A Holistic Methodology Based on Disturbance Analysis for Improvements in Planning, Operation and Protection in the Colombian Electric Power System

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***Abstract*— Development of defense plans for the Colombian power system started immediately after a 2007 blackout and have continued during the last few years. This article presents a methodology based on extensive disturbance analysis to identify improvements in the planning, operations, and protection aspects of electric power systems. A number of the key contributions of this article include: the methodology developed and its potential application to other electric power systems, the identification of an optimum time frame for the review of past disturbances, new findings regarding power system phenomena and the prioritization of the recommendations based on the impact and the timeframe needed for its implementation.**

The disturbance analysis reports of past events were independently reviewed in order to find the root cause for each event and to identify potential issues associated to operations, planning, or system protection practices. Operations issues include human error during maintenance, deviation of planning criteria, improper maneuvers, among others. Protection issues include errors in protection settings, use of inappropriate settings criteria, lack of dependability of protection schemes, and system level phenomena that can be addressed by implementing System Integrity Protection Schemes.

The root causes of the events reviewed included N-2/N-3 events with correct relay operations but also relay misoperations and relay miscoordination. While, in general, protection standards in Colombia compare well with international best practices, the review resulted in a total of eight protection specific recommendations. The event reviews, observations and conclusions leading to these recommendations are presented in the paper.

***Index Terms*— Defense plans, disturbance analysis, protection systems, systemic protection, bulk power system reliability improvements.**

I. Introduction

In present times, expansion of Bulk Power Systems (BPS) has a number of multi-disciplinary challenges. Increasing environmental restrictions, uncertainty of economic global cycles, fossil resources depletion, and new technologies for generation/use of electric energy are important factors that affect the reliability of the BPS's. These factors and the stricter policies and regulations for increased reliability of the power systems have motivated more detailed analysis of electric power system vulnerability and development of actions to mitigate system collapses. These actions are usually part of defense plans and are aimed to preserve the bulk electric power system reliability. Defense plans consider a set of coordinated automatic measures intended to ensure that the overall power system is protected against major disturbances involving multiple contingency events, generally not caused by natural calamity or common system faults. Defense plans are used to reduce the severity and consequences of low probability unexpected events and prevent system collapse [1].

Defense plans for the Colombian power system started immediately after a 2007 blackout with a complete new training program for the operators in parallel with upgrading technology for the SCADA/EMS control center. In addition to this, relationships with the electric sector, including generation, transmission and distribution operators, as well as with regulatory agents, have been reinforced to provide clear signals for the need of enhance power grid reliability. As part of those actions, during the beginning of 2012 and until mid-2013, an international benchmark seeking the good practices in planning, operation and protection of the power system was developed. The countries selected for this benchmark were the United States, Canada and Sweden. The project identified a set of recommendations in the areas of power system planning, operation and protection, based on the perspective of the system operator considering current technical/operative restrictions of the system and the existing regulatory framework in Colombia.

The objective of this article is to share with the industry at large the methodology developed during the 18 months duration project which initiated with an international benchmarking, continued with a detailed review of 64 events that affected the reliability of the Colombian electric power system, and provided tailor-made recommendations for improvements in planning, operations, and protection aspects that are needed to improve reliability [2].

One of the key contributions of this paper is the methodology and its potential application to other similar electric power systems in North America or in other countries to perform a similar disturbance analysis review and identify recommendations aimed to improve the reliability of the bulk

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electric power system. A second contribution is the finding that for a holistic review of past disturbances, 5 years back into the history, was proven as an optimum time for this type of endeavor. A smaller time period of 1-3 years would lack enough sample data and a period beyond 5 years would probably contain a power system state that would no longer represent the current operating conditions. A third contribution is related to new findings discovered during the 64 events detailed review, such as power system phenomena like out of step conditions and voltage instability. Additional transient stability simulations were required to demonstrate the conditions that were identified by reading power system disturbance reports. This uncovered phenomenon represents an area for which new remedial actions may need to be added to the current defense plans. A fourth and final contribution is the prioritization of the recommendations based on the impact and the timeframe needed for their implementation.

In order to achieve the objective, Section II of this article provides a high level overview of the national electric power system in Colombia, including its key transmission and generation characteristics as well as the bulk market structure. Section III presents a summary of the methodology developed for the disturbance analysis including the timeframe of analysis, criteria for events selection, analysis of events and reporting of findings. Section IV presents operational, planning, and protection related findings and recommendations. Section V presents a summary of one of the 64 disturbances that were analyzed. Finally the lessons learned and next steps are summarized in Section VI in which a number of the initiatives that follow these studies and work, are presented and discussed[1].

II. Colombian Interconnected Power System

The Colombian power grid is composed by 24392 km of transmission lines with voltage levels from 110 kV up to 500 kV, distributed as shown in Table 1. The system has an installed generation capacity of 14361 MW (at the end of 2012), dominated mainly by hydroelectric sources. The generation portfolio of the Colombian power system is also shown in in Table 1.

TABLE 1: KEY TRANSMISSION AND GENERATION CHARACTERISTICS OF THE COLOMBIAN ELECTRIC POWER SYSTEM.

Voltage level	Length (km)
110 - 115 kV	10,268
138 kV	15
220 - 230 kV	11,672
500 kV	2,437
TOTAL	**24,392**

Resources	MW (2012)	Participation
Hydro	9,185	64.0%
Termal	4,426	30.8%
Small generators	693	4.8%
Cogenerators	57	0.4%
TOTAL	**14,361**	**100.0%**

Regarding the bulk market structure of the Colombian power system, as described in Fig. 1, XM is in charge of operating the national interconnected power system and administering the wholesale electricity market through the national dispatch center (CND is its acronym in Spanish).

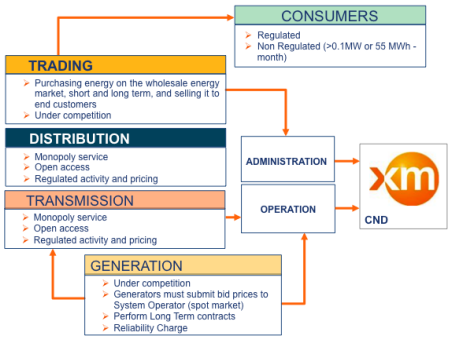


Fig. 1. Bulk market structure of the Colombian power system

The operation of the Colombian power system includes analyzing disturbances or events which cause certain impacts into the system according to the current regulations. In addition to XM's analysis, this activity also incorporates the investigations done by every agent involved in the disturbances [3], [4] and [5]. This is a collaborative effort to find the root cause of the disturbances and to define the actions to solve the associated problems.

III. Methodology

This section presents the methodology developed for disturbances analysis that was applied during the previously described benchmarking project. For this methodology, sixty-four (64) disturbance analysis reports for key events in the Colombian system were selected. Fig. 2 shows a high level sequence of the methodology that is further described next.

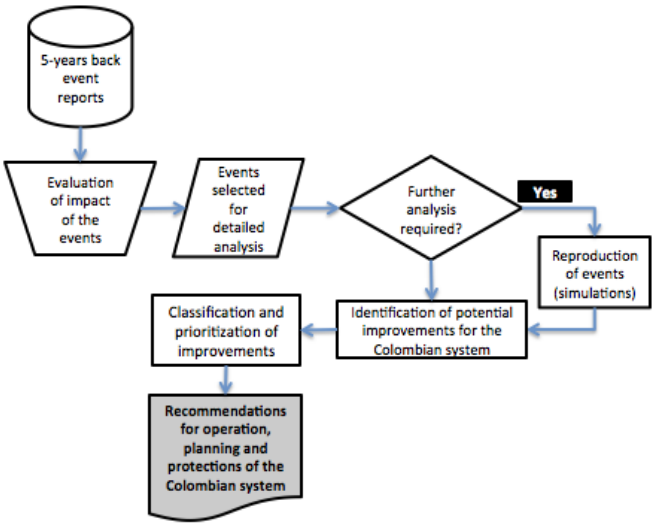


Fig. 2. Methodology overview

A. Timeframe of Analysis

This was the first parameter to select the group of events for further analysis. Based on a holistic review of past events 5 years back into the history was chosen. A past-time window of five years provides enough sample data to define potential

[1] The basic information for this article was taken from XM S.A. E.S.P Compañía de Expertos en Mercados under authorization and does not constitute confidential information of its customers or the company. The article presents the opinions of the authors and does not compromise XM's positions.

improvements for protection and operations in the Colombian power system, allowing the identification of events recurrence and trends. Although a longer time frame could give further detail, it is possible that the recommendations found would not have been applicable to the current grid due to changes of both system topology and protection schemes. A smaller time period of 1-3 years lacked enough sample data.

B. Criteria for Events Selection

Considering hundreds of events that occurred during a past-time window of 5 years, 64 events were chosen based on their impact on the Colombian power system. This impact was determined by evaluating the following characteristics: a) total or partial voltage collapses; b) severe frequency deviations; c) loss of big generation sources; d) unscheduled loss of load; e) disconnection of interconnection transmission lines to other countries. This criterion for events selection seeks the identification of issues for the Colombian electric power system from a systemic perspective.

C. Event Analysis

The disturbance analysis reports of the past 64 events were independently reviewed in order to find for each event its root cause and identify potential issues associated to operations, planning, or system protection practices. Operations issues include human error during maintenance, deviation of planning criteria, improper maneuvers, among others. Protection issues include errors in protection settings, use of inappropriate settings criteria, lack of dependability of protection schemes, and system level phenomena that can be addressed by implementing System Integrity Protection Schemes (SIPS) [6].

D. Additional Power System Simulations

A subset of the 64 events was selected and classified as a potential source for reliability improvements. A key characteristic of these events is the fact that with additional analysis based on simulations more findings around the root cause of the disturbance can be obtained; for example, the angular evolution of the system if Phasor Measurement Units (PMUs) were available that would mitigate the effect of the disturbance. This is one of the most significant contributions of the methodology as it allows testing the identified recommendations after event analysis in a simulation environment. For instance, the evaluation of the angular stability and voltage collapse performance of some parts of the system when a PMU-based SIPS operates after a contingency that separates two systems.

E. Inventory of Recommendations

In this step of the methodology, the recommendations are classified and organized based on the preceding technical analysis in three main groups: operations, planning, and protection. The recommendations are prioritized based on its level of severity (high, medium or low) and the expected time frame of implementation (long, medium or short term). The total number of recommendations classified by order of severity and time of implementation are shown in Table 2

TABLE 2: CLASSIFICATION OF RECOMMENDATIONS BASED ON IMPACT AND IMPLEMENTATION TIMEFRAME

Term	**Impact**		
	High	Medium	Low
Long	4	0	2
Medium	0	7	0
Short	12	1	1

The first set of recommendations, *Low Impact/ Short Term*, refer to those recommendations that can be immediately implemented into the Colombian power system as the regulatory requirements and current engineering practices are aligned. This represents an immediate set of recommendations that can be done with relatively minor effort. The second set of recommendations, *Medium Impact/Medium Term*, indicate recommendations that should be analyzed and discussed on a technical level in different technical committees and councils inside Colombia with the objective of arriving into a consensus prior its implementation. Finally, recommendations *High Impact/Long Term* require major collaborative efforts to be implemented, such as changes in regulatory requirements and changes in expansion planning criteria.

IV. OBSERVATIONS AND RECOMMENDATIONS

This section presents a sample of the observations and recommendations for operations, planning and protection practices.

A. Operations and Planning

A total of five observations and recommendations are summarized next.

1. *Performance requirements and expected reliability level improvements.*

A formal documentation of the system impact of contingencies related to the following causes is needed: a) bus bar and bus configurations; b) tower collapse resulting in the disconnection of two circuits; c) a stuck breaker. It is recommended to apply the definition of these types of contingencies within the context of power system planning and operation criteria and document the strength and limits of the Colombian system. After classification and documentation of the limits of the system, it is recommended to estimate the economic benefits of planning and designing the electric system to meet Category A, B, & C based on North American Electric Reliability Transmission planning Standards [7]. If the additional power system capacity does not have a reasonable cost/benefit ratio further emergency controls need to be developed as these controls can increase power system reliability without a major infrastructure investment. The results of the previous activities and studies will also be used to propose needed regulatory updates.

2. *Documentation of system level phenomena*

A number of system level phenomena such as out of step conditions and voltage instability were found during the subsequent analysis and re-creation of the disturbance sequence of events (previous section D). Out of step conditions occurred among different areas within the Colombian system as well as between Colombia and Ecuador interconnected electric power systems. Voltage instability was identified in the southern part

of the Colombian system under specific operating conditions. These phenomena should be fully documented in the disturbance reports. In several of these events, the current under frequency load shedding scheme was not able to avoid system collapse as the root cause of the events was not a generation / load unbalance but an out of step condition which led to voltage collapse. Therefore, additional defense plans, such as SIPS based in generation rejection should be developed.

3. *Power system operators role in power transmission expansion planning*

Currently in Colombia, the power system operator provides indicative recommendations to the national planning authority that is in charge of power transmission expansion planning. While the interaction among the two entities has worked very well, keep the link among the power system operator and the planning authority is strongly recommended in order as to close the loop between the power system operation challenges and the transmission expansion planning activities. The benchmark identified a strong role of the power system operator in transmission expansion planning in other countries such as United States of America, Canada, Norway, Sweden, and New Zealand. Additional responsibilities and roles of the national transmission planning authority in the national operations council were identified as the vehicle to establish the needed formal and regulated link.

4. *Operations and planning criteria*

The sequence of events as documented in a number of the events revealed violations to the current planning and operation criteria, for example tripping load under N-1 conditions. While these events are rare, it is a clear sign of some delays in power system expansion. It is recommended to include in the event reports written by the power system operator a clear statement in cases when events appear to be violations to the planning and operations criteria. This should enable the power system operator to have more influence in long-term transmission planning expansion.

Specific recommendations for improvements in planning and operating criteria include: a) the power system operator should consider three levels of thermal limits: normal, long-term emergency, and short-term emergency in order have more leverage and room for maneuver; b) the strength of the power system shall be verified against the loss of the largest single contingency for transformers, transmission lines and generation units; c) electric system should be designed to withstand the loss from the largest single contingency; d) the power system operator should maintain enough reactive resources to support its voltage under first contingency conditions. The impact on reliability and economics of these recommendations should be evaluated and regulatory modifications, as needed, proposed.

5. *Allocation of Automatic Generation Control (AGC)*

The power system operator should propose regulatory modifications in order to avoid the allocation of automatic generation control to only one or two machines in order to minimize the risk of losing a single machine and therefore losing a major portion of the AGC function from the power system. The regulatory modifications should include dividing the AGC based on the power system operating regions as it is the case in other countries [8], [9], [10].

B. Relay Protection

Root causes of the 64 events reviewed included N-2/N-3 events with correct relay operations, but also relay misoperations and relay miscoordination. While in general, protection standards in Colombia compare well with international best practices, the review resulted in a total of eight recommendations:

1. *Events caused by human errors*

While human errors are inevitable, there are measures that can be implemented to minimize its occurrence. The events observed in the study caused by human errors largely involved maintenance where relays tripped incorrectly due to wiring or switching errors. The majority of these involved maintenance in main and transfer bus substations, and while not directly a result of relay misoperations as such, the errors could have been avoided by simpler protection schemes where relay trip signals, or bus protection disconnector switch inputs would not need to be isolated or rerouted during maintenance work.

2. *Event reports, fault analysis and time stamps*

While again not directly a protection system issue, the importance of event reports and correct time stamps were evident from the study. Lack of proper records made root cause analysis difficult, and in some cases impossible, and could not provide a basis for corrective actions for improvements of the protection system. While regulatory requirements include the need for accurate time stamps of fault records, this has not been strongly enforced. In addition, there is a lack of a standard for which signals to record and how to label them that prevents quick evaluation of the event by the system operator and the agents.

3. *Zone 2 reach settings*

Distance relays on transmission lines are typically applied in a permissive overreach scheme, with the overreaching permissive zone set to 120% of the line impedance. The root cause of some widespread events was the failure of Zone 2 to detect a line end fault. This could be due to shortcomings of the relay design, high resistance faults, or inaccurate line parameters used for the settings. While 120% is commonly applied for stepped distance schemes, a longer reach setting is recommended for communications-aided line protection schemes. In North America, the typical setting is 150% of the line impedance. When such reach setting does not coordinate with the remote line section, time delayed tripping from Zone 2 is disabled, and a Zone 4 element set to 125% (or less) is used as a "conventional Zone 2" element.

4. *Communications channels*

The root cause of a number of events was failure of the communications channel used for communications aided line protection schemes. This caused a time-delayed Zone 2 trip for line end faults, and miscoordination with Zone 2 on adjacent lines. While redundant communications are typically applied, the regulations do not presently require that they should be independent, and a common power line carrier or fiber optic cable is often used for both the primary and secondary channel.

5. *Breaker failure relays*

While not a significant cause of events in the study, it was noted that a rather complex breaker failure scheme ("BF *Etapa* 0") is applied in breaker and a half substations due to not having current transformers on each side of the bus breaker.

Consequently, a fault in the "dead zone" between an open breaker and the current transformer (CT) will not be detected by the line protection and needs a special protection scheme (see Figure 3). By installing a CT on the other side of the breaker, the need for this scheme is eliminated, and the resulting breaker failure protection scheme is simplified.

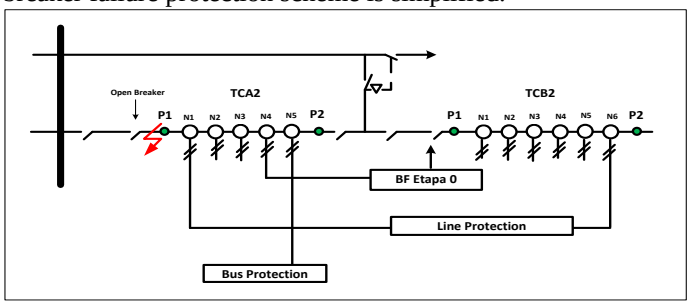


Figure 3. Special breaker failure scheme for breaker and a half configuration

6. *Overvoltage trip of lines*

Regulations specify acceptable voltage limits for the transmission system and transmission system owners have implemented trip of line relays when the voltage exceeds the upper limit. The current practice specifies a time delay for tripping lines and most of the events were caused by incorrect settings where the time was short. However, it was recommended that the practice of tripping lines on overvoltage should be discontinued altogether. International best practices are to use overvoltage trips only on apparatus, such as power transformers or generators, to protect against equipment damage which is not a concern for a transmission line.

7. *Ground overcurrent backup coordination*

Several events involved lack of coordination of ground overcurrent relays where an adjacent circuit or transformer would be tripped before the faulted line relays tripped. This lack of coordination resulted from different setting criteria in both end of the transmission lines when they are of different owners, and, in some cases, due to inaccuracies in the inverse time delay curves in the relay. In addition to enforcing settings coordination, it is recommended that the commissioning test includes a verification of the settings as inverse time delay curves and their accuracy varies between different products.

8. *Bus protection*

A significant number of events involved bus protection misoperation or misoperations of associated elements resulting in the loss of an entire substation. Presently, system stability analysis does not consider loss of a bus as a contingency. Apart from the recommendation to plan for such events, it is also suggested that, when possible, to use breaker and a half configurations instead of main and transfer bus, which is the most common 230 kV bus configuration today. For critical substations, it may even be beneficial to convert an existing main and transfer bus to a double bus, double breaker configuration. This would greatly simplify the protection schemes and improve reliability.

V. Detailed Description of One Event

As an illustration of the application of the methodology previously described and the type of event analysis performed, the description of one of the events analyzed is presented next.

A. Disturbance Sequence of Events

A summary of the disturbance sequence of events is presented below based on the review of the disturbance report.

- Within a time period of about 3.5 seconds, two 230 kV transmission lines which share the same right of way (A-B and A-C) tripped, followed by another 230 kV transmission line (D-E) trip.
- A generation unit 3 at bus D tripped for under-frequency conditions, following by the disconnection of the Colombia-Ecuador interconnection, tripping due to overvoltage and automatic controls (area separation scheme).
- The underfrequency load shedding scheme for the Colombian system operated. A total energy of 257 MWh was lost due to this event.

Fig. 4 shows the real and reactive power profile of the Colombia-Ecuador disconnection in the first 3.5 seconds of the event. As it can be seen, there is power inversion of both real and reactive power occurring in fast and abrupt conditions and just after about 2.5 seconds, the operation of the automatic controls, areas separation scheme, which responds to voltage and power variations occurred.

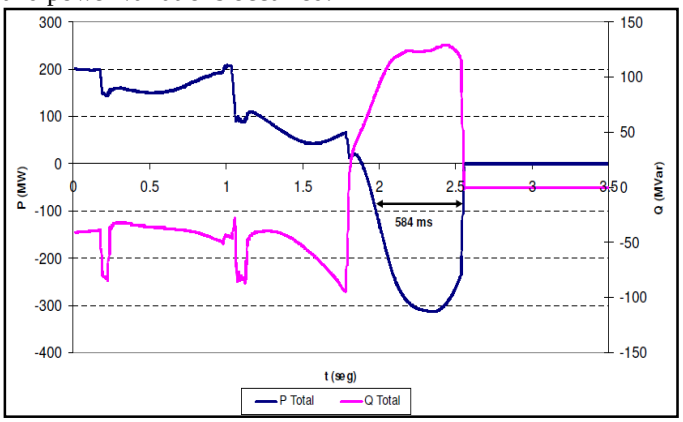


Fig. 4. Power transfer evolution Colombia-Ecuador **Error! Reference source not found.**.

Fig. 5 shows the voltage profile at one of the key buses that interconnect Colombia and Ecuador. At a time of about 2.5 seconds, following Line D-E trip, the voltage rose to 259 kV, just below the fast separation scheme limit of 260 kV.

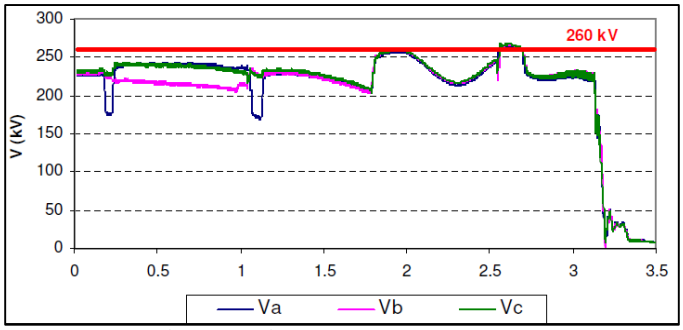


Fig. 5. Voltage profile at one of the key buses that interconnect Colombia and Ecuador.

A 230 kV transmission line (D-E) tripped due to load encroachment of its distance protection elements, zone 1.

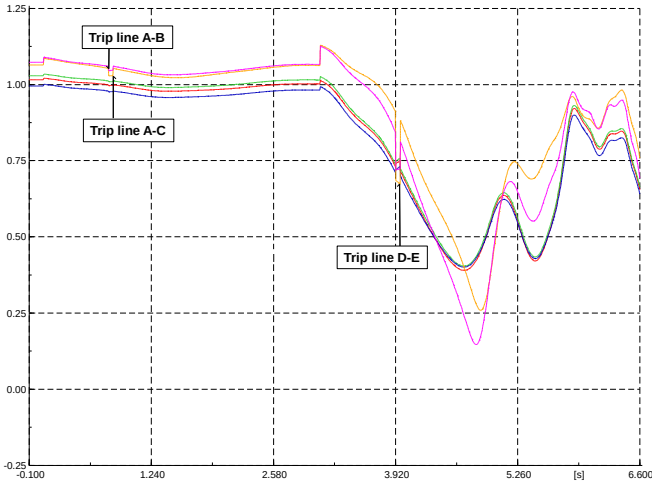
B. Further Simulations

As it have been demonstrated by the post event analysis of numerous wide area disturbances around the world, the operation of distance elements, usually zone 3, due to load encroachment is typically associated with stress in the system. The fact that the line tripped on zone 1, further indicates the presence of other system conditions that are causing the load encroachment such as power angle swings/voltage collapse. Based on the profile identified in Fig. 4, with power inversion of both real and reactive power occurring in fast and abrupt conditions, and the operation of zone 1 distance element due to load encroachment, this event was recommended for more detailed analysis including power system simulations of the disturbance sequence of events. Additional simulations were requested to be performed in order better appreciate the event. The particular items to further analyze included the following:

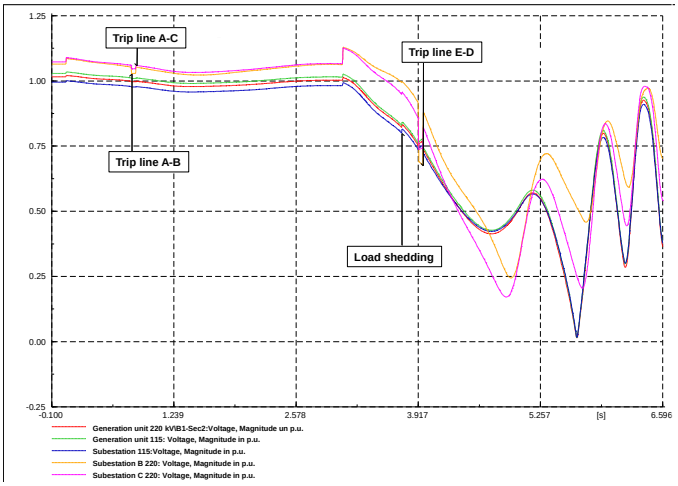
- Determine if zone 1 operation due to load encroachment could have been prevented, and if this could have diminished the disturbance scale.
- Evaluate the effectiveness of the under-frequency load shedding scheme.

C. Results of Additional Simulations

Fig. 6 presents power system simulations in which the transmission line D-E, which tripped due to load encroachment during the event, is left in service. Fig. 6 part a) shows the voltage profile *without* the application of load shedding and Fig. 6 part b) shows the voltage profile *with* the application of load shedding. As we can see in Fig. 6, the loss of lines 230 kV lines A-B and A-C put the system under an N-2 condition, and conduces to an increment in power flow towards Bus D to E and an extremely abrupt voltage depression. This causes the operation of the D-E line on zone 1 load encroachment. Power inversion is presented on the interconnection between Colombia and Ecuador, which results in voltage increments at Bus F.



a) Line D-E in service and without load shedding

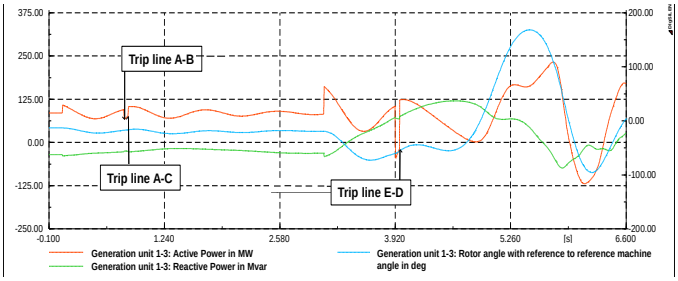


b) Line D-E in service and with load shedding

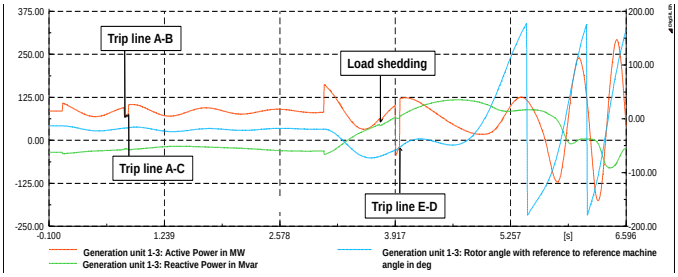
Fig. 6. Voltage Profile during the event, with Bus D in Service with and without load shedding.

As we can see from the results of Fig. 6, the in-service status of D-E transmission line is immaterial to the overall disturbance as the system is under extreme stress. This event is candidate for further analysis to better understand and document system events during out of step conditions and/or voltage collapse.

Fig. 7, part a) shows the angular performance of the generation unit that tripped during the event, *without* the application of load shedding and Fig. 7 part b) shows the angular performance of the generation unit that tripped during the event, *with* the application of load shedding.



a) D-E in service and without load shedding



b) D-E in service and with load shedding

Fig. 7. Angular separation between D and other generators.

From the analysis of Fig. 7, it is very likely that the N-2 condition presented in this event leads to bus D going out of step. Fig. 7 a) looks marginally unstable and it is very close to losing synchronism. Fig. 7 b) is clearly unstable as unit 3 generation is accelerating beyond stable conditions. A comparison of the angular performance with and without load

shedding seems to indicate that load shedding does not help in the event.

D. Final conclusions and recommendations

Upon the loss of the 230 kV corridors, the 115 kV remaining transmission presents a much higher impedance path that results in voltage collapse. The underfrequency load shedding scheme which would trip loads as a result of frequency reduction in reality could not do much for this voltage collapse event. From Fig. 6 and Fig. 7 we can conclude that this N-2 situation presents a severe voltage collapse/out of step conditions within a very small time period; about 2 seconds. Other emergency controls should be developed, such as a systemic protection based on generation rejection.

VI. Lessons Learned and Next Steps

Proper event analysis has been a key part of the Defense Plans of the Colombian power system. A detailed study of the phenomena occurred in most severe disturbances show important findings that can help the evaluation of the system strength and consequently the identification of risks for their secure and reliable operation. In the bulk power market structure of the Colombian power system, tasks related to event analysis are currently assigned to agents who own the assets involved in the disturbances and ultimately to the system operator. Consequently the actions derived from the analysis involved the collaboration of both of them. This was considered as a good practice in the Colombian power system. Good event analysis provides valuable information for proper solution of problems detected (corrective actions) but the results of this should be expanded to find solutions for future similar or major disturbances and for identification of weak points in the power system (preventive actions). As described earlier, those actions could involve agents, system operator, expansion planner (UPME), national operation council (CNO) and the regulator (CREG). This is illustrated in Fig. 8.

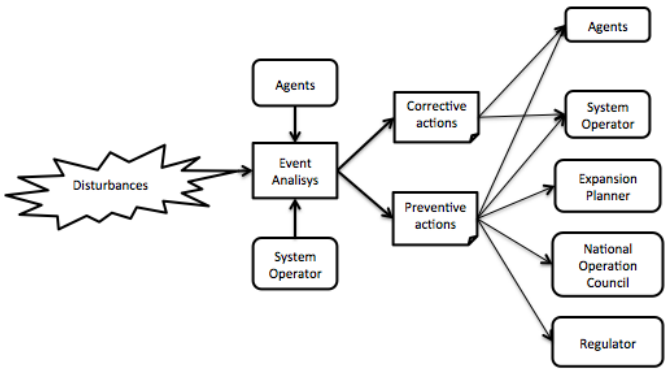


Fig. 8. Entities involved and types of actions in the event analysis

Additional actions to improve the reliability of the Colombian power system are part of the Defense Plans for the Colombian system and are summarized below.

A. Under Voltage Load Shedding

This kind of SIPS was recommended for further analysis for the Colombian power system to avoid wide-area voltage collapses, especially when transmission lines are out of service and N-1-1 or N-2 contingencies occurs causing grid stress and low voltages. In those cases, as the network is still interconnected, system frequency excursions are not presented and thus schemes based on the detection of low voltages are more suitable than those based on frequency measurements. Under Voltage Load Shedding (UVLS) can provide actions in the grid that increases voltage stability. Nevertheless, important considerations should be taken before implementing UVLS in order to identify and properly characterize system conditions that would be covered by this type of schemes [11]. For the Colombian power system, improvements in modeling of loads and generator controls as well as determination of generators reactive power capabilities, are key areas of improvement in parallel with the planning of UVLS on a wide-area scale. It is important to note that some local UVLS are currently implemented in Colombia at 115 kV and below, to avoid line overloads due to some contingencies, especially for radial operation in certain parts of the grid.

B. Under Frequency Load Shedding (UFLS) Evaluation

The current UFLS scheme implemented for the Colombian Power system has eight discrete steps where the last two steps are continuous (df/dt). Based on the regulatory requirements and through dynamic stability studies, the national dispatch center (CND) must determine for each operational area the number of steps to be implemented, the percentage of total demand to disconnect at each stage, and the corresponding timing of each disconnection. Distribution companies determine the load to be disconnected. A detailed evaluation of the UFLS is recommended for the Colombian power system taking as reference methodologies such as developed by WECC (Western Electricity Coordinating Council) for this purpose [12]. The evaluation and the studies for a new definition of the UFLS might consider fewer steps/wider frequency bands, which may allow more time for automatic controls into the system to perform before UFLS operation.

C. PMU-based SIPS

Phasor measurements in the Colombian power system are currently used for online visualization of small frequency oscillations in the control center and for off-line applications used in postoperative analysis. Nevertheless, some contingencies close to interconnection lines show the possibility to design PMU-based SIPS to ensure more reliable and accurate actions over the interconnected system. It also improves secure operation against severe contingencies.

Today, the separation schemes associated with Colombian interconnections are based on tripping lines when local measurements of voltages and active power reaches defined thresholds. PMUs installed in south Colombian interconnections could be used to record power angles between countries and provide data for a stability study across interconnecting lines as well as potential control actions.

VII. Conclusions

This article presented a methodology based on disturbance analysis to identify improvements in the planning, operations, and protection aspects of electric power systems. The methodology included key contributions and is suitable for its application in other electric power systems. The authors of this

paper plan to continue working and further develop the recommendations based on the identified priorities including formal petitions for changes to technical and regulatory criteria and rules. The results of this work is planned to be used as a guideline for improvements to the Colombian bulk electric power system reliability in the next 5 to 10 years.

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X. Biographies

Jorge Vélez is a Protections Analyst at XM Filial de ISA -the Colombian system operator. He has 9 years of experience in the field of protection systems as designer, analyst and testing and commissioning engineer of protection schemes. Jorge earned his Bachelor degree as Ingeniero Electricista in the Universidad Nacional de Colombia and is currently seeking a Master's Degree in Power Systems at Iowa State University. Before he joined XM in 2010, he worked at a consultant company in Colombia developing analysis and testing of the protection systems for different projects in transmission and distribution in Colombia and other countries in Central and South America. Once he joined XM, he continued working in the field of protections applying his knowledge to the systemic perspective. He has been primarily focused on the analysis and research to improve the reliability of the Colombian power system. Jorge has also worked as an Assistant Professor in Universidad Pontificia Bolivariana for the undergraduate program of Electrical Engineering.

David Elizondo, PhD., is the International Business Director and has more than 17 years of electric power systems experience, 10 years in the USA and 7 years in Mexico. Dr. Elizondo has a broad range of experience in electric power transmission planning and has participated in numerous transmission planning studies for most of the large utilities in the US. Dr. Elizondo has recent experience with the integration of synchrophasor measurement units into the Energy Management Systems of electric power networks. His work has been focused on the development of the visualization tools for the effective utilization and use of the synchrophasor based data to power system operators. Dr. Elizondo is the project manager for the PMU visualization project for Dominion and was responsible for the visualization specification for the NYISO PMU project. Dr. Elizondo earned his Masters and PhD degrees in Electrical Engineering at Virginia Tech and his Mechanical and Electrical Engineering Bachelor degree from the ITESM in Mexico. Dr. Elizondo is active presenting papers and talking in industry leading panels about diverse topics throughout the American continent.

Solveig Ward, MSEE is a principal advisor in Quanta Technology's Automation and Protection group. She has over 37 years' experience working in a variety of managerial, product management and marketing roles in the protective relaying and relaying communications area. Combining relay expertise with communications knowledge, she provides leadership in the area of communications systems for power system protection and control including IEC 61850, cyber security, special protection schemes, wide area protection and integration issues. Solveig is an IEEE Fellow and past Chairman of its System Protection Subcommittee. Solveig received an IEEE award in 2011 for PES Working Group Recognition Award - Outstanding Technical Report for "Redundancy Considerations for Protective Relaying." She also received an IEEE PES Prize Paper Award in 2011 as co-author of "Performance of Relaying during Wide-Area Stressed Conditions." Solveig has authored over 30 papers presented at domestic and international relay and power system communications conferences. Several of them have been published as magazine articles. She is co-author of three transaction papers, co-editor of one protective relay book, and holds one patent in the relay protection field. In Quanta Technology, Solveig has worked on several IEC 61850 projects, both internationally and in North America.