Power System Cascade Event in a 230 kV Grid by Power Generators Loss of Field

J. Piñeros, D. Echeverri, J. Llano, L. Agudelo, F. Montaño, G. Gutiérrez, T. Rivera

***Abstract*— Loss of field in power generators is a possible phenomenon that can occur in power plants. ANSI 40 protection function has the responsibility to detect loss of field condition and to trip the power generator to avoid a possible operation as a motor. Typically, power generators protection system is designed to have always a redundancy and local backup of all the protection functions. Two protection relays are including and considering power supply redundancy. The ANSI 40 protection functions normally does not have a remote backup in the transmission lines connecting power plant with the high voltage power system substations. In the case of a double contingency level failure of power supply of the power plant, ANSI 40 protection function will be out of service and the power generator could be exposed to high risk of motor operation condition if opening emergency systems are unable to open in a short time the generator circuit breakers. This work presents a detailed real post-disturbance analysis and its conclusions in the Colombian power system where a section of the 230 kV power system experimented a sequential undervoltage phenomenon caused by the loss of the field in the generators of a power plant. Finally, a discussion is presented around of the double contingency level of failure in the power plant power supply and how it is necessary to rethink to back up the ANSI 40 protection function to avoid a major cascade power system event.**

***Index Terms*— Loss of field, generators, redundancy, local backup and motor operation condition Protection Schemes Performance, Disturbance Analysis, EMTP/ATP Simulation.**

I. Introduction

Major power system events need to be analyzed in detail to provide feedback for protection coordination improvements including the philosophy and the criteria applied. According to experiences in several countries [1], some blackouts events are related to coordination protection issues and the lack of quality in the protection system design and settings. There are several issues associate to effective backup protection and redundancy to avoid high impact of the power system events when the level of contingencies is increasing and leading to possible blackout events.

According to NERC, State of Reliability 2018, incorrect settings/logic/design, relay failures/malfunction and communications failures are more than 50% of the causes of problems in protection coordination in power system events in the EEUU power system [2].

Considering the previously context, this paper presents, in the first part a detail description and analysis of a loss of DC power supply in a hydro power plant, connected to the 230 kV Colombian power system. Because of DC loss, simultaneously loss of field phenomenon was observed in two hydro generators, creating a high reverse reactive power and a voltage sag during several seconds.

In the second part of the paper a further analysis is presented based on DIgSILENT Power Factory RMS simulations to understand the behavior of the variables observed in the COMTRADE files of the protection systems. Based on the analysis, protection performance questions are clarified considering the point of view of the independent system operator.

In the third part of the paper a discussion about remote location backup protection is proposed. The discussion is focused on the philosophy of the backup considering a major level of contingency because a loss of redundancy at the same location. A new setting criterion for zone 3 of distance relay in the bay of the connection line of the generator transformer group at the side of the power system. This zone is set in the direction of the power generator transformer group and it will allow to have protection backup for loss of field from generator.

Finally, lessons learned are giving as a findings and recommendations to avoid the phenomenon observed in this paper and to reduce protection miscoordination. The recommendations are focused on the reliability of the protection system, coordination between generators control limiters - protection and in reducing the risk of a major event impact when DC power supply is loss in a power plant with the focus on redundancy.

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Presented at the 2019 Georgia Tech Fault and Disturbance Analysis Conference April 29-30.

II. Network and Initial Disturbance Description

A. System Summary

The Fig. 1 shows a 230-kV section in the Colombian network with some substations named as Sub (Substation) TS, Sub SB, Sub BN, Sub AL, Sub IB, MC and Sub JM. Sub TS, BN, AL, JM and IB contain several transmission lines, which are part of the connection of this area and the Colombian System.

The QB power plant has a total generating capacity of 396 MW with two hydro generators of 198 MW, each of them connected to Sub TS through a single transmission line of 2.7 kilometers. Whereas, the Sub BN with main and transfer busbar scheme has three hydro units each of them of 180 MW.

In addition to the connection between substation TS and QB power plant, this substation is connected to substations AL, JM and BN through transmission lines with a length of about 50 km, 46 km and 264 km, respectively, as is shown in Figure 1.

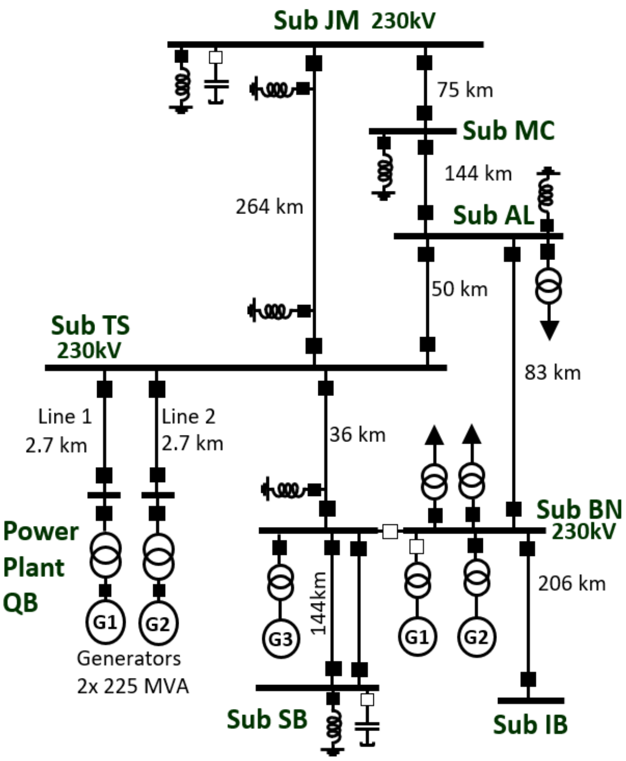

Fig. 1 Power system network – area of the event

B. Operational Conditions and topological considerations

Before the event the QB plant was generating about 360 MW with both units synchronized on the system, while units 2 and 3 connected to Sub BN were generating about 60 MW each, and unit 1 was out of service.

Complementary to the generation units reactive power production/absorption, Voltage-Reactive Controls (VRPC) were operative in substations SB and JM to regulate voltage at this area. In Sub SB was connected a 25 MW reactor while three shunt reactors were in service in Sub JM.

Additionally, in substation BN the main bus at 230 kV was operating in two sections because the busbar protection was not in-service due to maintenance. Considering operation reliability requirements in section 1 were connected unit 2 and the bay lines to Sub IB and Sub AL, while bays lines to Sub SB and Sub TS and the unit 3 were connected to section 2.

C. Event Description

Disturbance recordings from the lines that connect the substation TS to the substations AL, JM and BN indicated a progressive increase in the three-phase current amplitude without a significative variation of the zero-sequence current, as is showed in Figure 2. The maximum phase current variation was of 4 times the pre-event value (measured on the line bay to Sub BN in Sub TS). The phenomenon was also characterized by a voltage magnitude reduction in the area, reaching a value of about 0.7 p.u. after 1 second in Sub TS.

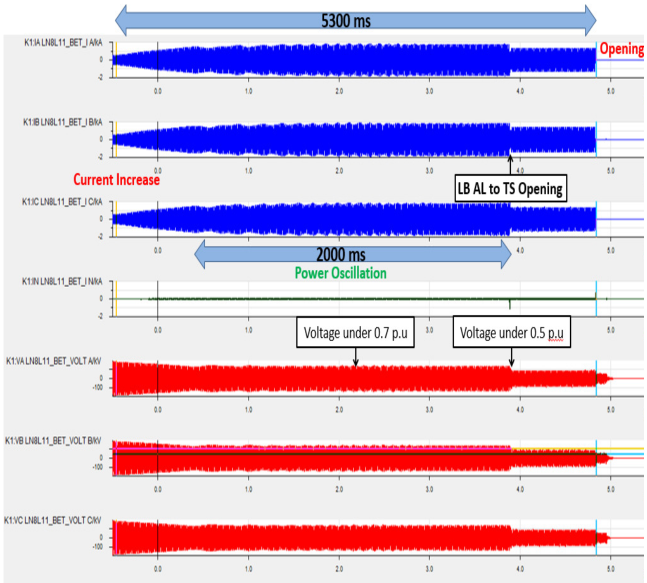

Fig. 2 Fault record - currents line bay 1 at Sub TS to Sub BN

Supplementary to the voltage and current variations detected, the behavior of the apparent impedance and the power measured on the line bays in Sub TS, after the current increases, show a reduction in the active power flow and a rise in the reactive power in the direction of the Sub TS and QB hydro units (see Figure 3).

The increasing of the reactive-power absorption by the QB hydro generator and the consequent undervoltage phenomenon was produced by a double contingence failure of the DC power supply in the QB power plant. This problem caused the loss of field and the unavailability of the generator protection systems associated with both units. The loss of field leads the generators from synchronous to asynchronous operation, producing a reactive-power absorption of about 600 MVAr as is shown in Figure 3.

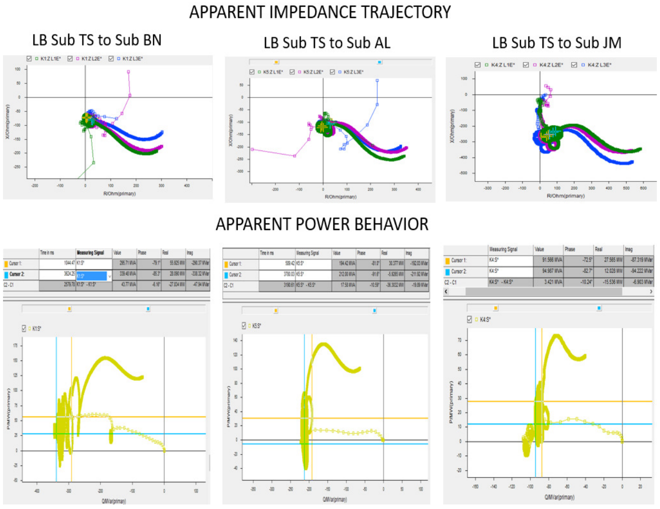

Fig. 3 Apparent impedance and power behavior

D. Preliminary Analysis

The summary of protection and control operation caused by the disturbance according to the revision of the Sequence of Events (SOE) and trip logs of the protection relays is described in the Table 1. It also considers tripped protection functions and final opening times.

Table 1 Operations after the current increase

Time*	Element	Operation	Function	System condition
1.300 s	BN unit 3	Pick-up	ANSI 21G T3>	Q 293 MVar P 102 MW
2.514	Reactor 1 and 2 Sub JM	Opening	VRPC control	-
4.147 s	25 MVAr Reactor Sub SB	Opening	VRPC control	-
4.365 s	BN unit 3	Opening	ANSI 21G T3>	P 60.7 MW Q 343 MVar
4.370 s	LB AL to TS 230 kV	Opening	ANSI 21 zone 3	I 759 A V 0.8 p.u.
5.279 s	Reactor 3 Sub JM	Opening	VRPC control	-
5.300 s	LB BN to TS 230 kV	Opening	ANSI 21 zone 1	I 1005 A V 0.54 p.u.
5.428 s	LB JM to TS 230 kV	Opening	ANSI 21 zone 3	I 884 A V 0.93 p.u.
5.400 s	LB TS to QB 1 230 kV	Opening	ANSI 27	-
6.289 s	Capacitor 3 Sub SB	Connection	VRPC control	V 1.067 p.u.
6.577 s	Capacitor 3 Sub SB	Opening	ANSI 59	V 1.113 p.u.

*Reference time is taken from the beginning of the current rise.

Distance protection in unit 3 of Sub BN power plant was picked-up after its predetermined current threshold was exceeded, because of the increase of its reactive power injection to compensate the undervoltage phenomenon. Impedance function stages zone 1 or zone 2 were not picked-up, but this protection tripped after the time delay of the current stage T3 was accomplished and disconnected the unit 3 when the reactive overload was greater than 500% of its rated capacity.

Although, unit 3 and 2 in Sub BN power plant were synchronized to the system during the undervoltage condition, the reactive power injection and the consequent current rise was worse in unit 3 due to lower electrical impedance connection path to the TS substation (Fig. 4).

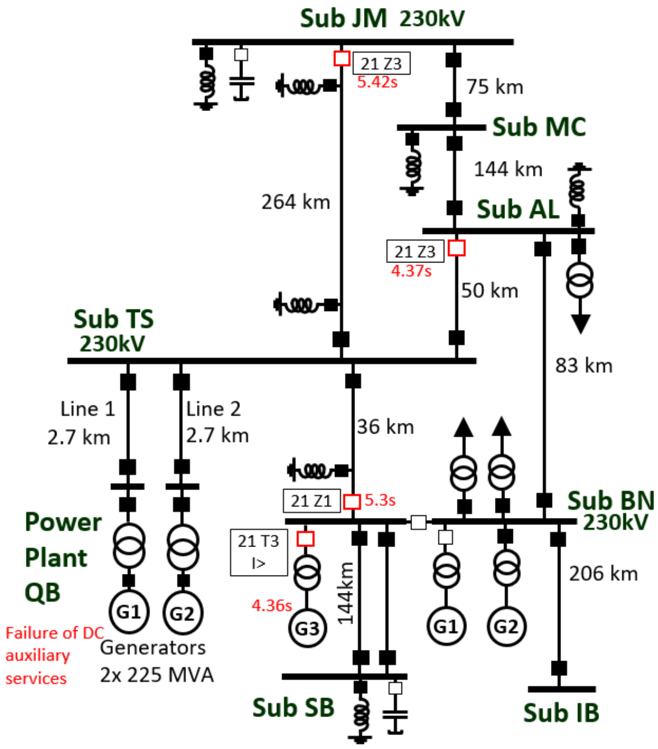

Fig. 4 Sequence of openings until the clearing of the phenomenon

Distance protection zone 3 in 230 kV line bays Sub AL to Sub TS and Sub JM to Sub TS tripped due to the current increase and the voltage reduction caused by the loss field in QB units. However, in the case of line bay BN to TS, after the disconnection of line Sub AL – Sub TS 230 kV and BN unit 3, the voltage measured was under 0.6 p.u., and the apparent impedance trajectory entered the zone 1 distance relay-operating characteristic, tripping this protection.

Additionally, during the undervoltage condition the VRPC disconnected the reactors 1, 2 and 3 in Sub JM and the 25 MVAr reactor of the Sub SB, as well as connected the capacitor bank of 60 MVar in Sub SB.

After the opening of the line bay Sub JM to Sub TS, the 230-kV substation TS was isolated from the system, and the bay lines Sub TS to Sub QB 1 and 2 were disconnected by their undervoltage protections. The 230 kV Substation TS isolation caused transitory overvoltage, which was controlled by the action of the control and protection systems.

The Table 2 describes a summary of protection stages that tripped during this phenomenon. The typical setting used in Colombia and relevant findings are also presented.

Table 2 Protection Function Operation and Findings

Function	Typical setting	Findings
Generator Impedance pick – up (ANSI 21G T3>)	I pick-up: 130% generator rated current Undervoltage seal-in: 70% rated voltage Intentional Time delay: 15 second	The intentional time was set up in 3 seconds, disconnecting the unit 3 in BN power plant before the generator reactive limiters operation.
Distance In Transmission lines (ANSI 21)	The forward reach characteristics in this function is setup as: $Z_1 = (70\ to\ 90\ \%) * Z_L$ $Z_2 = \text{Max}(120 * Z_L,\ Z_L + 50\%\ Z_{SAL}, Z_L + 80\% * Z_{eqTRF})$ $Z_3 = \min(Z_L + 80\% * Z_{eqTRF},\ 1.2 * (Z_L + 50\%\ Z_{LAL,})$ Z_L Protected Line Impedance Z_{SAL} Imp. Shorter Adjacent Line Z_{LAL} Imp.Longer Adjacent Line Z_{eqTRF} Equivalent Imp. Transformers	Most of these relays tripped by this function because the current increase and the undervoltage condition were identified as a three-phase fault condition into zone 3 or zone 1 and it was a backup protection operation because of relays of lines 1 and 2 Sub TS - Sub QB 230 kV did not tripped.
Distance In Power plant connection lines (ANSI 21)	This function detects a fault condition in the line with three zones, two forward zones and one reverse zone. $Z_1 = (70\ to\ 90\ \%) * Z_L$ $Z_2 = Max\ (120 * Z_L,\ Z_L + 80\% * Z_{equTRF})$	The relays in line bays Sub TS to Sub QB 1 and 2, did not tripped during the undervoltage phenomenon, because their zone 1 and 2 reach did not allow them to detect it.
Loss of field in generator (ANSI 40) [4]	$40_{Z_1} = \frac{\mu_n}{\sqrt{3} * I_{Ngen}} [\Omega]$ $40_{XZ_1} = \frac{-X'_d}{2} [\Omega]$ $40_{Z_2} = X_d [\Omega]$ $40_{Z_2} = \frac{-X'_d}{2} [\Omega]$ $T_{XD1} = 0\ s,\ \ T_{XD2} = 0.5\ s$	The relays in unit 1 and 2 of QB power plant were without DC power.
Overvoltage capacitors banks (ANSI 59)	This function detects overvoltage conditions.	The relays in Sub SB tripped because of the transitory overvoltage condition in this substation after substation TS Insolation.

III. Further Analysis

After the preliminary analysis of the phenomenon of the loss of field of QB power plant hydro generators some questions were still open. The questions were:

- Why did not DC power supply redundancy operate as designed at QB Power Plant?
- Why did QB hydro generators remain connected to the power system more than 4 after their excitation system were lost?
- Why the adjacent protection system in the transmission lines at the side of the TS substation was not an effective backup for the abnormal condition?
- Did the zone 3 at the line bays in substations JM and AL to substation TS operate correctly?
- Did the zone 1 at the line bay in Sub BN to Sub TS operate correctly?
- What is the cause of the oscillation observed in the currents at the line bays of the substation TS?
- Was the trip of the unit 3 at substation BN adequate?

A. Redundancy of the DC power supply

Question 1, after detailed analysis of the DC power supply loss, it was found that after a failure in the 125 Vdc system the charger of the battery system had a delay to transfer the DC power (failure in the dromping diodes calibration caused by a voltage protection) led to the total loss of the 125 Vdc system at the power plant QB.

B. Power Factory DIgSILENT Simulations

In order to answer the other questions (2 to 5) the entire data base model of the Colombia Power System in Power Factory DIgSILENT was used to perform an RMS simulation. This simulation considered the loss of field of Generators 1 and 2 at QB Power Plant at t=0.1.
Considering the network described in Fig. 1, some variables were analyzed to understand the behavior of the electrical phenomenon observed in this event.

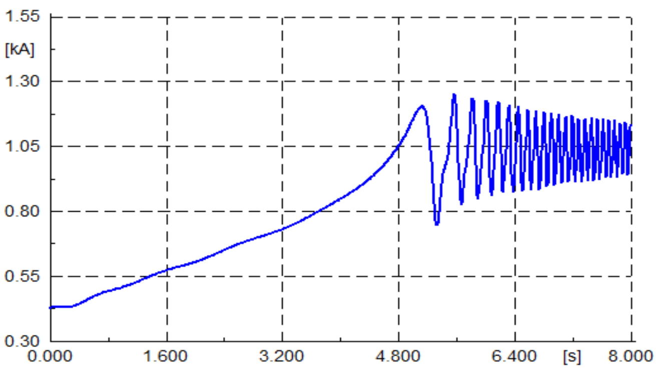

Fig. 5 Magnitude of Current in the line 1 Sub TS – Sub QB 230 kV

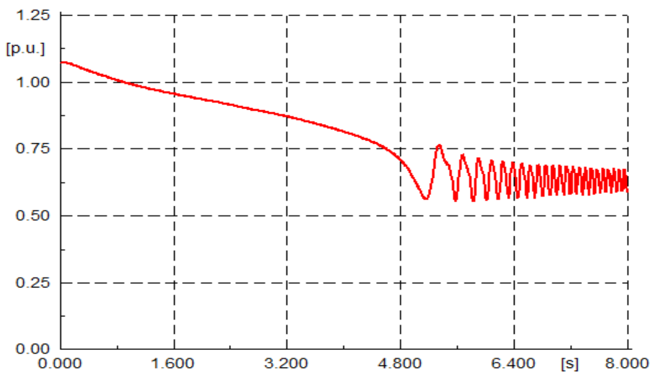

Fig. 6 Substation TS 230 kV Voltage Magnitude

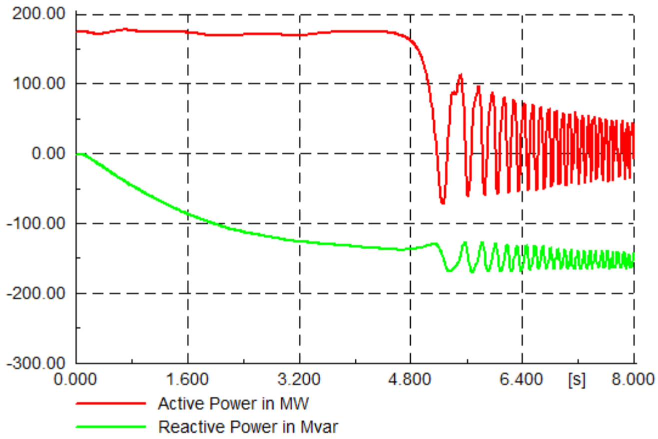

Fig. 7 Power Observed at the line bay 1 Sub TS to Sub QB

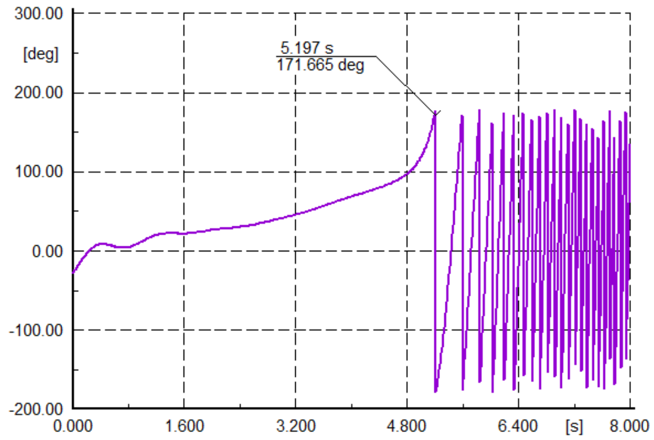

Fig. 8 Generator 1 Angle with reference of machine system slack

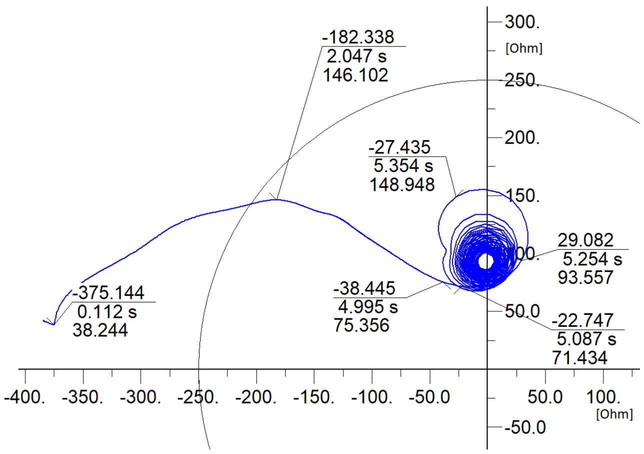

Fig. 9 Behavior of the impedance at the line bay 1 Sub TS to Sub QB Power Plant

Based on the simulation results and the analysis of the key variables the following points were identified.

- During the phenomenon observed two power hydro generators with loss of field remained connected to the power systems for more than 4 seconds. The current to the power plant QB, see Fig. 5, experimented an increase in an overload region (not a short circuit region) due to the reactive-power increment as is shown in Fig. 7. The generators at QB power plant began a transition from synchronous to asynchronous operation.
- The voltage reduction at substation TS, see Fig. 6, was caused by the amount of reactive-power required by the generators at the QB power plant, operating as asynchronous generators.
- Some seconds after of the loss of field, the simulation indicates that the generator rotor angle could reach an out of step condition and subsequent pole slips as is shown in Fig. 8 (answer to the question 6).
- The apparent impedance measured by the distance relays in the line bays 1 and 2 at TS substation to power plant QB shows that the generators moved to a loss of field impedance area as is shown in Fig. 9.

Considering the previous points and the data of the simulation, the answers to proposed questions are detailed below:

Questions 2 and 3, after losing the DC power supply and consequently the protections schemes at the QB power plant, the remote backup protection at the line bays 1 and 2 at TS substation were not able to identify the abnormal condition, because of the distance protection function settings. Two stages (zone 1 and zone 2) were setup with a maximum of 80% of the generator power transformer impedance, with that setting it was not possible to detect the abnormal condition in the generators as it is shown in Fig. 9.

Question 4, under a low voltage condition in the area of the event, distance protections at the remote line terminal of the TS substation started to detect the phenomenon caused by the generators 1 and 2 at QB power plant. Considering that both generators lost its field, from the power system point of view it was a virtual parallel failure, allowing zone 3 quadrilateral characteristics to detect the abnormal condition at substations AL and JM. The trip was then correct and the only backup available.

Question 5, the simulation shows that during the event both generators at power plant QB experimented several pole slips and they were operating as asynchronous machines, reaching in some moments motorization conditions, because of the oscillation between them and the power system due to the undervoltage condition. At substation BN, this condition and the fast change of voltage allowed the detection of the abnormal condition in zone 1.

The fast change of the impedance at line bay to TS at substation BN was a result of the trip of the generator 3 of the substation BN. This generator was tripped by the 21 T3 protection function which check the following conditions:

- Current Overload over 1.3 p.u.
- Time delay of T3 (setting was 3s)

The generator 3 at BN substation, at the moment of the trip, was around 190% in current, 1.0 p.u. voltage and reactive power was higher than 300 MVAr (over 400% of the capacity). The limiter of this generator had not been operated yet, showing that protections were not coordinated with the limiter (answer to the question 7). The trip of this generator is considered as miss coordination trip. A test performed to the limiter of this generator showed that the response time to reduce the power is around 3-4 seconds.

IV. Discussion About Power Plant Remote Backup

Considering the fact of the possibility of N-2 failure in an electrical system associate with protection systems and the impact of critical N-2 feasible events, Colombia Power System operator proposed to have a remote backup of the ANSI 40 protection function at the side of the transmission line that connects a power generator with the power system. For power system security the consequence of having a loss of field in all the generator of a power plant is a risk that must be covered due to high impact in the power system [3].

The proposed backup can be implemented as a zone 3 at the line bay in the direction of the power generator transformer group, covering a percentage of generator. Fig. 10 shows and example of the using a relay quadrilateral characteristic with the setting in X as the total impedance including the connection line, transformer and generator (zone 3).

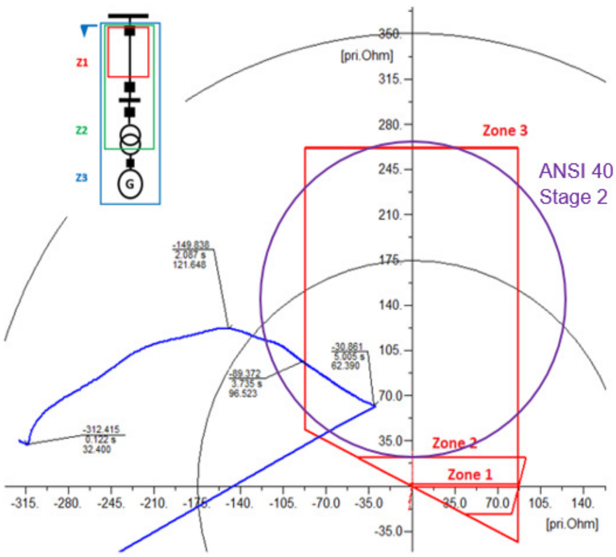

Fig. 10 Zone 3 for remote backup of generators ANSI 40 function

The value of resistive reach was calculated as the 45% of the minimal impedance of the load considering the total power of the generator transformer. The time delay of this functions must be estimated to avoid the pole slip of the generator if possible but checking the coordination with the ANSI 40 protection function considering:

- The ANSI 40 characteristic, external curve has to detect the impedance incursion before of the propose backup curve or characteristic.
- The margin time between ANSI 40 and the propose backup functions must be as minimum 500 ms.

For the case of this event, a time delay of 1.2 seconds provides a good margin to avoid a pole slip.

Considering the reactive reaching of the proposed zone 3, it is recommended to active the power swing blocking function – ANSI 68 for this zone, in order to avoid an undesired tripping under stable power swing conditions.

V. Findings and Recommendations

Post disturbances analysis identified very important findings and recommendations to improve the protection systems performance:

- In a situation of total loss of DC power supply leading to unavailability of the protection system of the power plant, the adjacent element (usually the transition connection line) must provide a suitable protection backup to avoid major power system disturbances.
- In power generators an adequate coordination between limiters time respond and protection operation times is required in order to reduce generator overload condition and avoid undesired disconnections.
- Power supply redundancy is an essential feature in power plants and it implies non-single point of failure design to reduce the risk of protection system unviability.

VI. Future Work

Because of the phenomenon observed in this event, it is necessary to work deeply about the concept of remote location backup. Every equipment of the power system needs a remote backup in a different location for all the major possible disturbances or failures. In power plants it is recommended to study the proposal of this paper about a backup of the ANSI 40 protection function and include it in the IEEE C37.246 Guide [5].

VII. Conclusions

For protection scheme selection in transmission lines that connected plants to the power system, it is recommended to consider functions or logics that provide remoted location backup for some generator key protection function, such as loss of protection function (ANSI 40).

Remote location backup functions require to meet some minimal features, such as coordination with the main function on power plant under normal and abnormal conditions, selectivity and adequate time delay setup to reduce effectively the disturbance impact on the power system.

Considering power plant to system connection characteristics, a remote location backup for loss of field protection (ANSI 40) is proposed. This backup is based on the protection functions available in a typical distance protection relay, and it uses the hybrid criteria applied for the loss of field and distance protection.

The power-reactive limiters include in the generator control must be coordinated with the protection in order to provide sequential tripping, allowing the generator to control the power output before undesired trip protection, especially when reactive power is required.

Effective redundancy in protection systems is key to avoid major disturbance events in power systems. For this reason, single point of failure needs to be analyzed to ensure that under real feasible failures the redundancy is not compromised.

Standards and technical guides need to consider the key findings in this post-disturbance analysis to include recommendations or examples to protection engineers to reduce the risk of similar events in the future.

ACKNOWLEDGMENT

The authors make acknowledge the participants and companies involved in this event for their efforts to improve the reliability of the protection systems and the security of the power system through hard collaborative work to understand the phenomenon occurred in this event and the necessary actions to be taken.

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