltage and current phase C – EMTP/ATP simulation

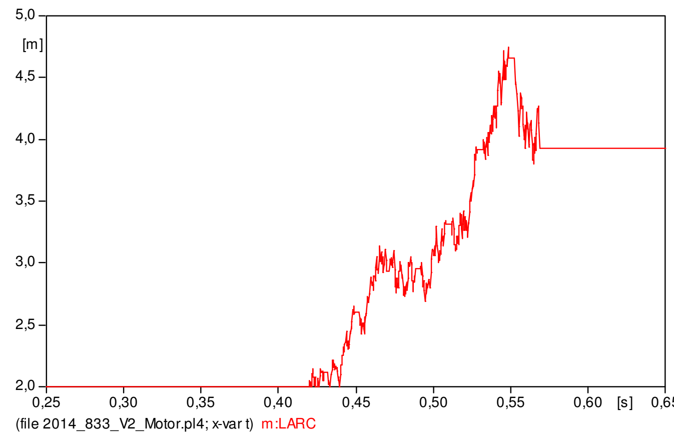


Fig. 10. Arc elongation dynamic by the new approach model – EMTP/ATP simulation

The results of EMTP/ATP simulations allowed to conclude that the phenomena observed was produced by ferroresonance between Sub S substation power transformer and a faulted line whose power source was a motor in the medium voltage side of the transformer that experiencing ferroresonance [7][10]. Fig 11 shows elements involves in ferroresonance.

The surge arrester energy absorption observed in a simulation case with 96 kV rated voltage surge arresters, was under 7%. According to the simulation results the ferroresonance phenomenon started to produce a high energy absorption rate only during the first 4 cycles. If ferroresonance first part is sustained by medium voltage permanent sources or if a permanent fault is generated, high energy absorption can still occur.

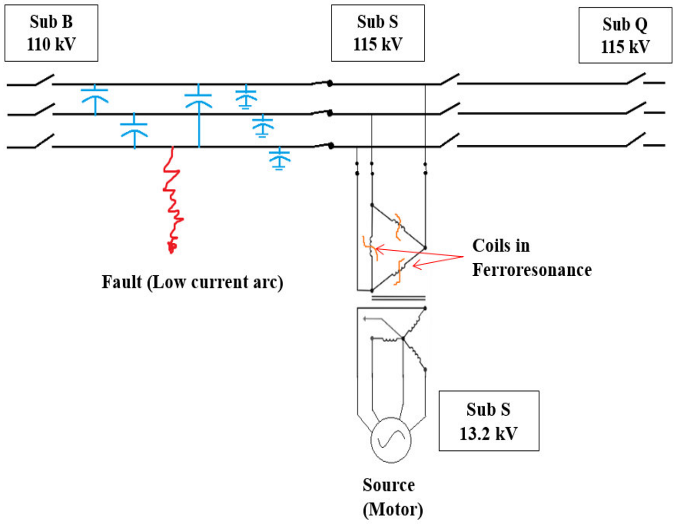


Fig. 11. Simplified schema – explanation how ferroresonance phenomena occurred in Sub S 115 kV substation.

The ferroresonance phenomenon disappeared due two factors. Firstly, the delta transformer winding didn't allow zero sequence current flow; faulted line capacitances sustained a low current fault arc (secondary arc) after Sub S substation was isolated from the power system. The secondary arc extinction was fundamental to removing the ferroresonance phenomenon. The second factor was the motor energy, speed observed was reduced when the sub S substation was isolated from the power system and ferroresonance phenomena started (see OMEGM signal in Fig. 14).

B. Sub S 115 kV Substation Protection Systems Performance

Protective relays in the line bay to Sub B in Sub S 115 kV substation picked up its overcurrent ANSI 67N and zone 4 (forward) functions, but no trips were observed. The distance relay fault locator indicated fault at 110%. The distance relay in Sub B 110 kV substation indicated fault at 37%. According to relays fault locations, high infeed effect affected distance relay in line bay to Sub B in Sub S 115 kV substation. It was expected, however, that the distance relay in Sub S would have detected the fault in zone 2. The distance protection underreach was influenced by high zero sequence impedance which reduces asymmetrical short circuit current.

From the above information on the protection relays in the line bay to Sub B in Sub S 115 kV substation, the following can be concluded:

- The ANSI 67N Overcurrent function was not properly programmed (trip).
- Zone 2 was not properly setup.
- Due to system low zero sequence impedance, distance relay polarization by zero sequence variables are not convenient.

IV. Findings and Short-Term Actions

According to event information and simulations some key points are offered regarding the operation, design and remedial actions to avoid this kind of events.

A. Operational findings

- Protection relays in line bay to Sub B in Sub S 115 kV substation presented trip omission due to problems in overcurrent and distance functions settings.
- The protection schemes of Sub B – Sub S 115 kV transmission line presented undesired trip at an external fault.
- Sub S 115 substation often is only powered by Sub B 110 kV.

B. Design issues

- The Utility reported that Sub B – Sub S 115 kV transmission line shares some structures with other line in a section near to Sub B 110 kV substation. The protection settings related with this line at Sub S 115 kV substation didn't consider this topological condition.

C. Remedial actions taken

- Overcurrent functions of relays in Sub S 115 kV substation were readjusted (trip equation) to ensure that this functions trip.

V. Logic to Detect and Trip by Ferroresonance

Typically power systems are not protected against the ferroresonance phenomena effects due to slow operation of overvoltage protections and low currents. According to this event 2.0 p.u. overvoltages can occur and may wear the equipment insulation and may reduce the lifetime of the surge arrester. A simple logic is proposed in order to recognize ferroresonance conditions based on asymmetrical amplitude overvoltage verification.

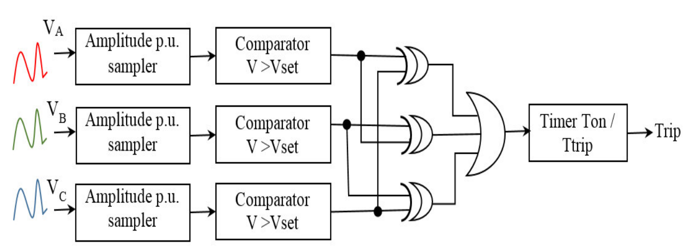


Fig. 12. Proposed logic to detect and trip when ferroresonance occurs.

Fig. 12 shown the proposed logic which is based on amplitude monitoring by time frames. When a phase amplitude is higher than Vset (Voltage threshold to consider the ferroresonance occurrence) the comparator is activated and if one or two phases present overvoltages (not all) a timer starts to countdown in order to trip possible elements involved in this kind of phenomena.

As an example, for demonstration purposes, Figure 13 shows the proposed logic parameter setup for this event, with a low time operation setup.

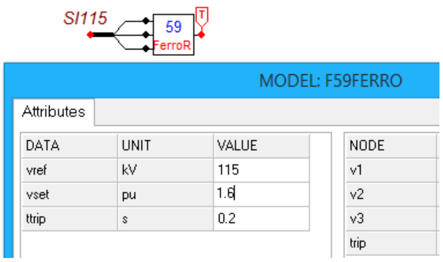


Fig. 13. Parameters – Example proposed logic, application to the event.

The time frame to check maximum absolute voltage (V1M, V2M, V3M) was setup to 20 ms.

Fig. 14. demonstrates how the proposed logic works. The FERRO signal is activated when an asymmetrical overvoltage (one or two phases) is higher than VSET, this value is selected with the surge arrester capability.

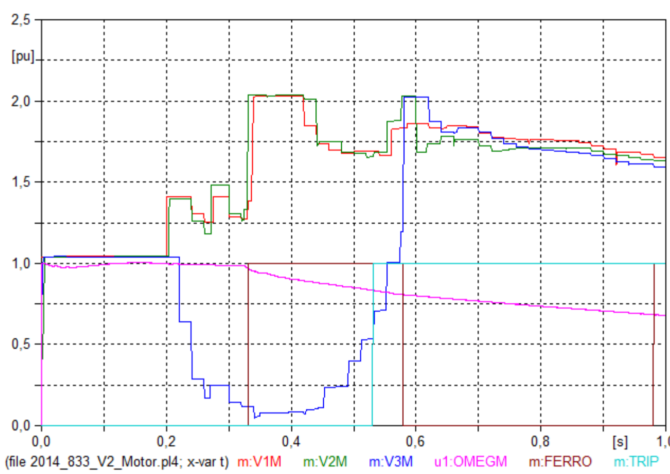


Fig. 14. Example signals - proposed logic proposed applied to this event EMTP/ATP Simulation.

According to simulation results the proposed logic detects ferroresonance condition and it starts the timer, for demonstration purposes timer was set in 200 ms.

For this event the trip signal can be used to open the 115 kV transformer bay in Sub S 115 kV substation. The criteria to use this signal is to disconnect the transformer that can experiment saturation.

VI. Lessons Learned and Next Steps

Based on this event following lessons were learned:

- This event shows that the ferroresonance phenomena can occur due to line bay trip omission associated with substations that can be powered from medium voltage sources.
- This phenomenon had occurred in topologies with substations related to petroleum industries which present high power motors in substations connected to a point of a transmission line after fault clearing. Fig 15. Shows a topology susceptible to present ferroresonance.

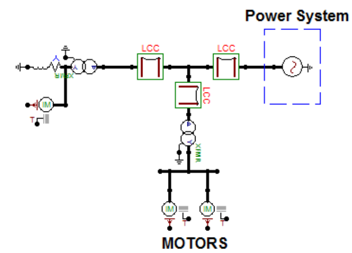


Fig. 15. Typical topology with ferroresonance risk at asymmetrical line faults.

- In the identified topologies that are susceptible to the occurrence of ferroresonance phenomena, the direct transfer trip (DTT) is a solution if the communication is possible. Usually this kind of system doesn't have this possibility, then the proposed logic can be a solution if relay devices can use voltage amplitude.
- If a weak medium voltage system instead of motors is the source for the ferroresonance phenomenon, it is expected that the phenomenon time duration will be longer and the surge arresters and the equipment's insulation may be damaged.
- The root cause of the fault can be more or less appropriate for the duration of ferroresonance phenomena Fault root cause can be more or less convenient to ferroresonance phenomena time duration. If the fault is produced by low impedance permanent element, the ferroresonance phenomenon would last longer than this event in which a lightning stroke was the root cause of the fault.

VII. Conclusions

High voltage substations which are susceptible to be disconnected from the power system and that remain connected to faulted transmission lines, can experiment the ferroresonance phenomena when medium voltage networks power the fault through motors or other sources. DTT must be used to avoid ferroresonance conditions when communication is available.

If DTT is unavailable, the proposed logic can be used to identify and trip in ferroresonance conditions to avoid insulation, surge arrester damage or equipment life reduction.

VIII. ACKNOWLEDGMENT

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IX. REFERENCES

[1] XM S.A. E.S.P. "Informe Evento 2014-0833", Dirección de Aseguramiento de la Operación, Equipo de Análisis de Eventos y Protecciones, publicado 22 de julio de 2014, 35p.

[2] J. F. Piñeros, J. A. Calderón, J. A. Vega, "Modelo Híbrido de Arco Secundario En ATP Para Análisis de Recierres en Líneas De Transmisión", Jornadas Técnicas ISA, 2015.

[3] A.T Johns, R. Aggarwal, Y. Song, "Improved Techniques for Modeling Fault Arcs on Faulted EHV Transmission Systems", IEE Proceedings, Generation, Transmission and Distribution, Vol 141, No 2 March 1994.

[4] M. Kizilcay, L. Prikler, G. Bán, P. Handl. "Interaction of the Secondary Arc with the Transmission System during Single-Phase Autoreclosure", 2003 IEEE Bologna Power Tech Conference, June 23th-26th, Bologna, Italy.

[5] S. Hassan, M. Vaziri, S. Vadhva, "Review of Ferroresonance in Power Distribution Grids" IEEE IRI, Las Vegas, USA, 2011.

[6] S. McKee, R. Simpson, "Ferroresonance and Preisach theory", IEE Colloquium on Warning! Ferroresonance Can Damage Your Plant (Digest No: 1997/349).

[7] M. Ibrahim, *Disturbance Analysis for Power Systems*, Wiley-IEEE Press, 2011, 736p.

[8] H.W. Dommel, *Electromagnetic Transients Program – EMTP Theory Book*. *Reference Manual*. Bonneville Power Administration U.S.A August 1986

[9] N. Watson , J. Arrillaga , *Power Systems Electromagnetic Transients Simulation*, IEE Power and Energy Series, 2002

[10] J. C. Das, *Transients in Electrical Systems: Analysis, Recognition, and Mitigation*, Mcgraw Hill, 2010.

[11] H. K. Høidalen, ATPDraw Users' *Manual – Reference Manual, Advance Manual*, version 5.6, 2009

[12] H. K. Høidalen, A. M. Bruce, N. Chiesa, "Implementation and verification of the Hybrid Transformer model in ATPDraw", *International Conference on Power Systems Transients* (IPST'07) in Lyon, France on June 4-7, 2007.

[13] H. K. Høidalen, N. Chiesa, "Developments in the hybrid transformer model – Core modeling and optimization*", International Conference on Power Systems Transients* (IPST2011) in Delft, the Netherlands June 14-17, 2011.