Event Analysis of a Fault Disturbance in the Colombian Power System Caused by a Light Aircraft Crash

Pedro Lozada and Sadul Urbáez, ISA Colombia.

ABSTRACT

Power systems faults occur regularly due to diverse reasons and have different consequences depending on how they evolve and are cleared. Post-mortem analysis of such disturbances allow the assessment of the protection system and the discovery of abnormal conditions that could lead to setting changes in order to improve the transmission system reliability and stability. This paper presents the analysis of a fault event caused by a light aircraft crash into a 220kV double circuit transmission line in the Colombian power system. The evaluation of this unusual disturbance was done using sequence-of-event (SOE), digital fault recorder (DFR) and relay records to reconstruct the fault and its evolution after one overhead line conductor was broken by the aircraft's propeller. Furthermore, it is shown in the analysis the impact of the disconnection and reclosures of both faulted transmission circuits in the power system where the protection schemes in an adjacent substation tripped out a capacitor bank bay and two 220kV line bays. The actions after the post-fault event analysis are also described.

INTRODUCTION

On August 5, 2011 at 07:10 there was a fault disturbance on the Colombian power system that resulted in the trip of the circuits Santa Marta – Termoguajira 1 and 2 220kV with 36MW each due to the operation of the distance protection relays at every end after a light aircraft crashed into the double circuit transmission line. Along with the tripping of the two circuits, four bays were affected at an adjacent substation, one line bay reclosed, and a line bay, a capacitor bank bay and a transformer bay were disconnected. Sequence-of-event (SOE) and event records from DFRs and relays were used to analyze this fault and the operation of the protection schemes implemented. Corrective actions were taken to improve the relay settings and the overall reliability of the power system.

THE EVENT

On 8/5/2011 at 07:10 the distance protections of line bays LN-815 and LN-814 at Termoguajira substation (TGJ) cleared an intercircuit fault in zone 1 and tripped one pole of CBs 8420 (phase C) of LN-815 and 8520 and 8530 (phase A) of LN-814 after a light aircraft used for aerial fumigation crashed into the double circuit transmission line. The conductor corresponding to phase C in the overhead line span between towers 80 and 81 of LN-815 was broken by the aircraft's propeller, as shown in figure 1, and the broken conductor strung on tower 81 (to TGJ) got tangled in the landing gear of the aircraft and as the aircraft continued going through the transmission cables, the parallel circuit LN-814 was also affected and it was how the intercircuit fault between phases C and A of LN-815 and LN-814, respectively, was caused. Despite of the breaker-and-a-half configuration of TGJ, only CB 8420 of line bay LN-815 tripped, because CB 8430 was in maintenance since the day before.

At the remote end, the distance relays at Santa Marta substation (SMT) did not trip for this fault, as the condition seen from this point was that of a broken conductor for LN-815, while for LN-814 there was no tripping since the distance element that picked up was the zone 2 and no teleprotection signal was received while the fault was present.

Tower 80 is located at 42.02km from SMT and 49.49km from TGJ while tower 81 is located at 42.57km from SMT and 48.93km from TGJ. Transmission lines LN-814 and LN-815 go from SMT to TGJ on double circuit towers. On the left side, facing the sea, is the LN-814 and on the right side is the LN-815, facing the mountains, see figure 2. The circuits are in opposite sequence to each other, LN-814 has an A-B-C sequence from top to bottom, while LN-815 has the opposite (C-B-A sequence from top to bottom).

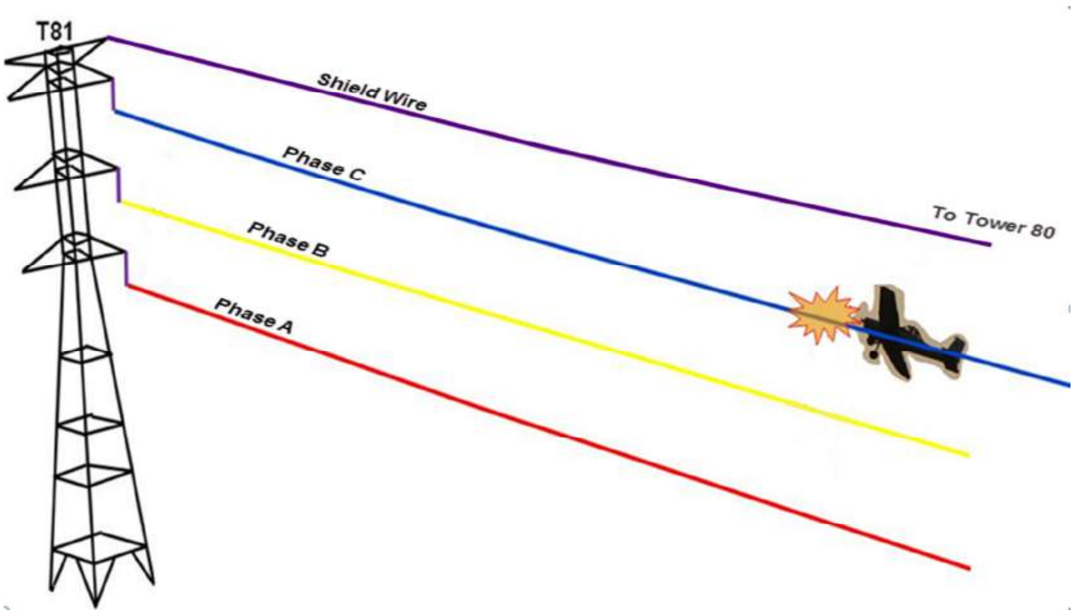


Figure 1. Aircraft crash into the double circuit structures of LN-814 (not shown) and LN-815.

Figure 2. 220kV double circuit overhead transmission line between SMT and TGJ (LN-814/LN-815) and crash site at approximately 42km from SMT.

As a result of this disturbance, circuits Santa Marta – Termoguajira 1 and 2 220kV were tripped and so were one line bay, one capacitor bank bay and an autotransformer bay at

Fundación substation (FUN) and one line bay at this same substation reclosed successfully. CBs tripped at each substation are identified in figure 3.

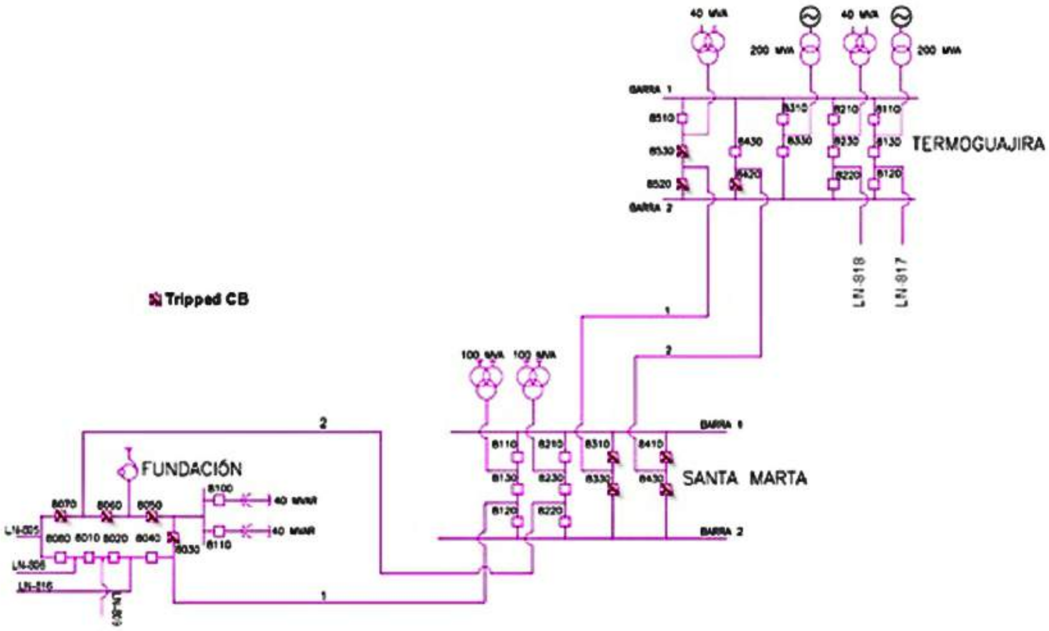


Figure 3. Disconnected bays at FUN, SMT and TGJ.

The line bay of LN-808 at FUN, the capacitor bank bay and the autotransformer bay of AT-FUN01 were energized after the closing of its CBs, and so was transmission circuit LN-814.

Given the multiples disconnections in this event, an aerial inspection of the two overhead transmission lines between SMT and TGJ substations was conducted. The aerial patrol found that phase C conductor and cross arm were affected in the line span between towers 80 and 81 of LN-815 and for that reason LN-815 was out of service for 36 hours while the corrective maintenance activities were made. It was not until the aerial patrol arrived at the crash site and confirmed the permanent nature of the fault that it was known that an aerial fumigation light aircraft had caused the disturbance when crashing into the circuits. Evidence found at the crash site is presented in figures 4 and 5.

Figure 4. Evidence found at the crash site.

Figure 5. Light aircraft used for aerial fumigation that caused the fault in circuits LN-814 and LN-815.

The evolution of the fault and all the disconnections and reclosures that took place were recorded on the DFR at SMT, the substation between TGJ and FUN. Three disturbance record files were merged into a new file as seen in figure 6, where also and each moment of the sequence is indicated.

As detailed above, the first moment of the fault was an intercircuit fault. The complete sequence of the event recorded on the DFR at SMT was as follows:

1. There was a condition of open conductor before the intercircuit fault of phases C and A of LN-815 and LN-814 took place in moment 1, as shown in figure 7. The intercircuit fault was first cleared at TGJ LN-815 and approximately one cycle after at TGJ LN-814 by the distance protections. Further details are provided through figures 8 to 10.

   Seen from SMT LN-815, the phase C conductor was broken and therefore the fault condition was not clearly detected. After the fault in LN-815 was cleared, voltages for phases A and C are the same for 59mS, which also indicates that the phase C conductor of this circuit came into contact with the phase A conductor of the parallel line. At SMT LN-814 there was no tripping since the distance element that picked up was the zone 2 and no teleprotection signal was received while the fault was present.

2. As the phase C conductor of LN-815 was broken, the part strung on tower 80 fell across phase B causing a new fault that was detected by the distance protections in zone 1 which tripped all three phases at both substations, CBs 8410 and 8430 at SMT and 8420 at TGJ. This new fault is depicted in figures 11 and 12 and was produced 733mS from the previous one and during the dead time of the single-pole auto-reclosing of phase C of line bay TGJ LB-815. Voltage signals of phases A and C are the same in figure 11 before the second fault which happens because conductors are in contact as in the first fault. After the three-phase trip, voltage signals for phases B and C are the same, just in the same way as in figure 12 and it confirms that phase C fell across phase B in LN-815 seen from SMT to TGJ.

   On the other hand, at the same time for LN-814, CBs 8310 and 8330 of line bay SMT LN-814 effected a single pole operation for phase A after a trip issued by distance protection in zone 1 as plotted in figures 13 and 14. At TGJ it was still running the dead time for the single-pole auto-reclosing of phase A.

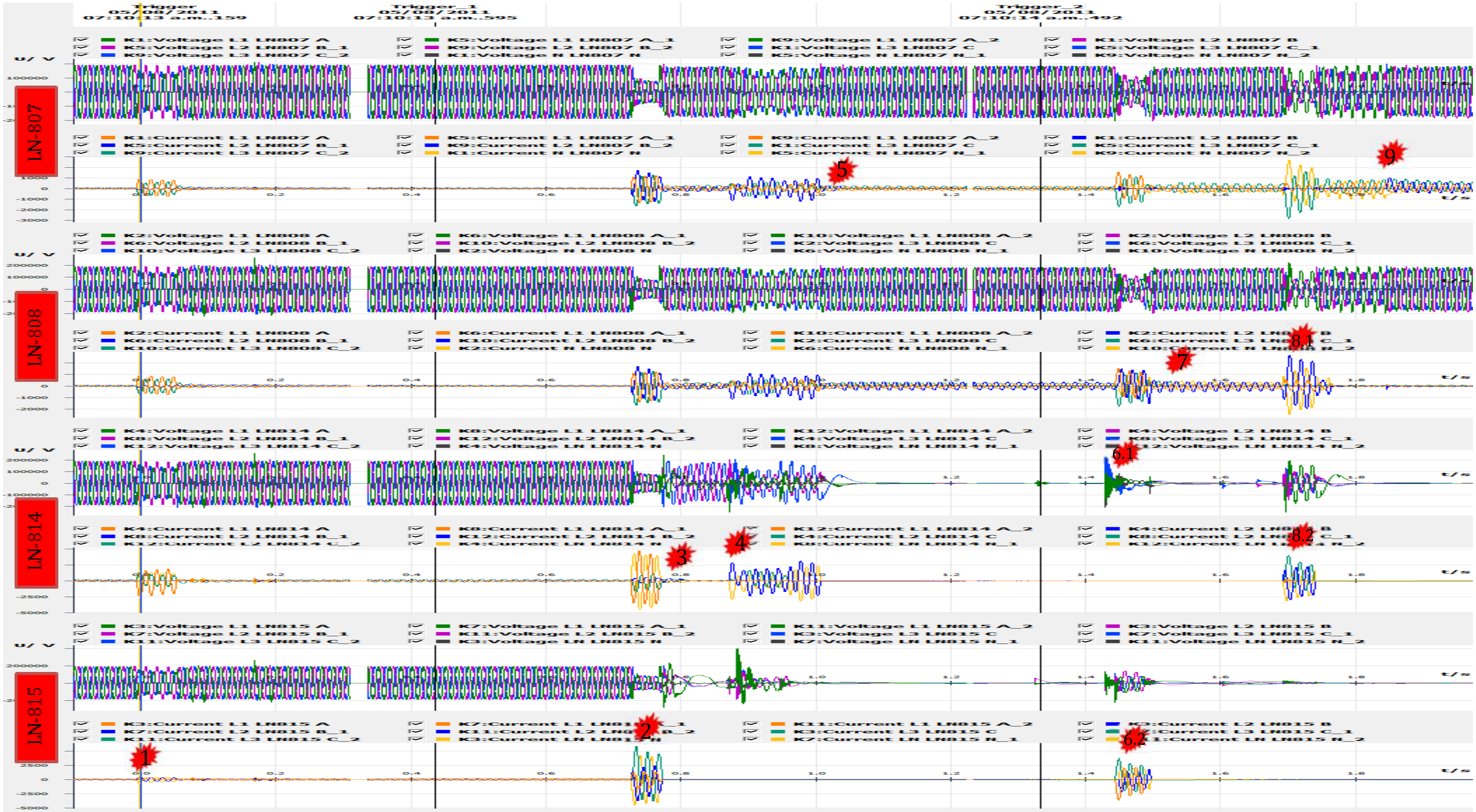
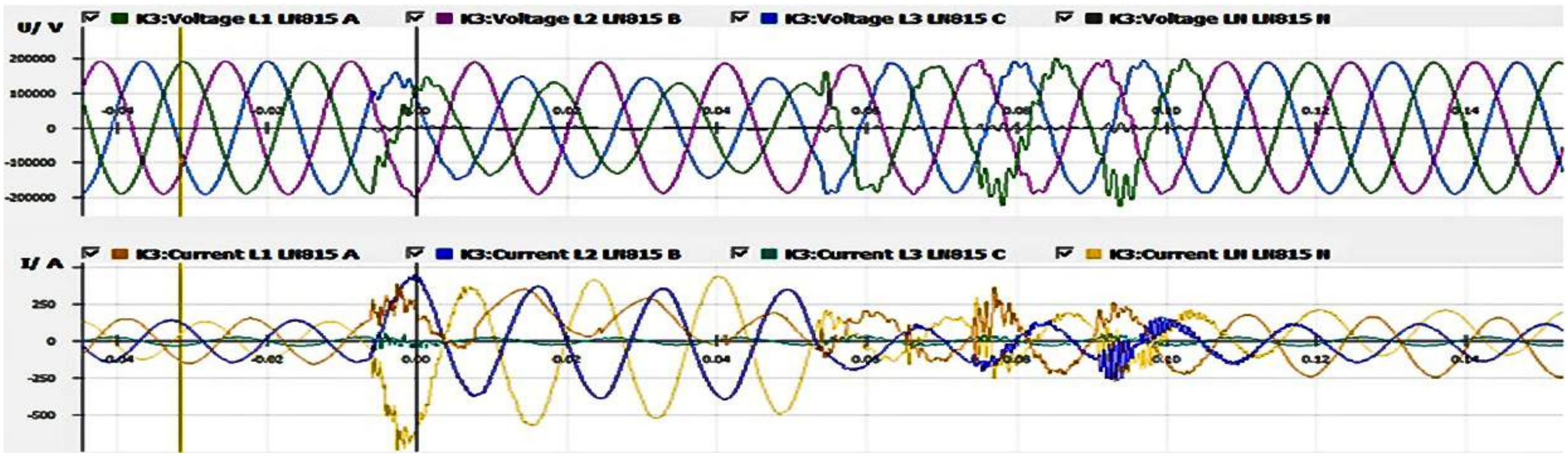


Figure 6. Complete disturbance data from the DFR at SMT.



(a). Voltages and currents of LN-815 at pre-fault.

Measuring Signal	Value	Phase
K3:Current L1 LN815 A	107 A	-40.3°
K4:Current L1 LN814 A	0.11 kA	-38.8°
K3:Current L2 LN815 B	98.6 A	-168.2°
K4:Current L2 LN814 B	101 A	-158.1°
K3:Current L3 LN815 C	19.8 A	0.0°
K4:Current L2 LN814 C	0.16 kA	85.2°
K3:Current LN LN815 N	89.3 A	92.9°
K4:Current LN LN814 N	0.059 kA	-92.1°
K3:Voltage L1 LN815 A	133 kV	153.6°
K4:Voltage L1 LN814 A	134 kV	153.5°
K3:Voltage L2 LN815 B	135 kV	33.6°
K4:Voltage L2 LN814 B	135 kV	33.6°
K3:Voltage L3 LN815 C	134 kV	-87.1°
K4:Voltage L3 LN814 C	135 kV	-87.1°

(b). Values measured from SMT at pre-fault.

Figure 7. Condition of broken conductor seen from SMT at pre-fault (yellow line). (a) Voltages and currents of LN-815. (b) Values measured at SMT.

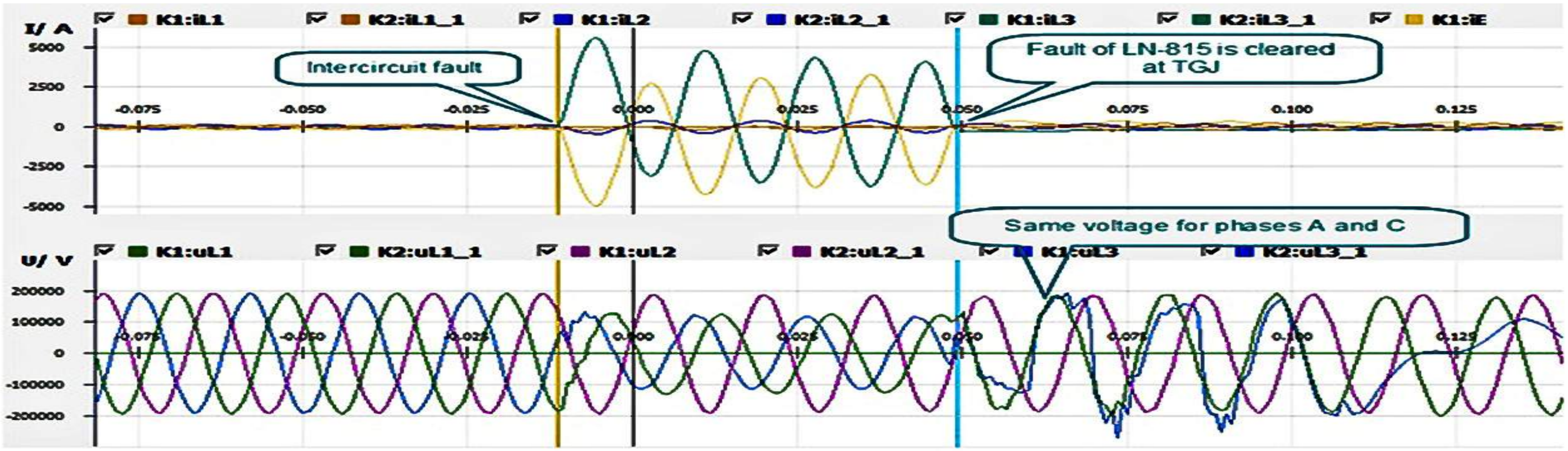


Figure 8. Event record at TGJ LN-815 for the intercircuit fault.

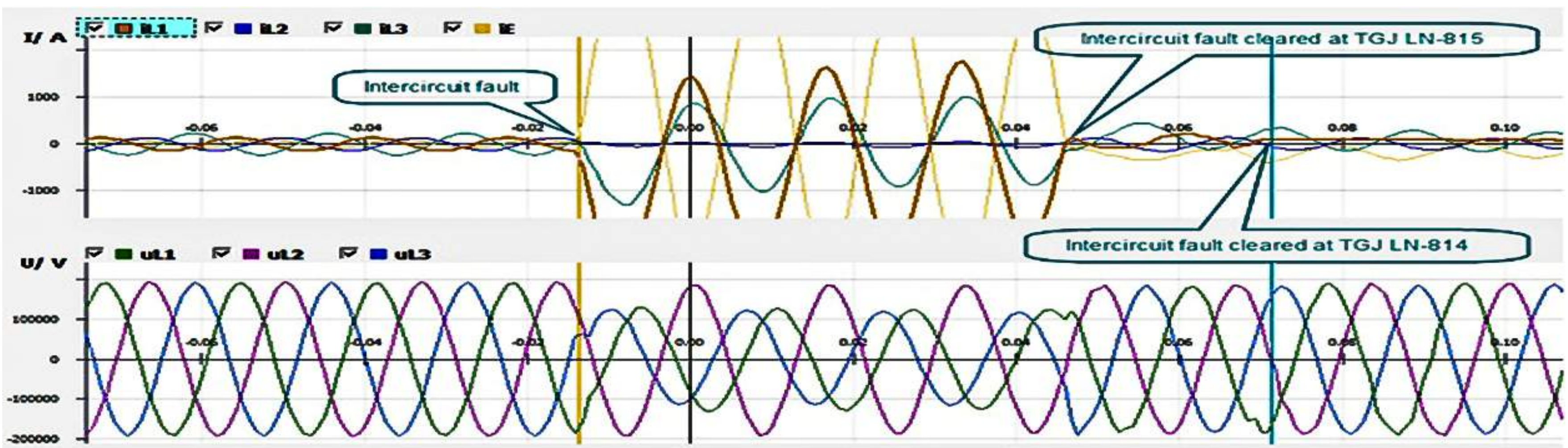


Figure 9. Event record at TGJ LN-814 for the intercircuit fault, which was first cleared by CB at TGJ LN-815 and one cycle after at TGJ LN-814.

Measuring Signal	Value	Phase
iL1	0.061 kA	0.0°
iL2	77.8 A	-49.6°
iL3	0.14 kA	-167.5°
iE	0.094 kA	74.0°
uL1	135 kV	-98.9°
uL2	134 kV	141.4°
uL3	135 kV	20.6°

Figure 10. Currents and voltages of LN-814 at SMT after the intercircuit fault was cleared. Phase A at TGJ was open.

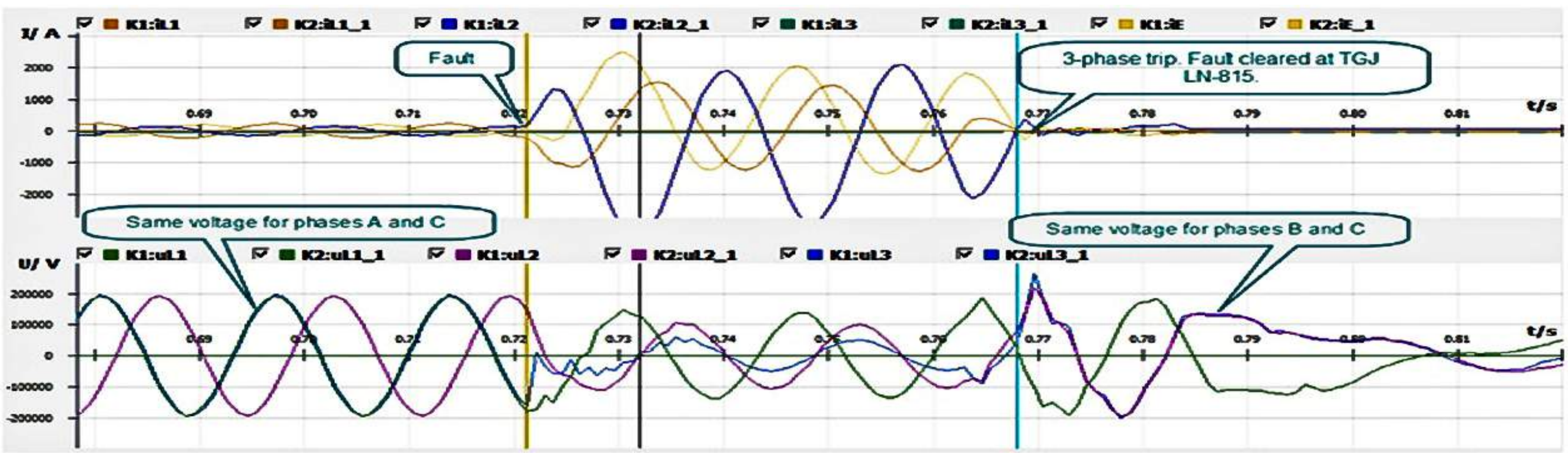


Figure 11. 3-phase trip at TGJ LN-815 during the dead time of the single-pole auto-reclosing of phase C. Before the fault, voltages for phases A and C are the same. After the trip, voltages for phases B and C are equal.

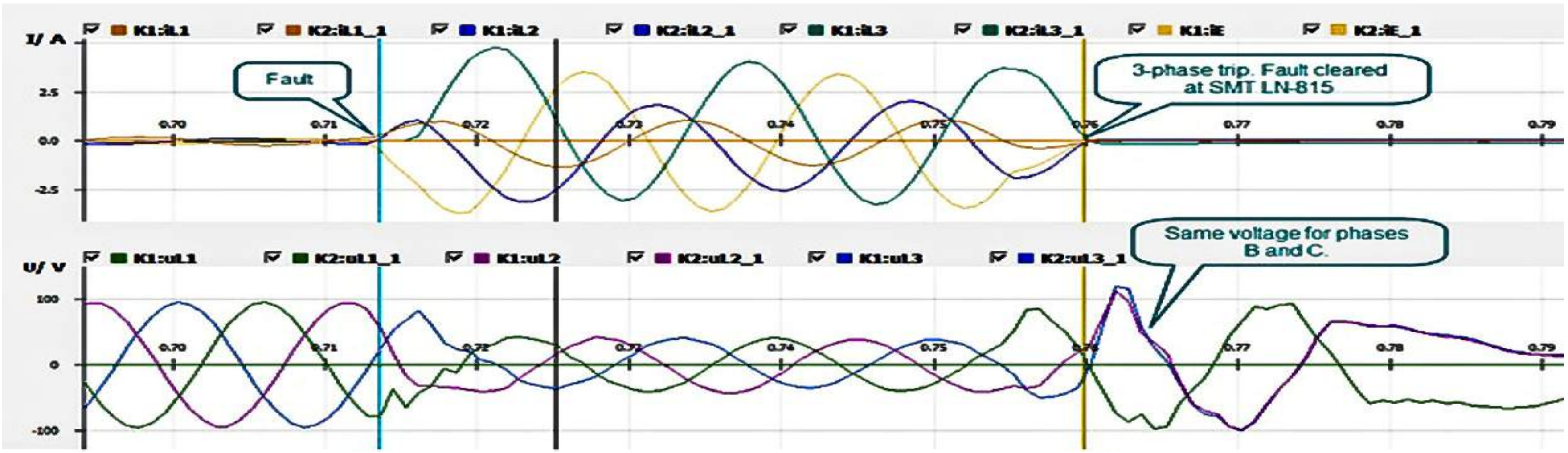


Figure 12. 3-phase trip at SMT LN-815. After the trip, voltages for phases B and C are equal.

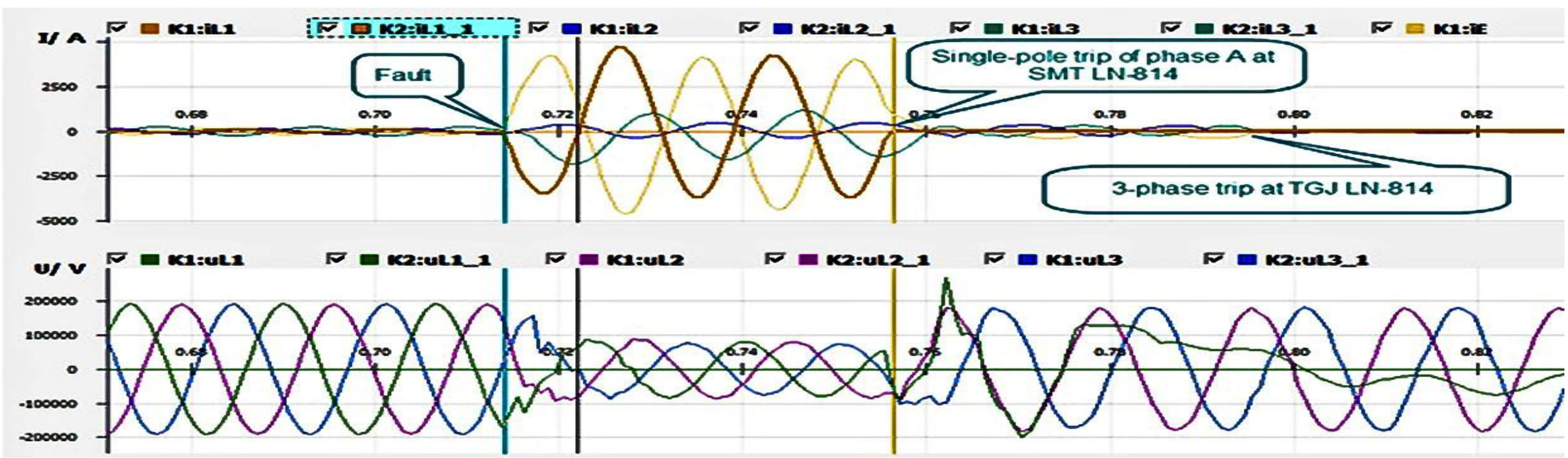


Figure 13. Single-pole trip of phase A at SMT LN-814 after distance element zone 1 operated.

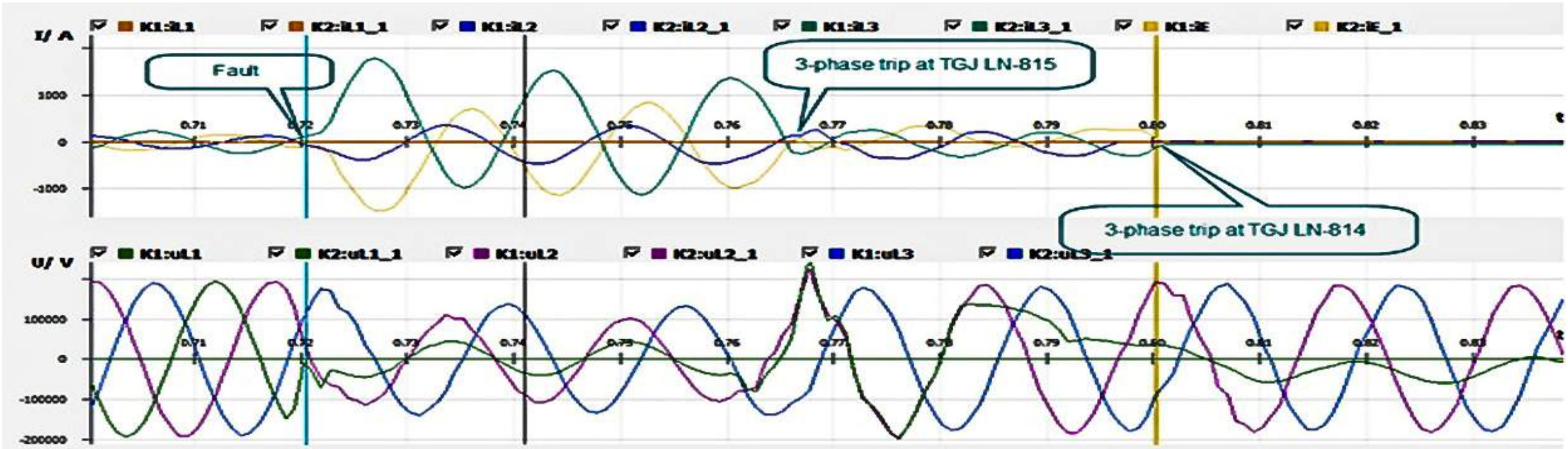


Figure 14. Three-phase trip at TGJ LN-815 in moment 2 and at TGJLN-814 in moment 3.

3. The third moment of the sequence is at 814mS, where CBs 8520 and 8530 of line bay of circuit LN-814 at TGJ are tripped after relay SEL-321 issued a three-phase trip command once a teleprotection signal was received with its distance element zone 2 picked up during the dead time after the previous tripping of phase A by Siemens 7SA522 at moment 1. Event records illustrated in figures 13 and 14 also show the moment when line bay of LN-814 at TGJ is tripped.

4. After the three-phase trip of CB 8420 of line bay LN-815 at TGJ, it reclosed into the line at 878mS, but as the fault was still present, all the poles tripped again at 963mS after the operation of distance protection and no further reclosing took place. During this failed reclose attempt, CB 8520 of LN-814 at TGJ also reclosed three poles on to the permanent fault at 903mS and tripped again at 973mS. Immediately afterward at 1014mS, CBs 8310 and 8330 at SMT LN-814 tripped when line protections issued a three-phase trip command during the reclose attempt at TGJ LN-814. This part of the sequence is represented through figures 15 to 17.

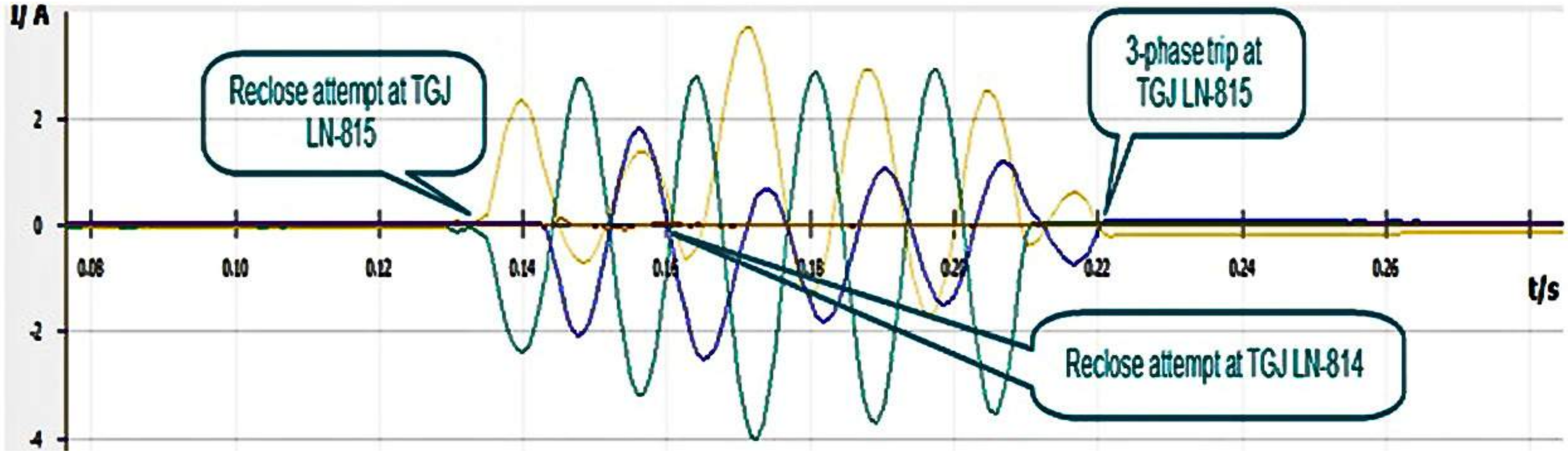


Figure 15. Reclose attempt and subsequent tripping of CB 8420 at TGJ LN-815.

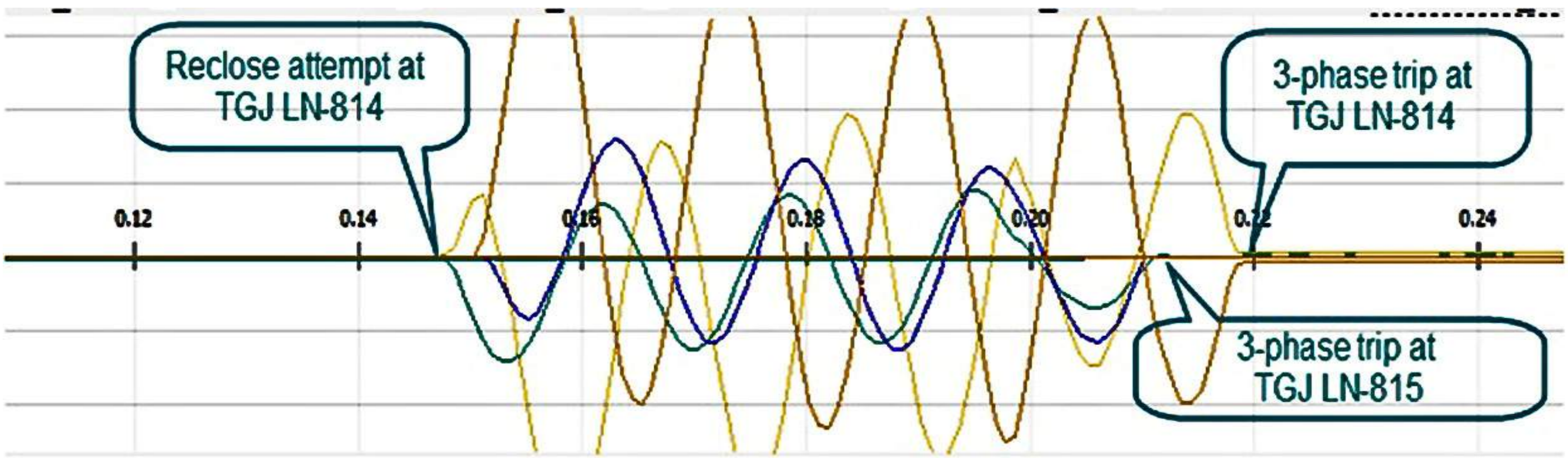


Figure 16. Reclose attempt and subsequent tripping of CB 8520 at TGJ LN-814.

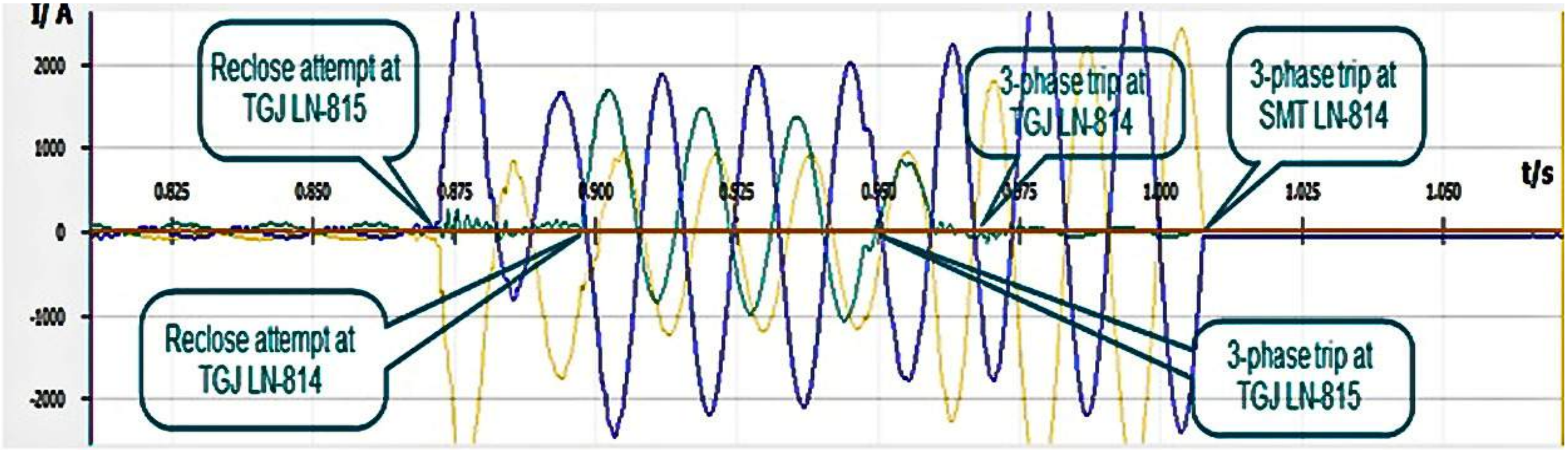


Figure 17. Reclose attempts and tripping of line bays LN-815, LN-814 at TGJ and three-phase trip at SMT LN-814 as recorded on DFR at SMT.

5. In this part of the sequence at 1044mS, CBs 8030 and 8040 of line bay LN-807 at FUN tripped the pole corresponding to phase B, as seen in figure 18. FUN and SMT substations are interconnected by power lines LN-807 and LN-808. This was an undesired operation of the distance relay SEL-321 (MP1) at this bay line, which overreached for an external fault. No event records from relay SEL-321 at this bay were available and from the Trip Log of Siemens 7SA522 (MP2) it was confirmed this second relay did not trip. The misoperation of MP1 was stamped on the SOE and also recorded on the DFR when the signal "TR21PL1-LN807" went high.

6. A second reclose attempt happened at TGJ LN -814 at 1434mS when CB 8520 reclosed three poles on to the permanent fault and so did CB 8410 of LN-815 at SMT 16mS after. The fault was once more cleared by distance protections at this line bays and those CBs tripped again and locked out at 1504mS. For line bay TGJ LN-814, it was a maloperation of the reclosing scheme, since this second reclosing attempt of CB 8520 was not conceived considering it must have locked out after the previous trip. Concerning the reclosing at SMT LN-815, it was 670mS after the three-phase trip at moment 2 and it was expected to occur. This moment of the sequence is detailed in figures 19 and 20.

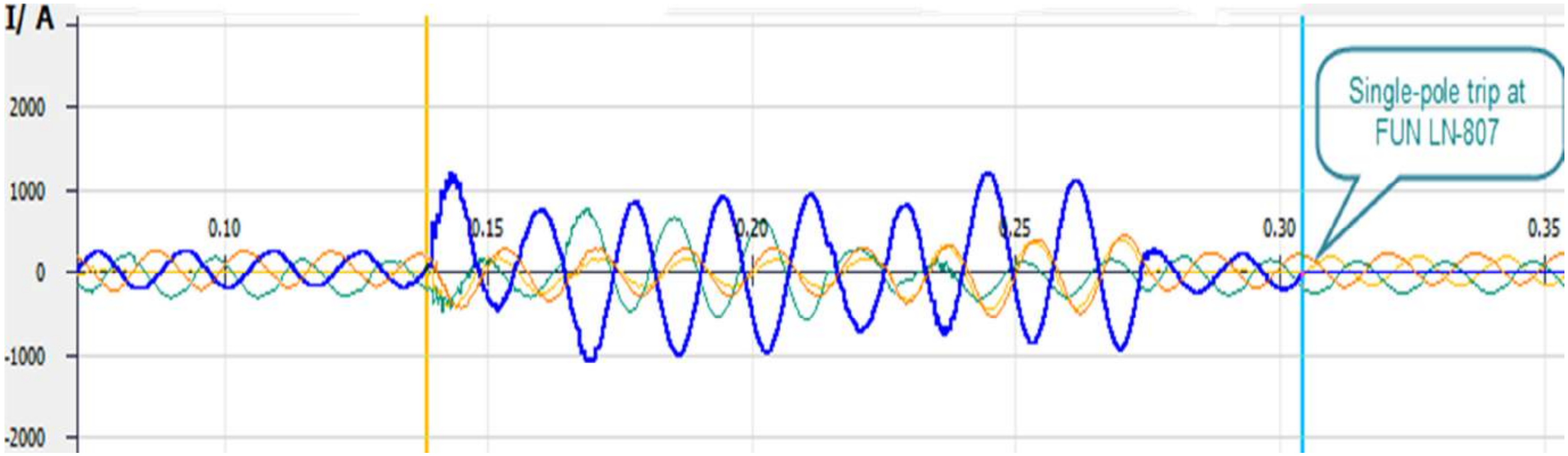


Figure 18. Single-pole trip at FUN of LN-807.

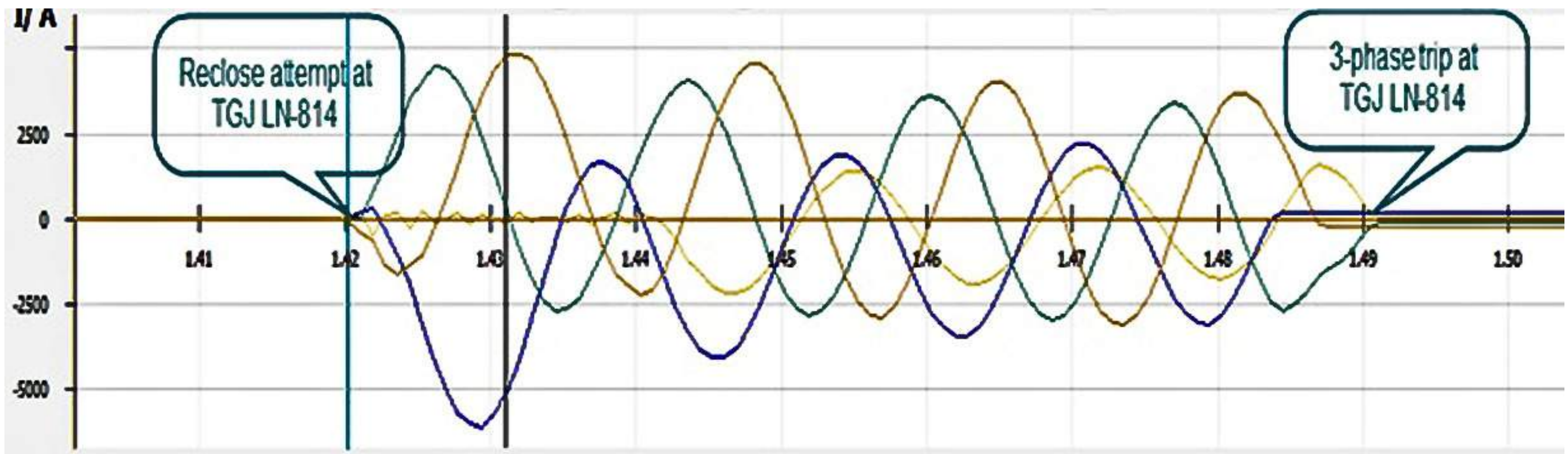


Figure 19. Reclose attempt and subsequent tripping at TGJ LN-814.

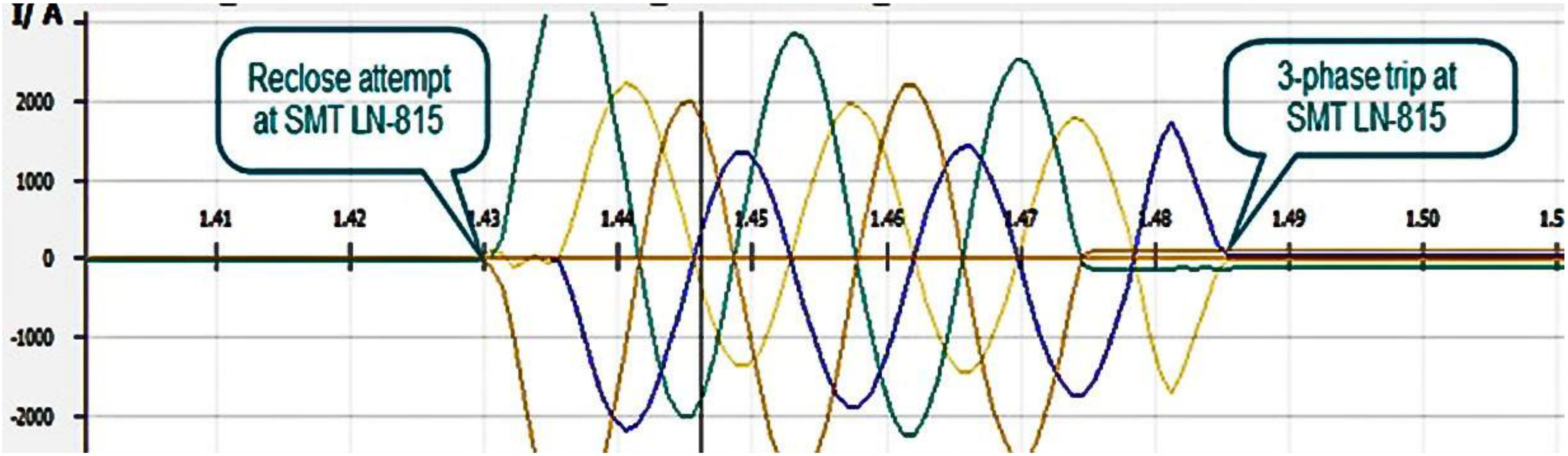


Figure 20. Reclose attempt and subsequent tripping at SMT LN-815.

7. During the fault presented in moment 6, relay Siemens 7SA522 (MP2) of line bay LN-808 at FUN issued a single-pole trip after the operation of the distance element zone 1 and CBs 8060 and 8070 tripped phase C poles at 1535mS, as illustrated in figure 21. Here there was another maloperation of the protection schemes at FUN after overreaching for an external fault.

8. Over the dead time of the two single-phase auto-reclosings at FUN (moments 5 and 7), CB 8310 of LN-814 at SMT also reclosed on to the fault at 1699mS and tripped again at 1748mS as a result of the operations of the distance protections. This fault caused the line protection MP1 of LN-808 at FUN to trip all the poles of CBs 8060 and 8070 after detecting a developing fault during the dead time. This time relay Siemens 7SA522 did not issue any trip and, in this case, relay SEL-321 was the one that misoperated. The operation of MP1 was confirmed on the SOE and on the DFR records as no event data from the relay was found. Three-phase reclosing is out of service for this bay line. These two trippings that took place in this moment are presented in figures 22 and 23.

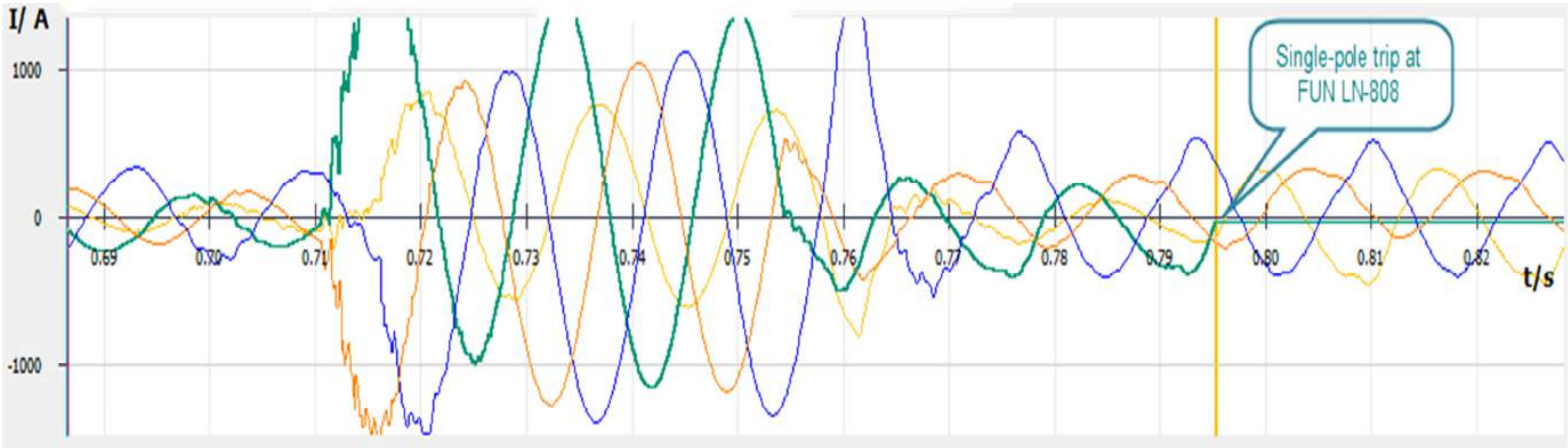


Figure 21. Single-pole trip at FUN of LN-808.

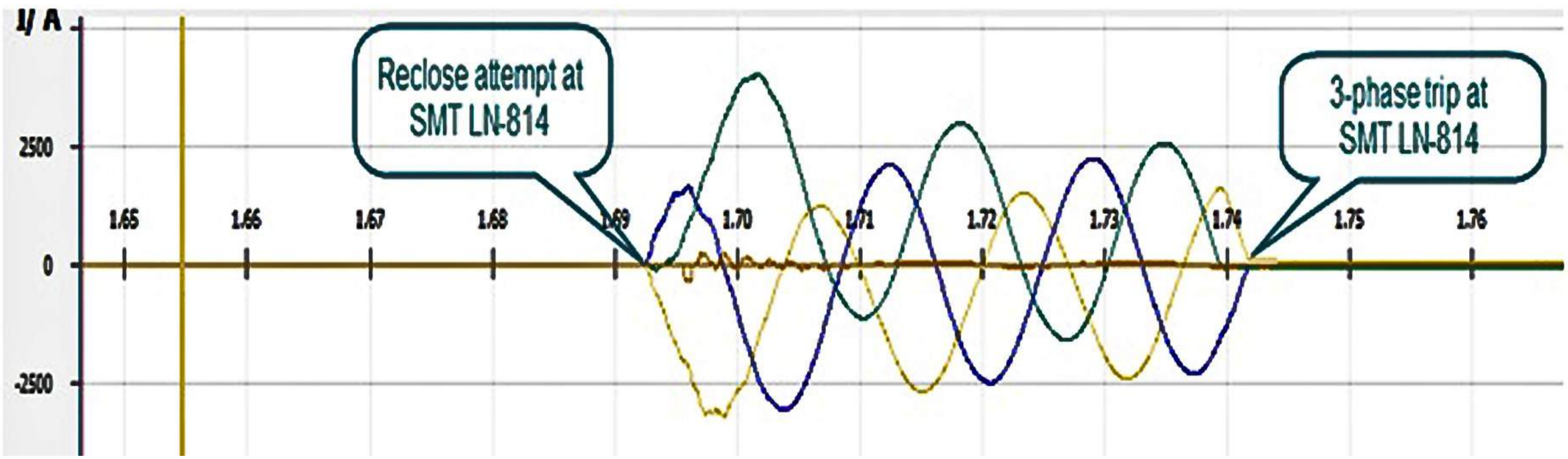


Figure 22. Reclose attempt and subsequent tripping at SMT LN-814.

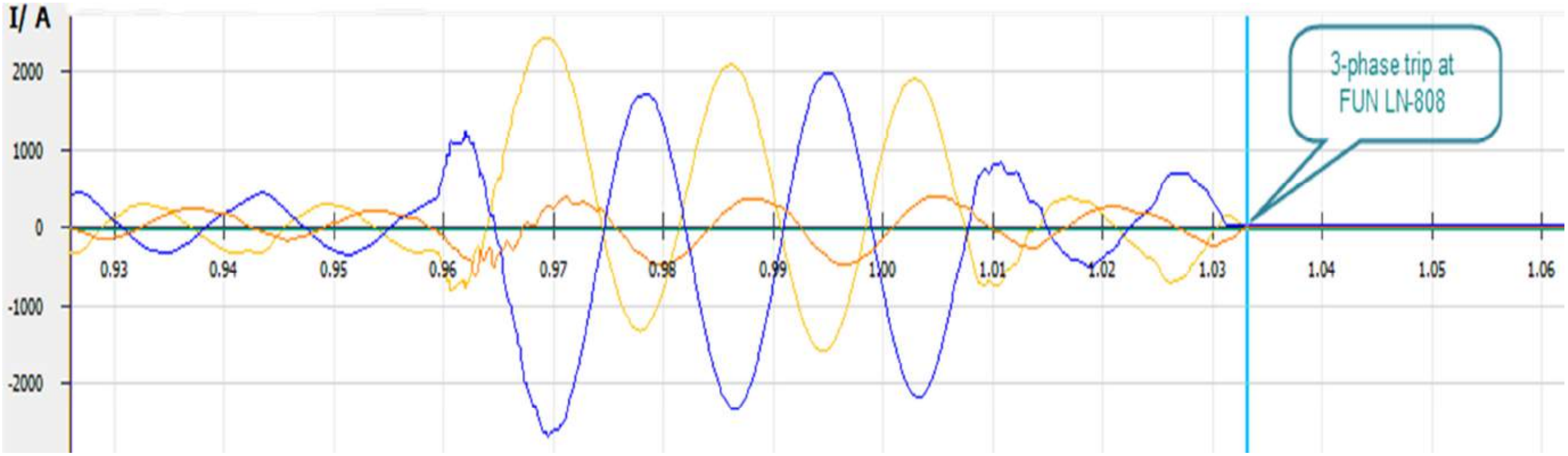


Figure 23. Three-pole trip at FUN of LN-808.

9. Successful single-pole reclosing of CB 8040 at FUN occurred at 1851mS. Nevertheless, as there had been an unbalance condition in the system with phases B (bay line LN-807 single-pole trip) and C (bay line LN-808 3-phase trip) tripped and taking into account the ring bus configuration at FUN the overcurrent relay of the capacitor bank operated. The capacitor bank bay is in the middle of the line bays corresponding to LN-807 and LN-808 and due to this topology the overcurrent relay tripped CBs 8030 and 8050.

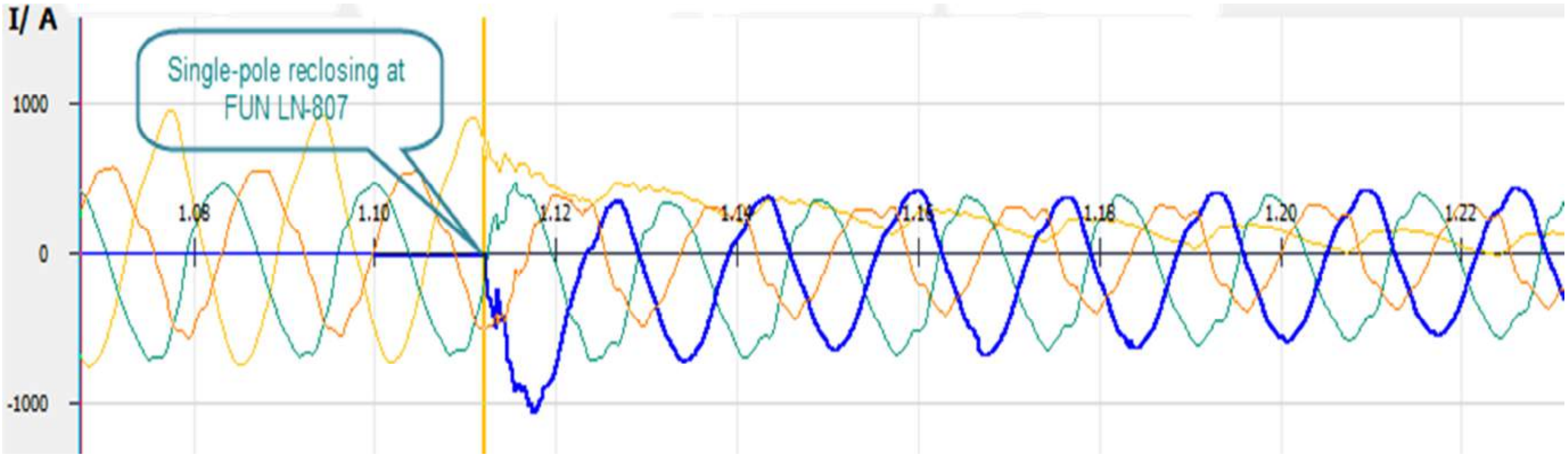


Figure 24. Single-pole reclosing of CB 8040 at FUN.

Along with the disconnection of the capacitor bank bay, the 220kV autotransformer bay of AT-FUN01 was also disconnected, not because any of its protections operated, but because of the tripping of CBs 8060 and 8050, which belong to this bay and were tripped with the disconnections of line bay LN-808 and the capacitor bank bay, respectively, as seen in figure 3. A summary of the sequence is presented in the next table.

COMPLETE SEQUENCE OF THE EVENT								
Time (ms)	TGJ-815	SMT-815	TGJ-814	SMT-814	FUN-807	SMT-807	FUN-808	SMT-808
0	closed	closed	closed	closed	closed	closed	closed	closed
60	Trip - Only phase C	closed	closed	closed	closed	closed	closed	closed
83	Phase C opened	closed	Trip - Only phase A	closed	closed	closed	closed	closed
780	3-phase trip (during dead time)	3-phase trip	Dead time running	Trip - Only phase A	closed	closed	closed	closed
814	opened	opened	3-phase trip (during dead time)	Dead time running	closed	closed	closed	closed
878	Reclose attempt	opened	opened	Dead time running	closed	closed	closed	closed
903	closed	opened	Reclose attempt	Dead time running	closed	closed	closed	closed
963	3-phase trip	opened	closed	Dead time running	closed	closed	closed	closed
973	opened	opened	3-phase trip	Dead time running	closed	closed	closed	closed
1014	opened	opened	opened	3-phase trip	closed	closed	closed	closed
1044	opened	opened	opened	opened	Trip - Only phase B	closed	closed	closed
1434	opened	opened	Reclose attempt	opened	Dead time running	closed	closed	closed
1450	opened	Reclose attempt	closed	opened	Dead time running	closed	closed	closed
1504	opened	3-phase trip	3-phase trip	opened	Dead time running	closed	closed	closed
1535	opened	opened	opened	opened	Dead time running	closed	Trip - Only phase C	closed
1699	opened	opened	opened	Reclose attempt	Dead time running	closed	Dead time running	closed
1748	opened	opened	opened	3-phase trip	Dead time running	closed	Dead time running	closed
1772	opened	opened	opened	opened	Dead time running	closed	3-phase trip	closed
1851	opened	opened	opened	opened	Single-pole reclosing	closed	opened	closed

Table 1. Complete sequence of the fault disturbance.

MISOPERATION IDENTIFICATION AND CORRECTION

Line Bay of LN-807 at FUN

Relay SEL-321 (MP1) of line bay LN-807 at FUN misoperated after it issued a single-pole trip for an external fault at moment 5 of the sequence. To assess the operation of the MP1 the IMPAP (software used to simulate the apparent impedance seen by relays developed by ISA) was used. The apparent impedance for phase B seen by MP1 did not enter the distance relay zone 1 characteristics, as depicted in figure 25, hence this relay did not trip for this reason and it is unknown what made the relay operate. However, it is believed that the relay might have tripped because of capacitive voltage transformer (CVT) transients due to overreach problems of distance elements of this type of relay in the past. The evaluation of the apparent impedance for this relay was performed with the event data recorded on MP2, relay Siemens 7SA522, and the DFR, because no event record from SEL-321 was available.

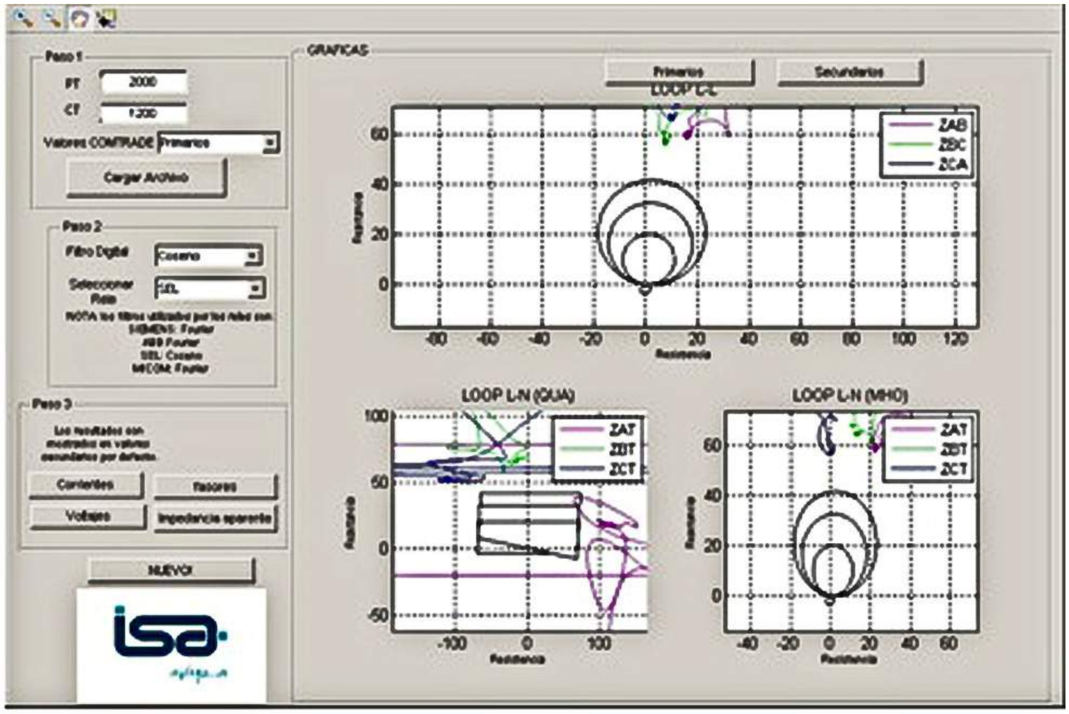


Figure 25. Apparent impedance trajectories on IMPAP for SEL-321 of LN-807at FUN.

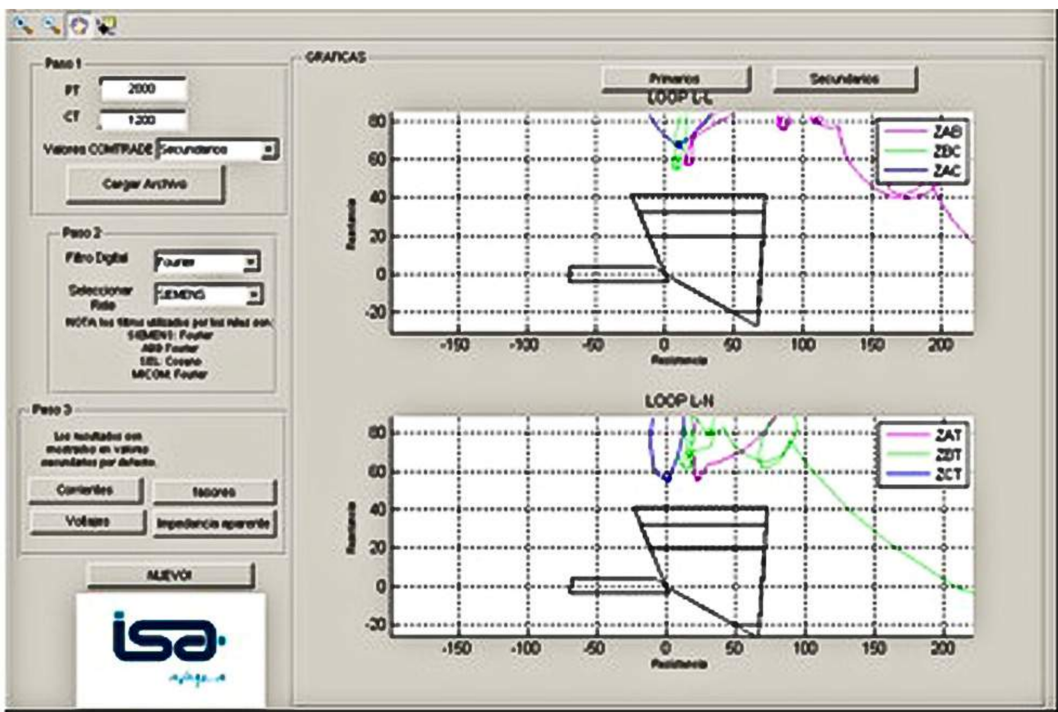


Figure 26. Apparent impedance trajectories on IMPAP for Siemens 7SA522 of LN-807at FUN.

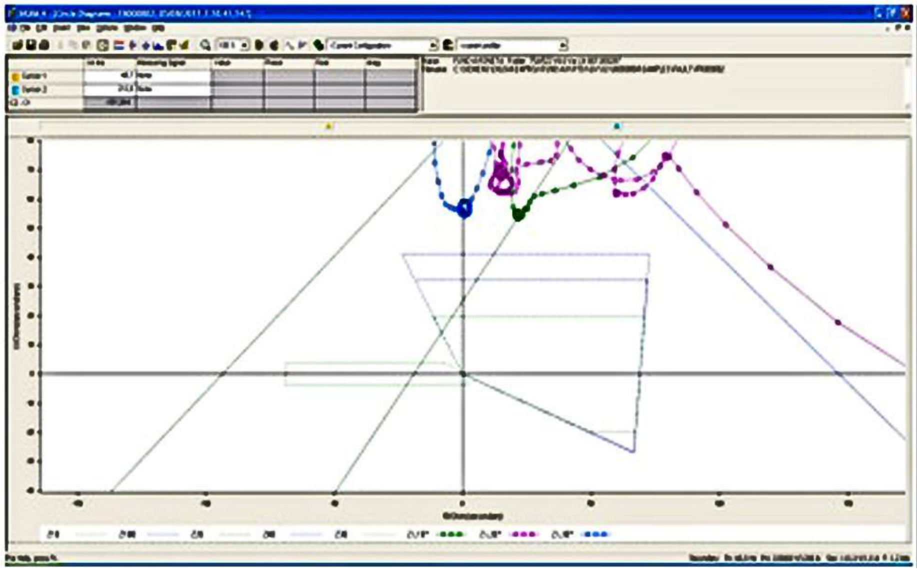


Figure 27. Apparent impedance trajectories as seen from Siemens 7SA522 of LN-807at FUN.

There were also problems with the labels of the reception signals of the directional comparison teleprotection scheme of LN-807 at FUN, because it was confirmed that the main protections at SMT did not send any teleprotection signal to the remote end. Although both relays, SEL-321 and Siemens 7SA522, saw the fault in the forward direction, they correctly blocked the communications-assisted tripping scheme for the current reversal phenomenon.

To correct the misoperations detected, new settings were recommended for MPs of this line bay. To assure no future malopeartions will occur for external faults, apparent impedance trajectories were estimated and the outcome is shown in figures 28 and 29.

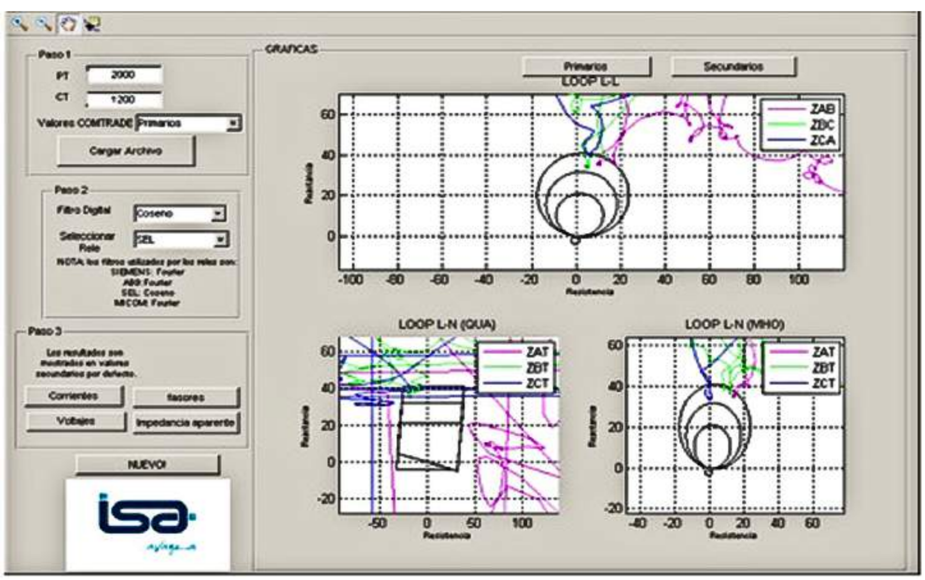


Figure 28. Apparent impedance trajectories estimated with new settings for SEL-321 of LN-807at FUN.

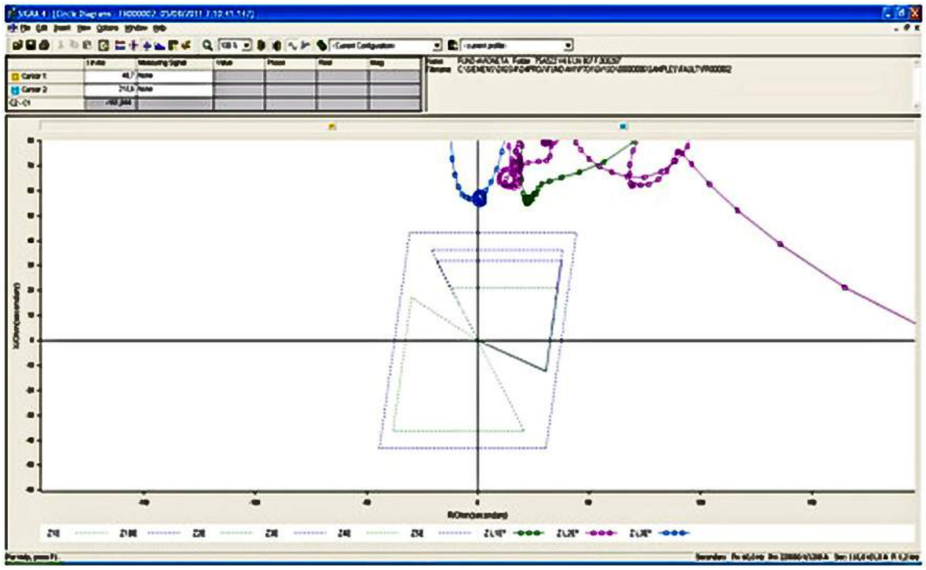


Figure 29. Apparent impedance trajectories estimated with new settings for Siemens 7SA522 of LN-807at FUN.

Line bay of LN-808 at FUN

For this bay relay Siemens 7SA522 (MP2) of circuit LN-808 at FUN also misoperated after it issued a single-pole trip for an external fault at moment 7 of the sequence. In this case, after the assessment of the apparent impedance on IMPAP it was found that the apparent impedance for phase C encroached under the relay zone 1 characteristic. For solving this problem the setting of the resistive reach of the quadrilateral ground distance characteristic adapted a value of 45% of the lowest load impedance of the transmission line.

Relay SEL-321 (MP1) received a permissive signal from the remote terminal and as its zone 2 element had operated, a three-phase trip command was issued. This operation was executed after a fault was detected during the dead time of the single-pole auto-reclosing initiated by the operation of MP2 237mS before, and as the three-phase reclosing was out of service the breakers did not reclose. The apparent impedance trajectories for BG and CA loops impinged on the border of the zone 2 impedance characteristic according to IMPAP. Regarding the trajectory for the AG loop in figure 30, it is clarified that the results on IMPAP were obtained after an interpolation and do not correspond exactly to the real trajectory during the event, which helped detect an improvement opportunity for the anti-aliasing filter of the software.

Since there was no event record from the relay SEL-321 (MP1) at SMT and additionally timestamps in the SOE were unsynchronized, it was not possible to confirm the sending of the teleprotection signal. However, using the event record of SEL-321 of the parallel circuit LN-807 at this same substation, it was found that this relay inhibited the sending of a carrier signal as a result of the blocking of the permissive tripping scheme during the condition of current reversal and it is then assumed that SEL-321 of LN-808 at SMT did not send any carrier signal, so the reception signal at FUN that originated the maloperation of MP1 might have been a noise in the protection signaling system.

Figures 31 and 32 plot the apparent impedance trajectories seen by relay Siemens 7SA522 and the one calculated with IMPAP.

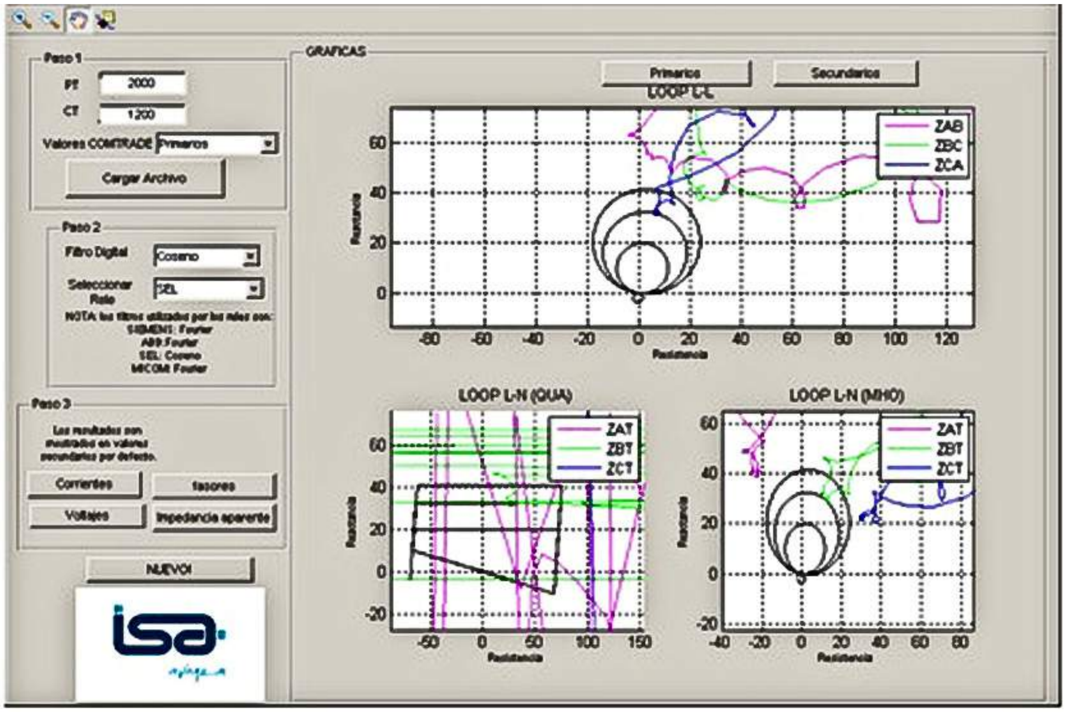


Figure 30. Apparent impedance trajectories on IMPAP for SEL-321 of LN-808 at FUN.

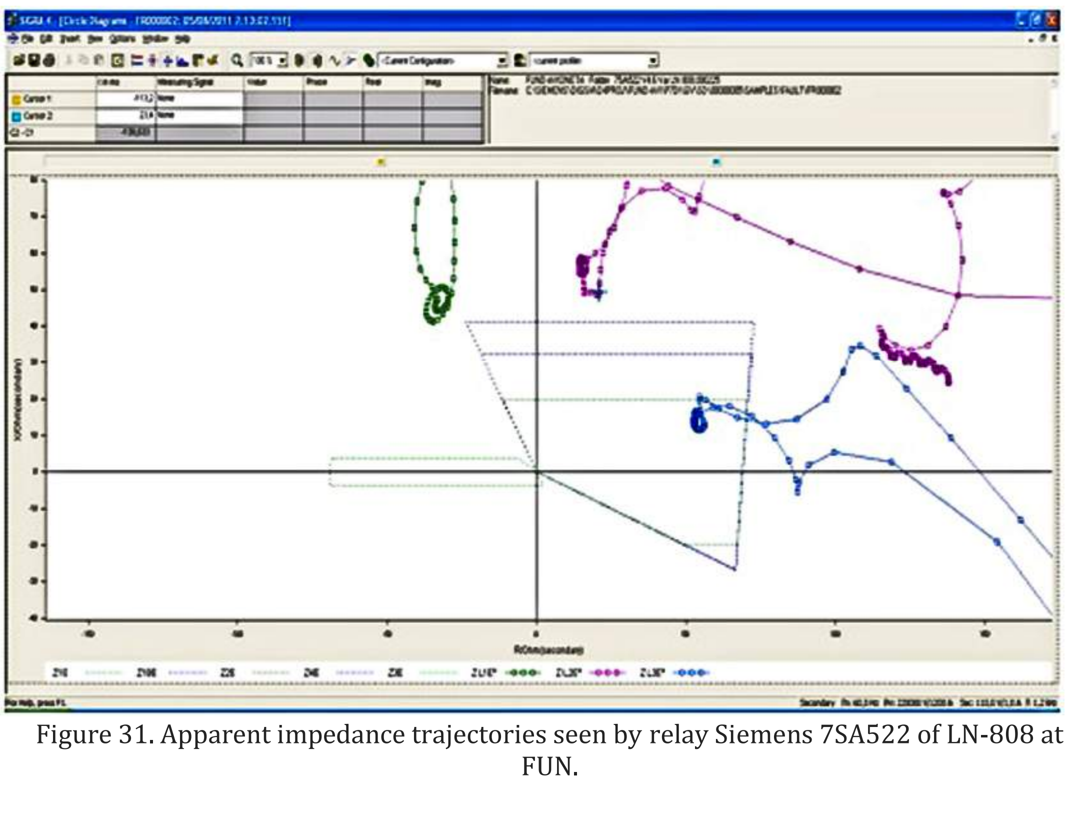


Figure 31. Apparent impedance trajectories seen by relay Siemens 7SA522 of LN-808 at FUN.

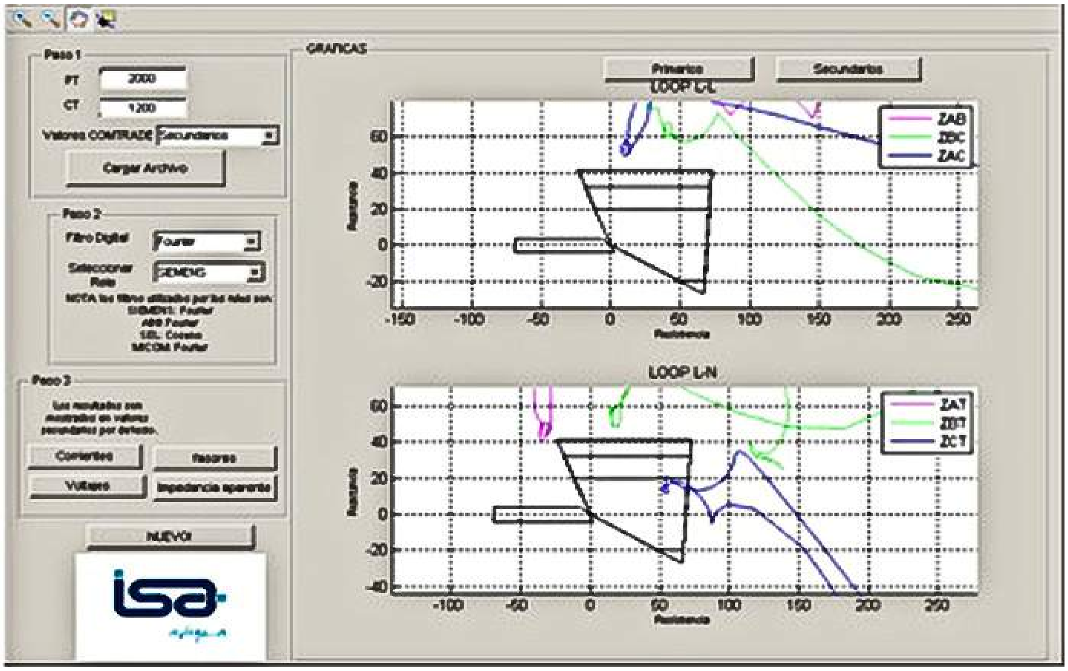


Figure 32. Apparent impedance trajectories on IMPAP for relay Siemens 7SA522 of LN-808 at FUN.

New settings for the relays of this line bay were calculated as well. The results of the apparent impedance trajectories on the IMPAP are as described in figures 33 and 34 for SEL-321 and Siemens 7SA522.

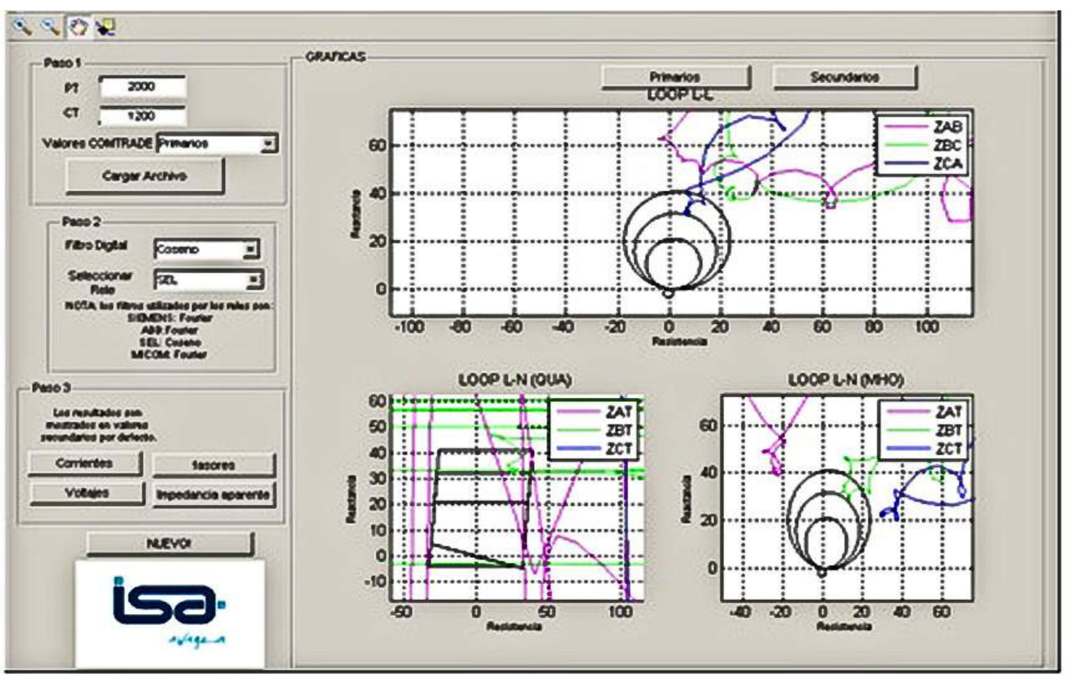


Figure 33. Apparent impedance trajectories estimated with new settings for SEL-321 of LN-808 at FUN.

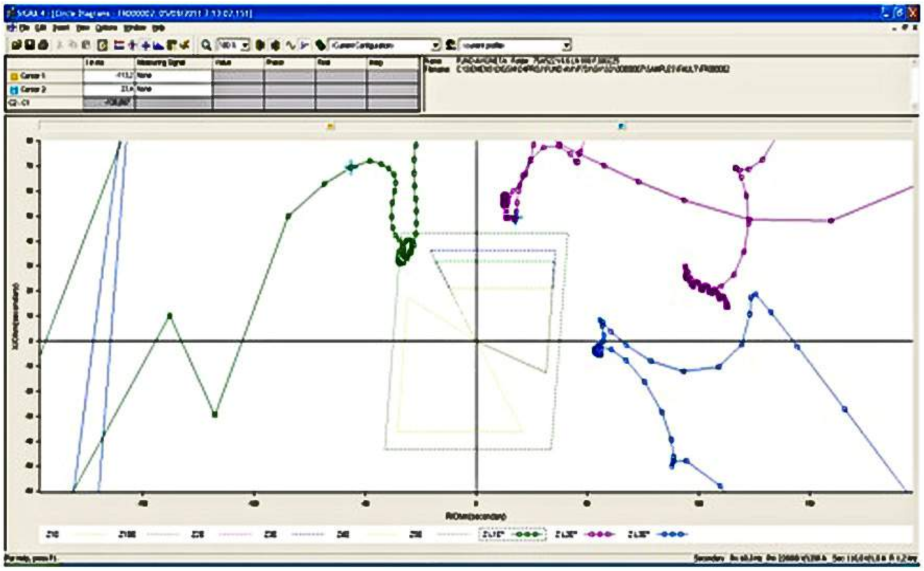


Figure 34. Apparent impedance trajectories estimated with new settings for Siemens 7SA522 of LN-808 at FUN.

Concerning the settings for the overcurrent relay of the capacitor bank, they were also modified so unbalance conditions do not make the relay maloperate again.

CONCLUSIONS

The reconstruction of the sequence and the evolution of a fault on transmission circuits LN-815 and LN-814 between Santa Marta and Termoguajira substations in the Colombian power system caused by a light aircraft crash into the power lines was made possible thanks to the analysis of sequence-of-event (SOE), digital fault recorder (DFR) and relay records.

Post-fault event analysis is very important for the detection of misoperations of protection schemes. In this analysis, maloperations of protections schemes at Fundación substation were detected and solved after main protections of line bays of circuits LN-807 and LN-808 that interconnect this substation to Santa Marta substation operated for an external fault on power lines LN-815 and LN-814.

Assessment of the protection schemes can lead to setting changes in order to improve the transmission system reliability and stability. With the new settings calculated for protections at line bays and the capacitor bank bay at Fundación substation, it is expected that those relays do not misoperate again for external faults.

Post-mortem analysis of disturbances on transmission lines obtains better results if complete, accurate and detailed information is available. When there is no information provided assumptions have to be made based on the data at hand.

There were no abnormal frequency or voltage excursions on the power grid during this disturbance and electricity supply in the area was not affected after the tripping of the circuits Santa Marta – Termoguajira 1 and 2 220kV and all other bays affected.

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REFERENCES

[1] Outage Incident Report 11032011, SIGO ISA TRANSELCA, August, 2011.
[2] Maintenance Report GPR-00441, Departamento Gestión del Mantenimiento, ISA TRANSELCA, August, 2011.
[3] System Disturbance Report Documento XM CND 2011 164, Dirección Aseguramiento de la Operación, XM, September, 2011.
[4] Technical Document GT-GO827, Dirección Gestión de la Operación, ISA, December, 2011.

BIOGRAPHIES

Pedro Lozada received his Bachelor's degree in Electrical Engineering from Universidad del Norte in Barranquilla, Colombia in 2008. Since that year, he has been working at Interconexión Eléctrica S.A. E.S.P. (ISA) in Medellín, first as an Engineer in Training and then, for the last two years, as a Junior Engineer in the group of fault and disturbance analysis of the transmission network. He is currently pursuing a specialization in transmission and distribution systems at Universidad Pontificia Bolivariana.

Sadul Urbáez received his Bachelor's degree in Electrical Engineering from Universidad industrial de Santander in Bucaramanga, Colombia in 1994 and a Master's degree from the same university in 1998. He has been working at Interconexión Eléctrica S.A. E.S.P. (ISA) in Medellín since 1997 and he is currently a Senior Engineer in the Operation Department at ISA.