Preventing Collapses with a Supplementary Protection Scheme for the Colombia – Ecuador Interconnection

G. Gutierrez

***Abstract*—The Colombian and Ecuadorian electrical systems are currently interconnected to each other by two double overhead transmission lines at 230 kV with 212 km of length each one. Although the normal operation of these lines is synchronized, sometimes it is necessary to trip them not only for a faulted condition but also for systemic events. In fact, this paper is focused on describing the ISA-INTERCOLOMBIA's Supplementary Protection Scheme (SPS) or Area Separation Protection Scheme (ASPS) for the electrical interconnection based on a machine relay application. It describes its settings, design, implementation and analysis of the scheme operation during the events. Furthermore, the dynamic simulations are included as part of the prior studies for the protection's settings and analysis of the events. This information will show how the protection used is preventing a collateral damage. Therefore, the recognition of these kinds of alterations opportunely using SPS contributes to avoid critical effects on the countries' power systems.**

Keywords: electrical interconnection, overhead transmission line, SPS, supplementary protection scheme, systemic events.

I. Introduction

In order to prevent total or partial collapses of the Colombian or Ecuadorian systems in the face of large-scale disturbances in Ecuador (or Colombia), ISA-INTERCOLOMBIA implemented a supplementary protection scheme called "Area Separation Protection Scheme" for both countries. This scheme trips the whole interconnection when some of the electrical variables exceed their thresholds, which are monitored by a special relay in the links of Pasto (Jamondino substation) - Quito (Pomasqui substation) interconnection at 230 kV.

The application exists in both countries Colombia and Ecuador with same stages and variables but different settings. The paper is focus on describing the Colombia's SPS application and its performance. The ASPS trips the local and remote circuit breakers of the four overhead transmission lines of the interconnection. The variables include: over-active power in forward direction, under-frequency and under-voltage with a time delay set. The Fig. 1 presents the SPS schemes at both ends [1]. The tripping will be issued over the whole links' circuit breakers locally and remotely by transmitting a Direct Transfer Trip (DTT) signal. This signal is especially useful to prevent an overvoltage condition on the Pomasqui due to the Ferranti effect attained by the long length of the lines (212 km each).

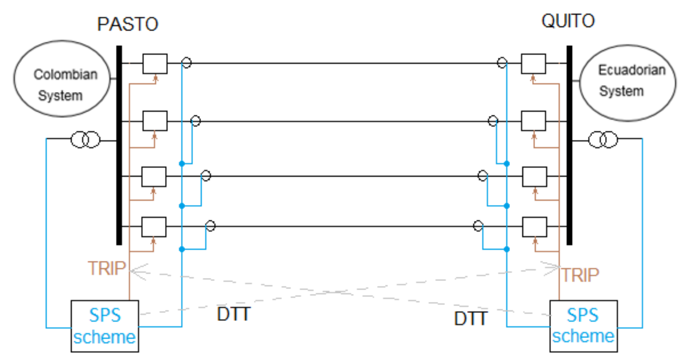

Fig. 1. Tripping of the Area Separation Scheme configuration and topology.

Tripping the eight circuit breakers of the interconnection circuits after detecting critical changes in the electrical variables assures that problems originated in one of the systems does not transfer to the other, avoiding critical impacts over the healthy power system. The variables involved in the scheme are illustrated in Fig. 2.

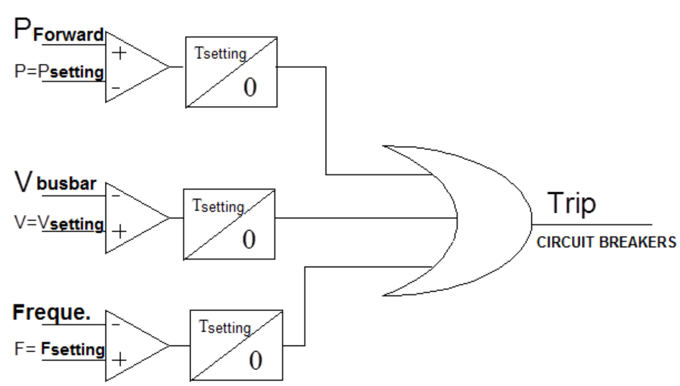

Fig. 2. Power system variables involved in the Area Separation Scheme for the Colombian end.

As it can be noticed, the variables are independent and compete each other. They are not combined since a greater reliability to relieve the electrical systems from a critical event will be issued. This will be analyzed in the chapter III.

II. Electrical Studies for Relay Settings

The relay settings were obtained for both systems starting of

This work was supported by ISA-INTERCOLOMBIA S.A.
G. Gutierrez is the Specialist of Protection Systems at ISA-INTERCOLOMBIA, Calle 12 sur 18-168, Medellin-Colombia (e-mail: gegutierrez@intercolombia.com).

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a complete model of the Colombian and Ecuadorian power systems included in the software "DIgSILENT PowerFactory 2017 version SP3" considering their equipment such as generators, lines, transformers and loads. Several escenarios were also considered to run dynamic simulation of different events on both power systems. Every equipment was modeled with especific parameters for rms representation. For example, reactance for direct and quadraure, torques and inercia for generators. Frequency and voltage dependecy parameters for loads, among others. Every electrical network was analyzed according to the limits of power transference and voltage stability from one country to another. The Fig. 3 shows a load flow simulation in the area containing the interconnection and further a portion of the topology. No equivalent sources were used in either site of the transmission link under study.

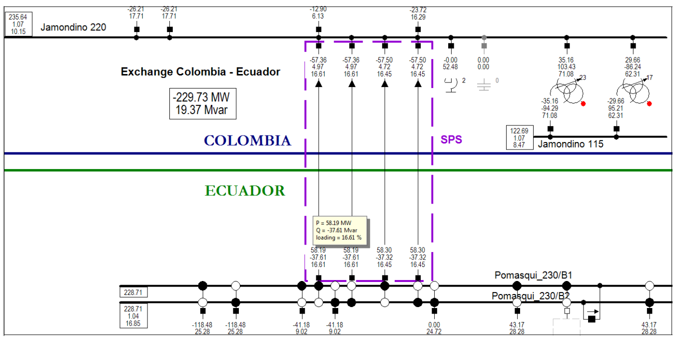

Fig. 3. Part of the power systems of Colombia and Ecuador modeled in DIgSILENT.

With this system several simulations of events were made to understand its electrical variables behavior when a tripping generation and load occurred in one of the countries. The Fig 4. depicts this analysis. This simulation starts with an importing condition to the Colombian power system about 230MW as shown in Fig. 3. Furthermore, several tripping of 7 generators in the Ecuador system were simulated to invert the power.

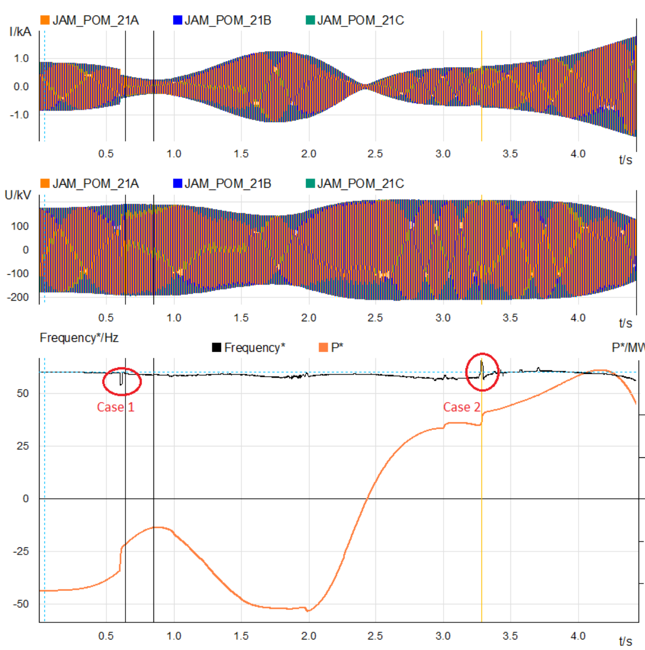

Fig. 4. Simulation of over-power in forward direction detected in the Jamondino's relay after several critical events in both systems.

The trips were made at different times of the simulation to invert the power direction and analyze the frequency. The evolution of the power over the time, after inverting, reaches the over-power status in the opposite direction: Colombia to Ecuador at 2.4 s. After 200 ms, the power exported has increased more than 150 MW in forward direction by more than 1.7 s: In addition to the power behavior, frequency changes appear as valleys and crests. The basins came up because of every Ecuadorian generation tripping, and the edges represents the operation of the Colombian Low Frequency Systemic Scheme (LFSS) stages. This scheme sheds loads as a response of low frequency due to each set of generators tripping on the time. It usually has 5 stages including a derived of the frequency. Furthermore, two dramatically changes were evidenced in the Fig. 4: Case 1 at 0.605 s and Case 2 at 3.29 s of the simulation. The first case is an operation of the instantaneous frequency derived stage trying to recover the frequency. This is a critical reaction of the LFSS after the first set of generators tripped in Ecuador. The second one is an operation of the last stage of LFSS which has the lowest frequency setting and the greater delay. This stage trips a larger area of load in comparison to the preceding stages. In fact, the frequency jumped to a higher value instantaneously taking the system to the over frequency. Therefore, for this case is necessary to prevent a collapse in the Colombian power system making the operation time of forward over-power be less than 1.7 s. This consideration will avoid further tripping of generation and shedding loads before the power system's tries to recover itself. In this way, every kind of the SPS's setting was analyzed using a variety of event simulations like this.

Another example of the importance of power evolution is treated in this case of study. The Fig. 5 compares the evolution of the frequency in the substation La Union 34.5 kV (close to Jamondino) before and after enabling the over-power function. 750 MW of generation was instantly tripped in the Ecuadorian system. It is observed that by not having this function enabled, the frequency of the system could fall below the threshold of action of the LFSS, producing load shedding. In contrast, the timely detection of the phenomenon by the over-power stage protection prevents that in the event of a significant disconnection of generation in the Ecuadorian system leads to an amount of load disconnection in the Colombian system.

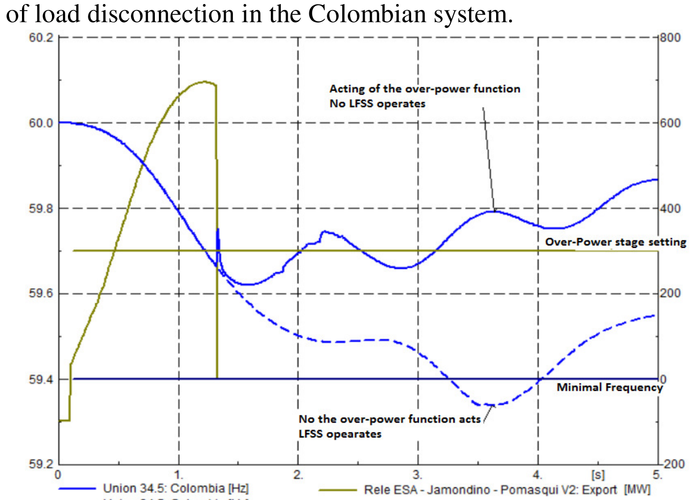

Fig. 5. Possible evolution of the frequency in comparison to the over-power function tripping [3].

The conceptualization of the over-power thresholds starts from the characterization of the phenomenon which is based on the standard deviation of the real power from planned power. This has been observed in the interconnection with generation shedding in the Ecuadorian system, as well as the power values that can be exchanged between both countries. Operational experience shows that a generation tripping in Ecuador is reflected in an exchange deviation of the order of 80% of it. Between both countries, the power exchange is about 400 MW. This characterization is relevant in the import region, considering that in the export region a significant disconnection of generation in the Ecuadorian system is detected by the low voltage function. The conceptualization is illustrated in the Fig.6.

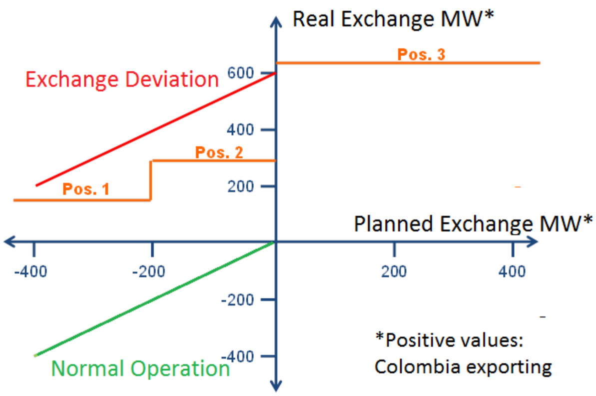

Fig. 6. Formulation of the need for an over-power function.

After these studies [1], the final settings were also defined:

- Over-power of shipment in Colombia to Ecuador:
  - ✓ Position 1: 150 MW with delay of 0.8 s.
  - ✓ Position 2: 300 MW with delay of 0.8 s.
  - ✓ Position 3: 650 MW with delay of 2.0 s.

The selected position depends on the exchange programmed by the Colombian system as follows:

- ✓ Position 1 is selected for an import higher than 200 MW.
- ✓ Position 2 is selected for an import lower than 200 MW.
- ✓ Position 3 is selected for exporting.

- Low voltage: 0.85 p.u. (187 kV with base 220 kV), with delay of 0.5 s. The limit of voltage collapse for Colombian power system is 80%.
- Low frequency in Jamondino: 58.2 Hz with a delay of 0.5 s. The criterium of this function was to serve as backup of both schemes LFSS stages and SPS.

This implied a special design of an application to choose the relay setting according to the exporting or importing conditions. Using a relay to set the variables indicated in Fig. 2, it was possible to configure settings and implementation [3] that will be shown in the figures 7 to 11. The Fig. 7 illustrates the reference of the apparent power calculated of the relay.

No.	Settings	Value
0251	Rated Primary Voltage Generator/Motor	230.00 kV
0252	Rated Apparent Power of the Generator	637.40 MVA
0242	Starpoint of Side 1 is	Solid Earthed
0244	Starpoint of side 2 is	Solid Earthed

Fig. 7. Reference apparent power calculated from the nominal primary values of the transductors: 230 kV and 1600 Amp in the machine relay.

The Figs. 8 and 9 show the configuration for Voltage and frequency variables settings respectively.

No.	Settings	Value
4001	Undervoltage Protection	ON
4002	U< Pickup	93.6 V
4003	T U< Time Delay	0.50 sec
4004	U<< Pickup	10.0 V
4005	T U<< Time Delay	oo sec
4006A	U<, U<< Drop Out Ratio	1.01

Fig. 8. Under-Voltage settings. Only the first stage is considered in this format.

No.	Settings	Value
4201	Over / Under Frequency Protection	ON
4203	f1 Pickup	58.20 Hz
4204	T f1 Time Delay	0.50 sec
4206	f2 Pickup	40.00 Hz
4207	T f2 Time Delay	100.00 sec
4209	f3 Pickup	40.00 Hz
4210	T f3 Time Delay	100.00 sec
4212	f4 Pickup	40.00 Hz
4213	T f4 Time Delay	100.00 sec
4214	Handling of Threshold Stage f4	Freq. prot. stage underfrequency
4215	Minimum Required Voltage for Operation	10.0 V

Fig. 9. Under-Frequency setting. Only the first stage is considered in this settings format.

With these values, a tripping by under-voltage or under-frequency will be issued. Regarding active power, it was necessary to configure three settings and a logic to pick up the proper setting according to the transference direction of the power. The over-power function settings for exporting power from Colombia to Ecuador will be shown as follow. The Fig. 10 corresponds to the 650 MW setting.

No.	Settings	Value
3201	Forward Power Supervision	ON
3202	P-forw.< Supervision Pickup	0.5 %
3204	T-P-forw.< Time Delay	oo sec
3203	P-forw.> Supervision Pickup	102.0 %
3205	T-P-forw.> Time Delay	oo sec
3206A	Method of Operation	Method accurate

Fig. 10. Over active power in forward direction settings for exporting power from Colombia to Ecuador. Only the second stage is considered.

It is important to note that delay time is set to "oo" which means "infinite" or time does not matter. This implies that only the pickup setting is relevant, and its value corresponds to 102% x 637.4 = 650 MW. This criterion should be applied to the other two settings to achieve the real values. The Fig. 11 represents the other two over-power stages.

No.	Settings	Value
8501	Measured Value for Threshold MV1>	Active Power P
8502	Pickup Value of Measured Value MV1>	24 %
8503	Measured Value for Threshold MV2<	Disabled
8504	Pickup Value of Measured Value MV2<	-47 %
8505	Measured Value for Threshold MV3>	Active Power P
8506	Pickup Value of Measured Value MV3>	47 %
8507	Measured Value for Threshold MV4<	Disabled
8508	Pickup Value of Measured Value MV4<	-47 %
8509	Measured Value for Threshold MV5>	Disabled
8510	Pickup Value of Measured Value MV5>	100 %
8511	Measured Value for Threshold MV6<	Disabled
8512	Pickup Value of Measured Value MV6<	40 %

Fig. 11. Over active power in forward direction settings for importing power from Colombia to Ecuador. The First (MV1>) and third (MV3>) stages are considered in these settings.

In this case the real values of MV1> and MV3> are 153 MW and 300 MW, respectively. As it can be noticed, these settings are a little bit upper than the expected study values.

The logic to choose one of the three settings by a button is shown in Fig. 12.

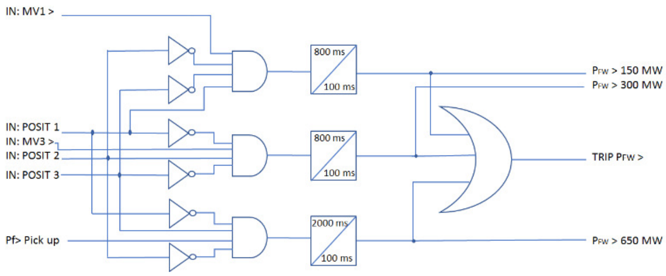

Fig. 12. Logic to choose the over active power in forward direction settings according to the transference and direction of power.

Every gate "AND" has four inputs managing two direct signals from a power setting stage and a binary input enabled by a button. The other ones are negative entries, and they come from the opposite entries which were not selected. A picture of set of the buttons created in the SCADA is illustrated in Fig. 13.

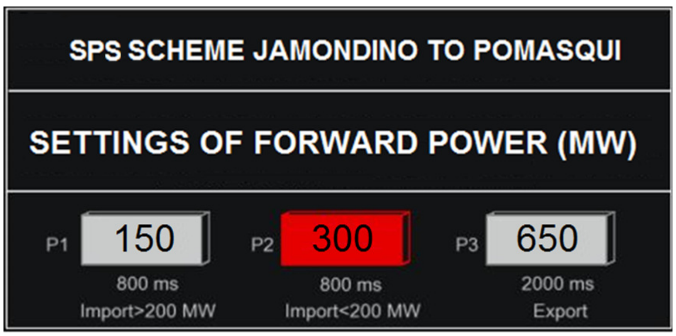

Fig. 13. Push buttons to enable one of the logic inputs to select the over-power settings.

This Area Separation Scheme was satisfactorily tested with all these implementations. Consequently, it will issue a trip during a critical electrical event occurring in one of the two countries. This operation will work according to the power settings previously selected fitting to the prior condition between the Colombia – Ecuador links. Nowadays, it is chosen the 300 MW option (red color). Some of these events are discussed in the following chapter.

III. Operation Results of the Area Separation Scheme on the International Interconnection Colombia - Ecuador

Several events in any of the two countries have appeared affecting the power, frequency and voltage stability of the healthy power system. In this way, the operation of every ASPS has been relevant and satisfactory. The Fig. 14 summarizes the performance statistics of the Area Separation Scheme from April to November 2016.

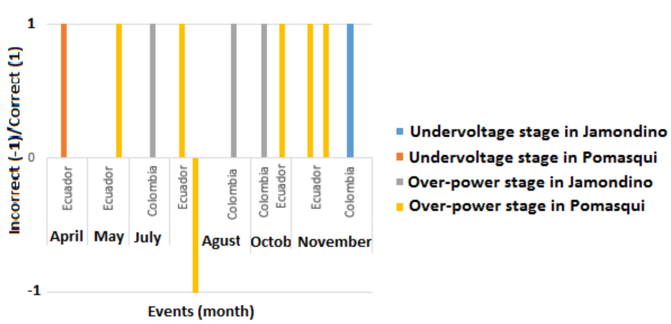

Fig. 14. Performance statistics of SPS- April to November 2016.

An event is observed in August 2016 where it was concluded that the operation of the ASPS was incorrect. According to the scheduled exchange between Colombia and Ecuador, the selection of the relay settings in 230 kV Jamondino and 230 kV Pomasqui should be in position 3, according to the positions indicated in chapter II. However, The Area Separation Scheme operated in Pomasqui for the over-power function was selected as position 1. This was the mistake that led to a mis-operation of the SPS in Pomasqui.

Several events of the last figure and its operations [4] will be shown next. Descriptions, analysis and simulations to understand the operation of the SPS located in the Jamondino to Pomasqui lines will also be presented.

A. *Tripping condition due to over-power.*

In this situation (event 10/16/2016) the importing power button selected was the second one (<200 MW). Before the event, Colombia was receiving less than 200 MW, almost 0 MW. In the event, some Ecuador's generators tripped, dropping 360 MW. A reverse power condition emerged in the interconnection. This created an over-power in forward direction from Colombia to Ecuador. The Fig. 15 shows this event and the operation of the protective relay.

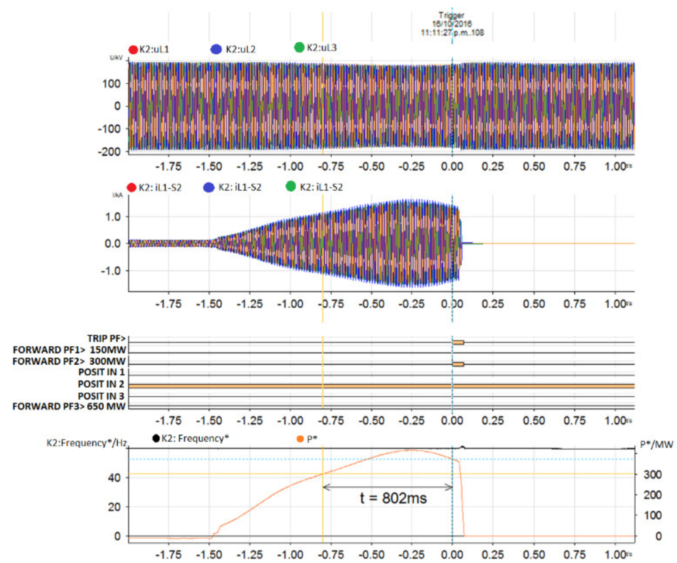

Fig. 15. Operation of one of the over-power stage of the Jamondino substation's SPS- event 10/16/2016.

As it can be seen in this figure, the setting selected of over-power in forward direction was the button 2 (Position 2 in the digital signal). Hence, the tripping signal FORWARD PF2> was seemly released in 300 MW after 802 ms. The frequency and voltage did not suffer alterations during the event.

As part of the analysis a RMS simulation of this event was also considered. Starting with the over-power condition of the last figure, a representation of the event will be simulated properly in order to achieve the final conditions of both Colombian and Ecuadorian power systems with and without (w/wo) acting SPS.

The Fig. 16 illustrates the conditions of the overpower during the event w/wo over-power stage.

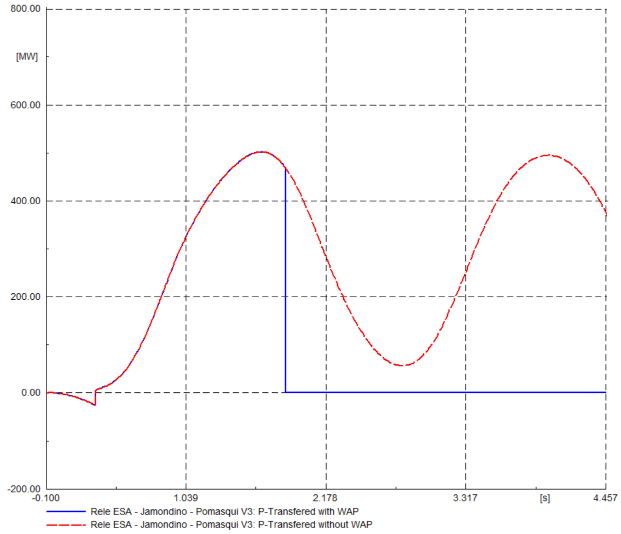

Fig. 16. Depicting of the power evolution in the event 10/16/2016 with (blue color) and without (red color - dashed line) tripping for over-power stage of the Jamondino substation's SPS.

According to this simulation, an oscillation in forward direction of the power between 50 and 500 MW would appeared if the SPS had not operated. Voltages and frequency of the busbars close to the interconnection would be affected. These consequences are shown in the Fig. 17.

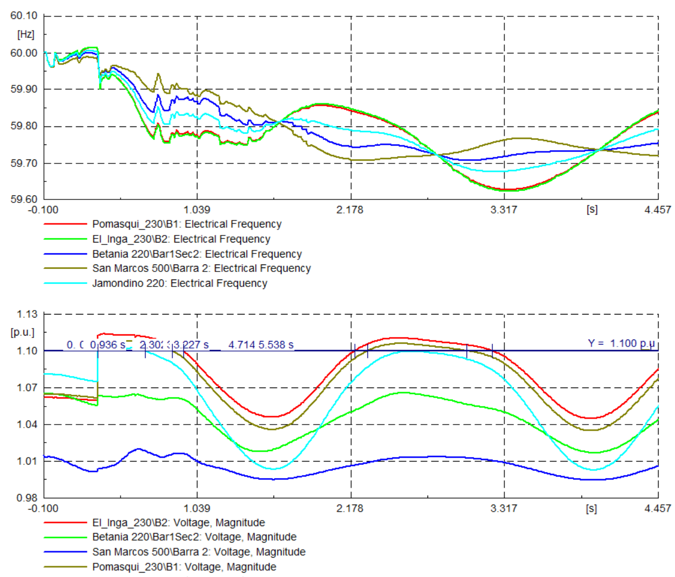

Fig. 17. Frequency and voltage evolution in the event 10/16/2016 without tripping by the over-power stage of the Jamondino substation's SPS.

In this case, the frequency would have been decreased close to the LFSS limits what leads to activate the load shedding in the Colombian busbars. Furthermore, temporary overvoltages would appear in both countries busbars specially in Ecuador. This situation would lead the operation of the over-voltage protection scheme fast step. All these disconnections would have disintegrated the power system, finishing in a complete collapsed of both power systems.

Thanks to timely operation of SPS, the frequency and voltage variables remained under control as shown in the Fig. 18.

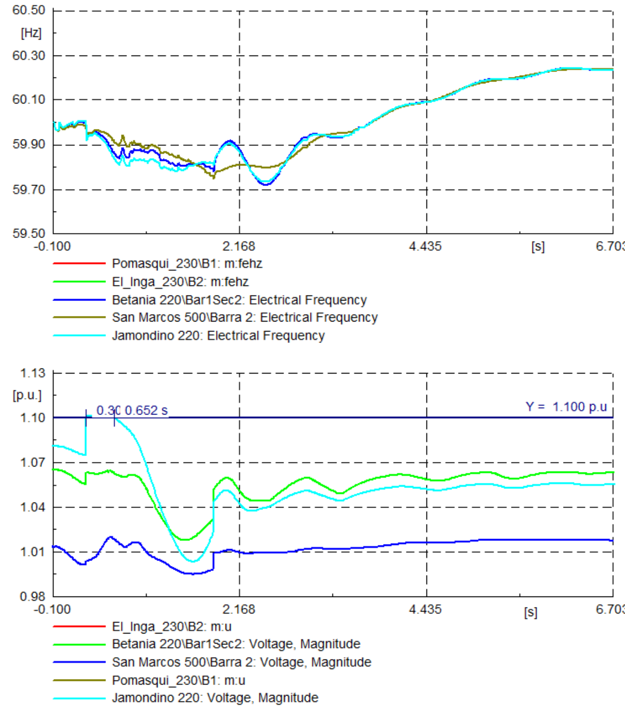

Fig. 18. Frequency and voltage evolution in the event 10/16/2016 tripping by over-power stage of the Jamondino substation's SPS.

B. Tripping condition due to under-voltage

In this case (event 11/30/2016), a power swing condition was presented in the interconnection lines as a result of a 950 MW disconnection of generation in Ecuador (a sudden generation tripping). The Fig. 19 shows this event and the operation of the protective relay of the SPS.

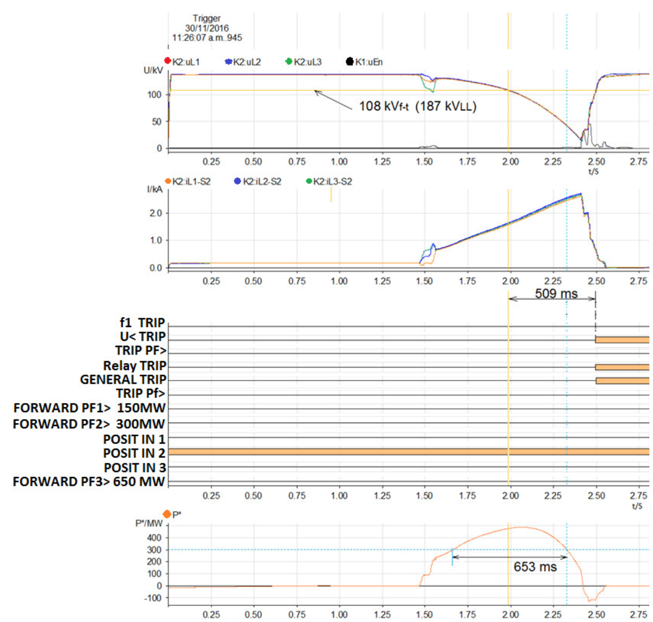

Fig. 19. Operation of under-voltage stage of the SPS.

As it can be noted, the voltage reached its setting faster (500 ms) than the over-power in forward direction (800 ms), releasing a trip by under-voltage parameter (U<).

Continuing with the same procedure in the analysis of the events by using RMS simulation, the power evolution of this event w/wo acting of the SPS is shown in the Fig. 20 as well.

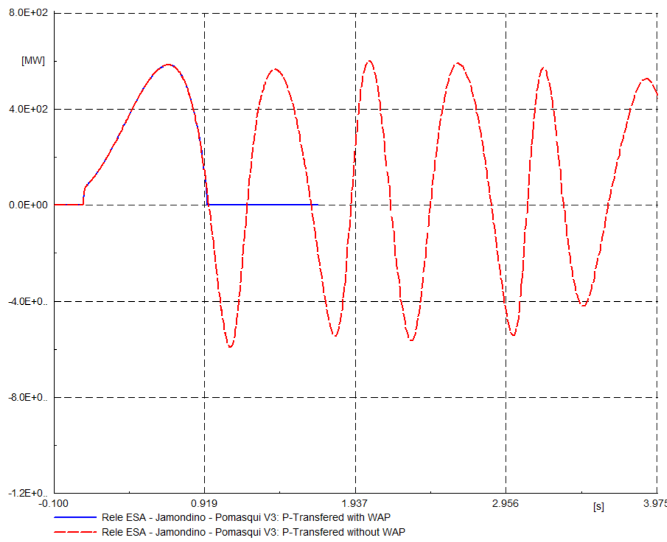

Fig. 20. Depicting of the power evolution in the event 30/11/2016 with (blue color) and without (red color -dashed line) tripping for under-voltage stage of the Jamondino substation's SPS.

A power swing condition between -450 and 450 MW would appeared if the SPS had not operated. Similarly to the previous case, the voltages and frequency signals of the busbars, close to the interconnection, would have also been critically disturbed. The Fig. 21 illustrates what would have happened.

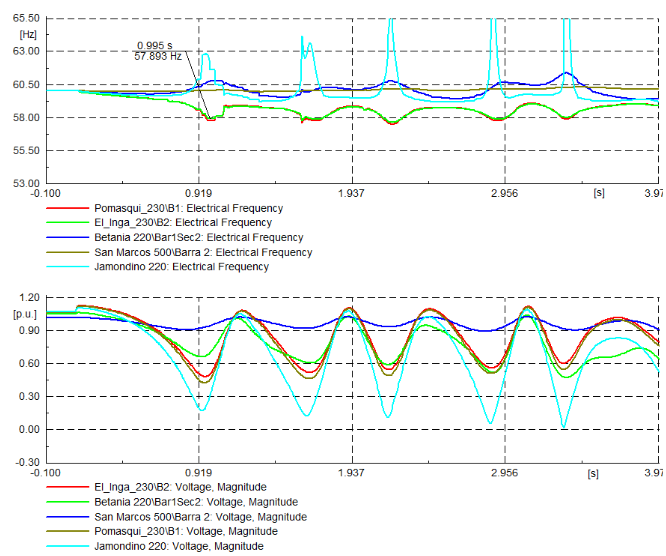

Fig. 21. Frequency and voltage evolution in the event 30/11/2016 without tripping by the over-power stage of the Jamondino substation's SPS.

Both variables would oscillate exceedingly. In fact, the under-frequency would conduct to operate of the LFSS due to the low frequency in the Ecuadorian power system whilst an over-frequency phenomenon in the Colombian network would come up finishing in the generators coming loose after LFSS of Colombia acted.

Additionally, Voltages would swing from 0.2 to 1.0 p.u. in a big period leading to the both systems collapse for low voltage in the first valley period of the oscillation. This would achieve a total blackout.

IV. Conclusions

The Area Separation Scheme implemented in the international interconnection Colombia - Ecuador protects the power systems of both countries, especially when several events of a great magnitude occur in any of these networks. Its operation is coordinated with the electrical protection system, particularly with distance protections. Therefore, its variables such as over-power, under-voltage and under-frequency tripping times are above zones 2 timing of conventional electrical protection system, it means, longer than 400 ms. This can be noted that SPS' stages tripped adequate at 500 and 800 ms by under-voltage and over-power conditions, respectively.

The scheme proposed by this work increases the reliability of both power systems, and prevents problems related to over-voltages, overloads and blackouts in both countries.

Events have demonstrated how logics and settings applications obtained during the studies, implementation and tests were accomplished satisfactorily, which make the Area Separation Scheme safer for power systems. Following the methodology of previous electrical studies, analysis, criteria and implementation employed in this work, it would be possible to use the SPS to other electrical networks with a successful performance to separate two or more countries or electrical areas in the same country.

Finally, this SPS presents an alternative to improve the operation of the power systems and reduces the impacts on the electrical systems. Others involve Phasor Measurement Units (PMU) that are being evaluated for this interconnection.

V. References

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G. Gutierrez received his B.S. degree in Electrical Engineering from Universidad Nacional de Colombia, Medellin - Colombia, in 1997 and the M.Sc. degree at Universidad Pontificia Bolivariana, Medellin - Colombia 2002. Since 2004 he has been working at GRUPO ISA, Colombia, and nowadays he is working as a Specialist of Operation at ISA-INTERCOLOMBIA in Medellin - Colombia. His research interests include electrical protection studies for power system, relay settings and tests, and fault disturbance analysis.