Cascading disturbance caused 1,800 MW generation lost in Colombian Power System

Nolasco Orrego, María N. Arboleda, Jaime A. Zapata, *XM S.A. E.S.P.*

***Abstract* -- The most important activity after a disturbance in the power system, is the disturbance analysis. In the decade of the 80´s and early 90´s in Colombia, those analyses were performed using information from operators, electronic fault records and analog frequency measurements. Those analyses took a very long time to be processed by this way. In the mid-90´s Digital Fault Recorder (DFR) and Digital Relays (DR) allowed advances in terms of oscillographic waves signals records. With these gadgets, analysts were able to improve analysis and reduce time of reporting. In the early 21st century, Colombia´s Independent System Operator (XM), in order to know the behavior of the electrical power system after disturbances occurred in the Interconnected Power System, implemented a phasor measurement network known as iSAAC proyect.**

The aim of this article is to briefly describe a disturbance event which caused a 1,800 MW generation lost in Colombia´s Interconnected Power System (CIPS) on March 9th 2011. That event represented a 20% of total peak load in maximum demand and it was made up of two disturbances occurred at the same hour.

Index: Electrical Power System (EPS), Electrical Protections (EP), Automatic Generation Control (AGC), Digital Fault Recorder (DFR), Digital Relays (DR).

I. INTRODUCTION

Colombia's power system is made up of around 53 Generation Utilities (**GU**), 11 transmission system utilities (**TM**), 32 Distributor Operator Utilities (**DOU**) and 92 Marketers Retailers. The **CIPS** has an installed capacity of 13,500 MW approximately. Around 65% of the total electrical generations comes from hydro generation, 33% comes from thermal generation and 2% comes from another generation sources. The **CIPS** has 6,259 mi of transmission lines at 115 kV, 7,253 mi at 230 kV and 1,490 mi at 500 kV. Additionally, the **CIPS** has another 3 international interconnections, each at 230 kV: 2 with Venezuela and the other one with Ecuador.

The **CIPS** frequency is 60 Hz; the normal operation voltage band is between 0.9 p.u to 1.1 p.u; the common mismatch between load forecast and real load is around ±5%.

Fig. 1 Colombia´s electrical network

Figure 1 shows a small electrical portion of **CIPS** at 230 kV and 500 kV.

II. PREDISTURBANCE CONDITIONS

Before the first disturbance at 17:13 hours, the **CIPS** dispatching conditions were as follows:

1. Frequency was at 59.96 Hz.
2. Total load was 7,341 MW.
3. The Colombian **BIAS** scheduled was 600 MW/Hz.
4. The Automatic Generation Control (**AGC**) mode was Tie Line Bias (**TLB**) between Ecuador power system and **CIPS**.
5. The **AGC** ancillary services, in **CIPS,** were supplied by:
   a. **U** hydroelectric power[1] plant through one unit with 30 MW (11%).

[1] U's hydroelectric power plant is made up of 3 units of 85 MW each one.

b. **Ch** hydroelectric power[2] plant through units 2, 3, 4, 5 and 6 with 255 MW in total (89%).

6. The interconnection power flow from Colombia to Ecuador was 280 MW.

Before the second disturbance at 17:18 hours, the **CIPS** dispatching conditions were as follows:

1. Frequency was at 59.99 Hz.
2. Total load was 6,800 MW.
3. The interconnection flow from Colombia to Ecuador was 64 MW.

III. Disturbance Description

At 17:13 hours, a lightning stroke near the **G** substation, on phase **C** of **G** - **C** 2 transmission line at 230 kV. This single fault was cleared through trippings remote ends of **G** substation, in a sequentially manner, at 1,346 ms. In other words, no breaker at **G** substation were opened. That disturbance caused 10 transmission lines were disconnected and a 1,170 MW generation loss of **CIPS**. After that disturbance, the frequency of **CIPS** decreased from 59.96 Hz to 59.14 Hz, and it caused that the Under Frequency Load Shedding Scheme (**UFLSS**[3]) tripped the load until the second stage with 774 MW approximately. The electrical conditions of **CIPS**, at that moment, caused that **Ch** power plant increased its power generation, while voltages near **G** and **Ch** substations at 230 kV and the other **CIPS** electrical nodes decreased.

Around five minutes later (17:18 hours) the Intelligent Electronic Devices (**IED**) protections of **Ch** power plant tripped with 650 MW (5 of 7 units). This new disturbance caused that **CIPS** frequency decreased again, from 59.99 Hz to 58.91 Hz. The **UFLSS** tripped the load until the third stage with 384 MW approximately. Finally, the interconnection between Colombia and Ecuador was tripped with 64 MW.

Figure 2 shows the influenced area of the disturbance and some information of time disconnections in transmission lines.

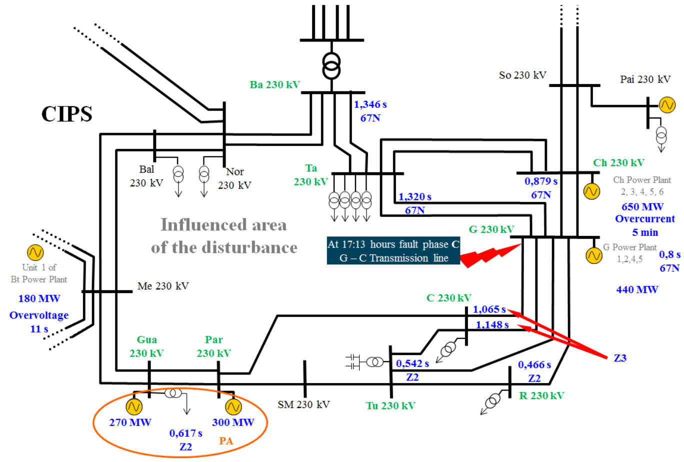


Fig. 2 Disturbance influenced area

IV. Event Sequence

Table 1 shows the Sequence of Event (**SOE**) of the first disturbance. The disturbance was at 17:13 hours.

Table 1 SOE First Disturbance

Time [ms]	Substation	Line	Event	Action	P [MW]
0	C	G 1+2	P2 phase C	Start	
0	Ba	Ta 1+2	PL2 21 phase C	Start	
0	Ch	G 1+2	PL1 67N	Pick up	
0	Ch	G 1+2	PL2 21 phase A	Start	
0	Ta	G 1+2	PL2 67N	Start	
1	Ba	Ta 1+2	PL2 67N Communication	Send	
4	C	G 2	Teleprotection Chanel 4	Send	
466	R	G	BKR	Open	143
485	Tu	G	P1 Distance Zone 2	Trip	
542	Tu	G	BKR	Open	77
617	PA	5 UNITS	hydroelectric power plant	Trip	570
800	G	4 UNITS	hydroelectric power plant	Trip	440
837	Ch	G 1+2	PL2 21	Trip	
879	Ch	G 1+2	BKR	Open	174
880	Ta	G 1+2	PL1 85 Communication	Send	
1.042	C	G 2	P1 Distance Zone 3	Trip	
1.065	C	G 2	BKR	Open	96
1.106	C	G 1	P2 Distance Zone 2	Trip	
1.126	C	G 1	P2 50BF Stage 0	Trip	
1.148	C	G 1	BKR	Open	96
1.276	Ba	Ta 1+2	PL2 21	Trip	
1.276	Ba	Ta 1+2	PL2 67N	Trip	
1.280	Ta	G 1+2	PL1 21	Trip	
1.290	Ta	G 1+2	86 Lockout Relay	Operated	
1.320	Ta	G 1+2	BKR	Open	186
1.335	Ba	Ta 1+2	86 Lockout Relay	Operated	
1.346	Ba	Ta 1+2	BKR	Open	12
11.000	Bt	1 UNITS	hydroelectric power plant	Trip	180

Table 2 shows the **SOE** of the second disturbance. The disturbance was at 17:18 hours.

Table 2 SOE Second Disturbance

Time [ms]	Substation	Line	Event	Action	P [MW]
0	J	Po (1 to 4)	DTT	Received	
41	J	Po 1+2	BKR	Open	32
1.137	Ch	UNITS 3-4	hydroelectric power plant	Trip	260
2.137	J	Po 3+4	BKR	Open	32
2.137	Ch	UNITS 2-5	hydroelectric power plant	Trip	260
5.137	Ch	UNIT 6	hydroelectric power plant	Trip	130

[2] **Ch**'s hydroelectric power plant is made up of 8 units of 127 MW each one

[3] One of the System Integrity Protection Schemes (**SIPS**)

V. ANALYSIS OF DISTURBANCE

The following list shows the causes that produced disconnections in elements of the **CIPS**, during the first disturbance:

- The protection relays of **G** substation at 230 kV, related to **G** - **C** 2 transmission line, were blocked because the **MCB**[4] tripped 30 minutes before the first disturbance.
- The breaker at **R** substation at 230 kV, related to **R** - **G** transmission line, was correctly opened due to the tripping at zone 2 of its line distance protection.
- The breaker at **Tu** substation at 230 kV, related to **Tu** - **G** transmission line, was correctly opened due to the tripping at zone 2 of its line distance protection.
- The five units of **PA**[5] hydroelectric power plant were wrongly disconnected due to the tripping at zone 2 of its generator distance protection. The setting for zone 2 was mistaken. Figures 3 and 4 shows the wrong and the right setting zone 2 for **PA**'s generator distance protection.

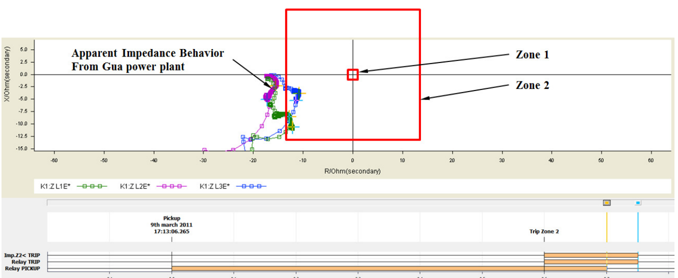


Fig. 3 Wrong setting for zone 2 generator distance protection

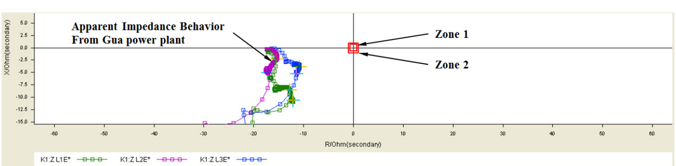


Fig. 4 Right setting for zone 2 generator distance protection

- The four units of **G** power plant were wrongly disconnected by the tripped of ANSI 67N that protected its generating ducts[6]. Mistaken polarizations produced ANSI 67N operation.
- The breaker at **Ch** substation at 230 kV, related to **Ch** - **G** transmission line, was correctly opened due to the tripping by ANSI 67N function protection.
- The breakers at **C** substation at 230 kV, related to **C** - **G** transmissions lines 1 and 2, were correctly opened due to the tripping by zone 3, looking forward, of its line distance protections.
- The breakers at **Ta** substation at 230 kV, related to **Ta** - **G** transmissions lines 1 and 2, were correctly opened due to the tripping by ANSI 67N function protections.
- The breakers at **Ba** substation at 230 kV, related to **Ba** - **Ta** transmissions lines 1 and 2, were correctly opened due to the tripping by ANSI 67N function protections.
- Due to the tripping of ANSI 59G Function, included into the generator's multifunctional protection, the only unit of **Bt**'s[7] hydroelectric power plant was wrongly disconnected. The setting for ANSI 59G Function was mistaken. Table 3 shows the Trip Log relay. Figure 5 explains the reason for the pickup of ANSI 24G Function.

Table 3 Trip Log relay of **Bt** power plant

Number	Indication	Value	Date and time
00301	Power System fault	2685 - ON	09.03.2011 17:13:24.914
00302	Fault Event	2685 - ON	09.03.2011 17:13:24.914
00501	Relay PICKUP	ON	0 ms
05370	24-1 V/f> picked up	ON	0 ms
06568	59-1 Overvoltage V> picked up	ON	7238 ms
00511	Relay GENERAL TRIP command	ON	10238 ms
06570	59-1 Overvoltage V> TRIP	ON	10238 ms

After the fall of Colombia's frequency, the recovery of **CIPS** frequency and the voltage at **Bt** substation at 230 kV increased at the same time. These combined phenomena caused the pickup of ANSI 24 Function.

4 The MCB tripping was not supervised at that moment.

5 PA is a name related to Par and Gua substations.

6 The generating ducts of **G** power plant have 0.32 miles from house machines to **G** substation at 230 kV. The ANSI 67N is located at the end **G** substation at 230 kV. **G** power plant has two ducts and five units of 240 MW each one.

7 **Bt** power plant is made up of 3 units of 180 MW each one.

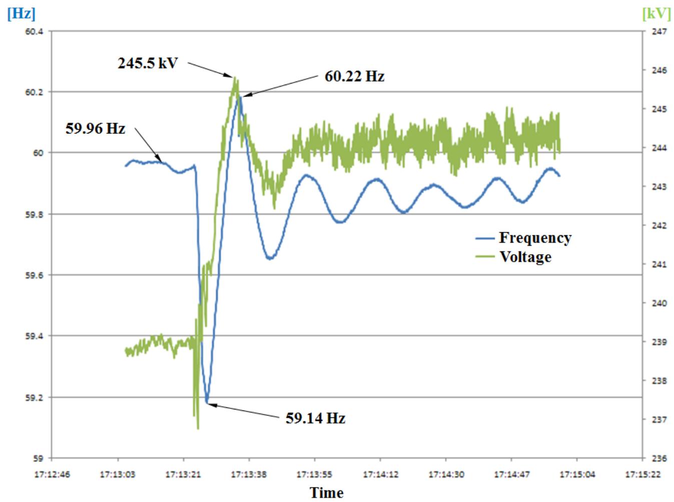


Fig. 5 Voltage in **Bt** substation at 230 kV Vs CIPS Frequency

Figure 6 shows the summarized of the first disturbance.

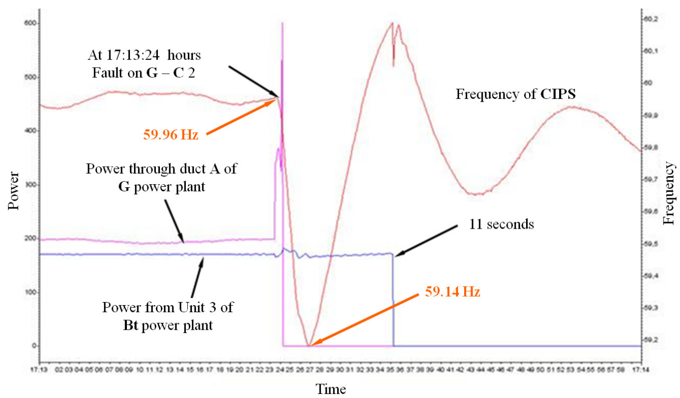


Fig. 6 Summary of the first disturbance

This is the list of reasons that caused the disconnection of **CIPS**'s elements for the second disturbance:

- The breakers at **J** substation at 230 kV, related to **J** - **Po**[8] transmission lines 1, 2, 3 and 4, were correctly opened by Direct Transfer Trip (**DTT**) from Ecuador. The overpower protection sending scheme was tripped.
- The five units of **Ch**'s power plant were correctly disconnected due to the tripping of its generator multifunctional protection. Those units were disconnected by actions of a phase overcurrent function which waited for 3 seconds maximum after reached 120% of In.

The power flow, at **Ch** substation at 230 kV, are shown in figure 7. It is visible that the power flow through **Ch**-**Ta** transmission lines were highly increased while power flow through **Ch** - **G** transmission lines, were shut down.

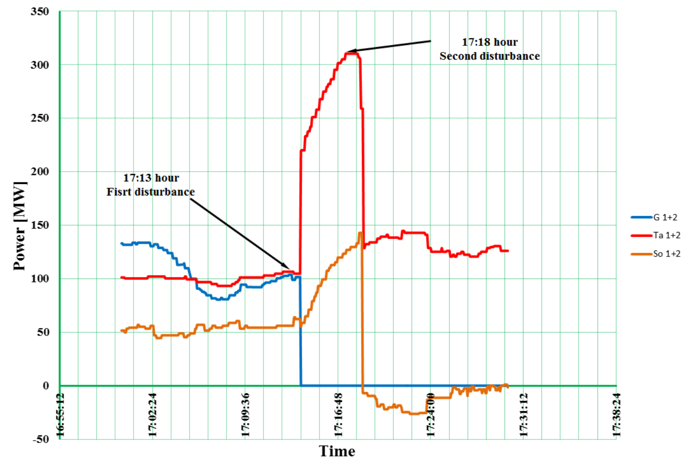


Fig. 7 Power flow at **Ch** substation 230 kV

Between 17:13 hours and 17:18 hours, the power flow through **Ch** - **Ta** transmission lines required a higher consumption of **CIPS** reactive power. Figure 8 shows those phenomena.

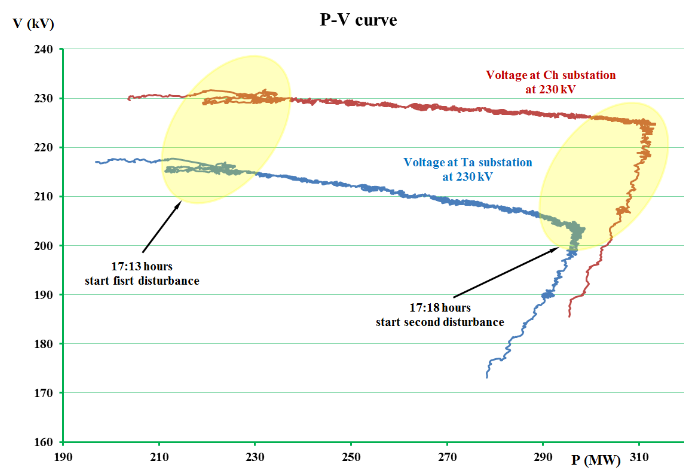


Fig. 8 PV Curve at **Ta** and **Ch** substations both at 230 kV

Finally figure 9 shows the summarized of both disturbances.

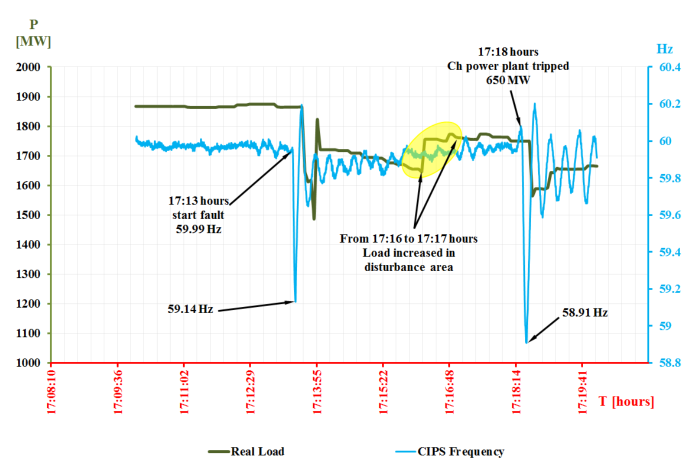


Fig. 9 PV Summary of the entire event

[8] **Po** substation belongs to Ecuador´s EPS

VI. Actions and Recommendations

- Has been replaced all MCB related to secondary voltage transformer at **G** substation at 230 kV and has been implemented a supervision of all **MCB**´s position.
- Has been reviewed all generators' protection settings at **G**, **Ch**, **PA** and **Bt** power plants.
- Conducting **AGC** assignment study (benefit-cost). Answer this question, ¿All the **AGC** in one only power plant or distributing the **AGC** between **CIPS**'s electrical areas?

VII. Conclusions

1 A hidden failure, a lightning stroke and mistaken settings of the generators' protections, caused 1,800 MW power generation lost in **CIPS**.

2 The performance of backup protection systems at the remote ends at **G** substation at 230 kV, were satisfactory.

3 Those disturbances proved, in real time, that the performance of **UFLSS** of **CIPS** for this major event, was satisfactory.

4 The analyses of those disturbances allowed us to identify their principal causes, to propose improvements to the systems' protections and to develop a defense plan to protect the **CIPS**.

VIII. Biographies

Nolasco de Jesús Orrego Palacio is an Electrical Engineer from Universidad de Antioquia (Medellín, Antioquia, Colombia). He obtained the title of Master in Engineering with emphasis in Electrical Power Systems at the Universidade Federal de Santa Catarina, Brazil in 2000.

Since 1995 he joined Interconexión Eléctrica SA (ISA), where he worked as Analyst for the Control and Protection Department.

In 2003, he assumed the position of Analyst in the Planning Department of the National Control Center. In 2005, he was transferred to XM Compañía de Expertos en Mercados (subsidiary of ISA) as Planning Specialist.

In carrying out of his duties, he has developed significant expertise in the areas of maintenance as well as in the areas of electricity and energy planning, particularly on issues related to the Operation of Power Systems.

He has studied planning and operation of electrical systems in Colombia, Peru and Panama, specifically in the field of electrical protection.

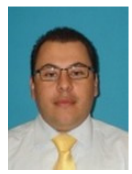
He has led from 2004 until 2010 the National Group Protection, (GNPYC) in Colombia.

He has participated as a researcher in the field of optimal operation of hydrothermal systems, Optimal Power Flows and Competitive Power Markets and author of several journal papers for IEEE and for the Centre of Excellence in Regulating Electricity Markets (CERME) Brazil.

Maria Nohemi Arboleda Arango is the Manager of the National Dispatch Center at XM Compañía de Expertos en Mercados S.A., subsidiary of Interconexión Eléctrica S.A. – ISA since 1988.

She obtained the Electrical Engineer degree from Universidad Nacional de Colombia and her Specialization and Master degrees in Electrical Engineer are from Universidad Pontificia Bolivariana de Colombia. She attended a Training course in Sweden in Control and Operation of Power Systems and attended an Advanced Management Program at the Universidad de los Andes.

XM is a company responsible of operating the National Interconnected System and managing the wholesale power market in Colombia.



Jaime Alejandro Zapata Uribe is the Operation Assurance Director at XM Compañía de Expertos en Mercados S.A., subsidiary of Interconexión Eléctrica S.A. – ISA since 1988.

He obtained the Electrical Engineer degree from Universidad Pontificia Bolivariana de Colombia and his Specialization in Business Law and Master degree in Economy from Universidad Externado de Colombia and Universidad EAFIT de Colombia, respectively.

XM is a company responsible of operating the National Interconnected System and managing the wholesale power market in Colombia.