Vulnerability of the Colombian Electric System to Blackouts and Possible Remedial Actions

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***Abstract*—The consequences of big blackouts that have recently affected electric systems worldwide motivated to carry out a study in order to determine the vulnerability of the Colombian electric system to this type of incidents, and to establish the applicable actions to maintain a reliable operation. The study is based on the lessons learned about prevention and management from the most representative incidents worldwide, as well as from the regulations governing reliability and related aspects in other countries. The most important subjects about the regulation of a country should make emphasis to avoid the occurrence or minimizing the impact of blackouts are identified. An analysis of the Colombian regulation is carried out discovering main deficiencies and leading to regulatory actions that may solve the deficiencies found. Conclusions extending the results to other countries are also presented.**

***Index Terms*—Power system faults; Power system monitoring; Power system protection; Power system reliability; Power system security; Power system stability.**

I. Introduction

In the last ten years, several blackouts catalogued as very serious have taken place in North America, Latin America, Asia and Europe. Considering only 2003, five major blackouts with worldwide repercussion occurred, which is worrisome considering the important economic, social and even political consequences that these incidents have. In economic terms, they mainly affect the commercial and industrial sectors; in the social level they affect the population well-being, the security, the entertainment, the educative and cultural activities, etc., and in the political level they generate distrust and credibility loss in the governments and are a direct cause of the loss of prestige of the involved electrical companies.

Knowing these consequences and the importance of preventing this type of incidents to occur in any country and in Colombia in particular, a study to determine the vulnerability of the Colombian electric system to blackouts and to establish the actions that must be applied to maintain a reliable operation was performed.

The study focuses on the transmission system reliability, given that most of the available literature is dedicated to the causes and recommendations related to high voltage grids and because of their major impacts on power systems.

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II. Case Analysis

The study of international experiences in the topic of blackouts is centered on the revision of the main characteristics of nine major incidents that occurred in the world during the last decade [1]-[12], their comparison and classification, the recognition of the conditions previous to the blackouts, the available reaction times, as well as the verification of the causes of said incidents.

A. Characteristics of the Studied Blackouts

The revision of the characteristics of the incidents was done based on five significant indices. These indices correspond to Number of Customers without Service, Lost Load (MW), Blackout Time Duration, Affected Population (Percentage of total country population), and Severity (System-minute).

Table I shows the indicators corresponding to the first three indices for each one of the nine incidents analyzed. These figures were determined from the blackout final analysis reports.

TABLE I
INDICATORS (PART I)

Blackout	Customers without Service (Number)	Lost Load (MW)	Time Duration
North America November 9, 1965	30.000.000	20.000	More than 13 hours
North America July 2, 1996	2.000.000	11.850	30 minutes to some hours
North America August 10, 1996	7.500.000	28.000	Few minutes to 9 hours
Brazil March 11, 1999	75.000.000	24.731	Up to 4 hours
Iran March 31, 2003	22.000.000	7.063	8 hours
London August 28, 2003	410.000	724	37 minutes (0.62 hours)
Denmark and Sweden September 23, 2003	4.000.000	6.550	5 hours
Italy September 28, 2003	57.000.000	24.000	5 to 9 hours
North America August 14, 2003	50.000.000	61.800	16 to 72 hours in United States and up to 192 hours in Canada

It is observed that the blackout that affected the largest amount of customers occurred in Brazil, followed by the blackout of Italy, and the blackout of North America on

August 14, 2003. This last incident was the event in which the largest amount of load was lost and is also the one reporting the longest duration. The more localized blackout with fewer customers affected, smaller loss of load and smaller duration was the blackout occurred in London in the same year.

Other two indices used to study the incidents were Affected Population (%) that run out of electricity due to the blackout (1), and Severity (System - minute) (2) [1]. These are calculated as,

$$\text{Affected Population } (\%) = \frac{\text{Number of customers without service}}{\text{Population of the affected country(ies)}} \times 100 \qquad (1)$$

$$\text{Severity (System - minute)} = \frac{\text{Energy not served (MWh)}}{\text{Base of Power (MW)}} \qquad (2)$$

The classification of incidents according to the Severity level is as following:

TABLE II
DISTURBANCE SEVERITY CLASSIFICATION

Classification (Level)	Severity (System – minute)	Interpretation
0	<1	Acceptable
1	1 to 10	Not severe
2	10 to 100	Severe
3	100 to 1000	Very severe
4	>1000	Catastrophic

Table III shows the calculated indices for each one of the nine incidents, and the blackouts classification as per Table II. N.a. means that there was not available information for some incidents.

TABLE III
INDICATORS (PART II)

Blackout	Affected Population (%)	Severity (System – minute)	Classification (Level)
North America November 9, 1965	14,12	N.a.	N.a.
North America July 2, 1996	0,68	N.a.	N.a.
North America August 10, 1996	2,54	N.a.	N.a.
Brazil March 11, 1999	44,65	117	3
Iran March 31, 2003	32,22	30	2
London August 28, 2003	5,43	2	1
Denmark and Sweden September 23, 2003	27,86	33	2
Italy September 28, 2003	100,00	225	3
North America August 14, 2003	15,51	28	2

From the calculated indices it is clear that the blackout of Italy was the most severe, with 100% of Affected Population and a Severity Level of 3, ranking it as Very severe. The next severe one would be the blackout of Brazil, with the same Severity Level but with Affected Population of 44,6%. The less severe blackout with this classification is the one of London (Severity Level 1). The North American blackout had an Affected Population of 15,5% and a Severity Level of 2.

In order to have a graphical presentation of the results a suggested way to present the blackouts is shown in Fig. 1. The six blackouts with data are shown there, using a logarithmic scale for the Severity in the Y-axis, and presenting the Affected Population in the X-axis. From left to right the blackouts of London, North America, Denmark and Sweden, Iran, Brazil and Italy are represented.

In addition, to enhance the classification of the blackouts, a color code based on the relation between those two indices is proposed. The transition from a yellow color for less impact blackout with a trend towards red for the most serious is proposed. Table IV shows the meaning giving to each color.

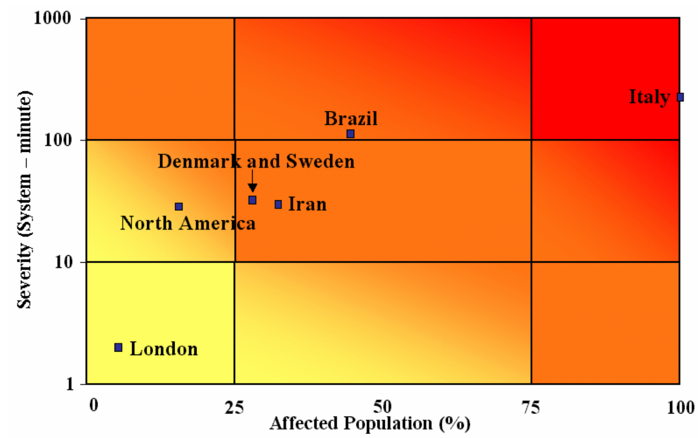

Fig. 1. Severity vs. Affected Population

TABLE IV
PROPOSED COLOR CODE

Color	Meaning
(yellow)	Low impact: It corresponds to Low Severity blackouts and a Low percentage of Affected Population
(yellow–orange)	Middle – Low impact: It corresponds to Middle Severity blackouts and a Low percentage of Affected Population, or Low Severity blackouts and a Middle percentage of Affected Population
(orange)	Middle impact: It corresponds to Middle Severity blackouts and a Middle percentage of Affected Population, High Severity blackouts and a Low percentage of Affected Population, or Low Severity blackouts and a High percentage of Affected Population
(orange–red)	Middle – High impact: It corresponds to High Severity blackouts and a Middle percentage of Affected Population, or Middle Severity blackouts and a High percentage of Affected Population
(red)	High impact: It corresponds to High Severity blackouts and a High percentage of Affected Population

B. Previous Conditions and Reaction Times

Table V shows some conditions before the start of the blackouts, the hour in which the sequence of events began, and the time the operators had to react until there was no form to avoid them.

It is observed that transmission lines and generators maintenance are among the preexisting conditions for four of the studied blackouts. Regarding reaction times, for three of the incidents with available information, the operators had between 30 minutes and four hours to take appropriate actions to avoid or minimize the blackout consequences.

TABLE V
PREVIOUS CONDITIONS AND REACTION TIMES

Blackout	Previous Conditions	Start Hour	Reaction Time
North America November 9, 1965	- Normal temperature - Normal load level	17:16	Few minutes
North America July 2, 1996	- High temperature	14:24	One minute
North America August 10, 1996	- High temperature	15:48	One hour
Brazil March 11, 1999	- Normal temperature - Normal load level	22:16	N.a.
Iran March 31, 2003	- High load level - Some plants and transmission lines out of service	21:20	N.a.
London August 28, 2003	- Two transmission lines out of service	18:11	Few minutes
Denmark and Sweden September 23, 2003	- Five transmission lines and four generation units out of service - Normal temperature - Normal load level	12:30	Few minutes
Italy September 28, 2003	- Normal temperature - High power transfers toward the country	3:01	Half and hour
North America August 14, 2003	- High temperature - High load level - Some generators and five capacitor banks out of service	12:15	Four hours

C. Causes of the Blackouts

The analysis of the blackout causes lead to the following:

- The incorrect protection elements operation was the predominant factor, in five incidents, and a factor that accelerated the system outage for two additional ones. Inadequate operation was reported in one additional one.

- The contact of lines with trees by inadequate vegetation trimming was a common element for four of the incidents.

- The inadequate defense or load shedding plans were reported for three incidents, while design problems were evidenced for two additional ones.

- Deficiencies in voltage stability support and the supplying of reactive power appeared in four of the incidents.

- The lack of inspection and maintenance programs, as well as inadequate system sizing criteria was reported for one of the blackouts. In general, the reports call for more robust networks to minimize the impact.

- Absence of the sense of urgency before the situation degraded, as well as communication failures and regulatory and institutional problems were reported in two incidents.

- The reliability organizations not bringing the necessary support, the operators' inadequate training, information technology problems, and partial visibility of the transmission system were reported in one of the incidents. The lack of generation reserves was also evident in another one.

These results are summarized in the following graph:

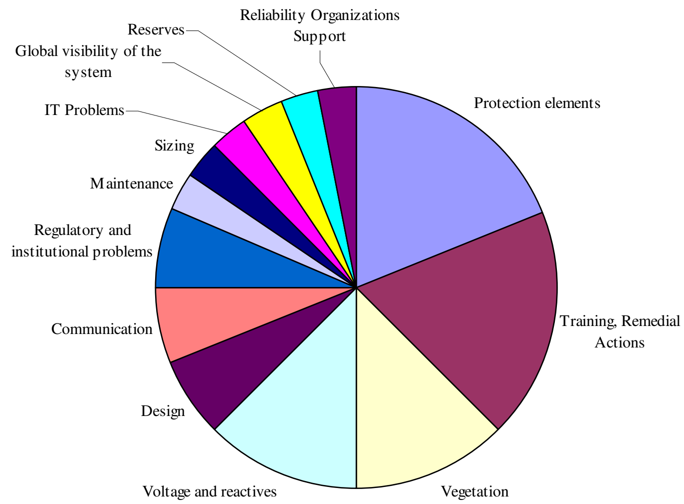

Fig. 2. Causes of the blackouts analyzed

III. RELIABILITY IN INTERNATIONAL REGULATIONS

The revision of the final reports indicated that the causes and recommendations are directly related to reliability problems. This further indicated the need to review the regulations governing this subject in some countries.

The selected ones were: In Europe UCTE (Union for the Coordination of Transmission of Electricity) [13] and Nordel (entity for the cooperation between the Transmission System Operators of the Nordic countries) [14], in South America Argentina [15], and North American NERC (North American Electric Reliability Council) [16].

The main contributions of these regulations with emphasis on reliability to avoid the occurrence of possible blackouts or at least to diminish their impact were studied. Tables VI to VIII present the main subjects with the following conventions: "×" means that the regulation addresses the identified subject while "⊗" denotes detailed treatment.

As it is observed, the treatment of these aspects by the examined regulations has allowed to carry out their classification in those strongly regulated, fairly regulated, and little or no regulated, as well as to identify the main strengths and weaknesses of the regulations in relation to the reliability, since for each one of them it is evident from the look if they treat or not the considered subjects.

Also in these tables the topics where main deficiencies were identified for the Colombian system are highlighted. Section IV explains in detail these deficiencies.

TABLE VI
SUBJECTS STRONGLY REGULATED

Thematic	Subjects about reliability	Regulation			
		UCTE	NOR.	ARG.	NERC
SR	Restoration plan	⊗	×	×	⊗
SR	Black start	×	×	×	×
PO	Reactive power management and voltage control	×	×	×	×
PO	Emergency plans	⊗	×	×	⊗
PO	Manual load shedding	×	×	×	×
PO	Electrical islanding	×	×	×	×
PO	Security criteria	×	×	×	×
PO	Permanent verification of the protection system	×	×	×	×
PO	Under frequency load shedding	×	×	×	×
IS, PO	Redundant telecommunication systems	×	×	×	×
M	Maintenance coordination	×	×	×	×
PO	Upgrade of information for planning and operation	×	×	×	×
IS, PO	Communications during emergencies	×	×	×	×
PO	Regulation reserves	×	×	×	×
IS	Event record systems	×	×	×	×
IS	Exchange of information between areas or systems	×	×		×
HF	Training	×		×	⊗
PO	Specification of functions for reliability entities	×		×	×

TABLE VII
SUBJECTS FAIRLY REGULATED

Thematic	Subjects about reliability	Regulation			
		UCTE	NOR.	ARG.	NERC
PO	Technical requirements of the supervision and control system	×			×
PO	Grid stability	×			×
HF	Staff certification			×	×
IS	State estimator and contingency analysis	×			×
IS	Alarms	×			×
SR	Relays operation during the system restoration	×			×
IS	Continuous upgrade of IT systems	×			×
PO	Interruptible customers			⊗	×
PO	Back up control center	×			⊗

TABLE VIII
SUBJECTS LITTLE OR NO REGULATED

Thematic	Subjects about reliability	Regulation			
		UCTE	NOR.	ARG.	NERC
SR	House load operation	×			
PO	SCADA and communication security				×
M	Relay maintenance				×
IS	Screens				×
PO	Dynamic models				
M	Vegetation management				
PO	Distance protection relays				

IV. COLOMBIAN REGULATION ANALYSIS

The Colombian regulation analysis [17]-[18] consisted on the comparison of how the identified subjects of section III are addressed against the international regulations. Also the studied blackout analysis and causes were taken into account for comparison purposes. This allowed to determine deficiencies of the Colombian regulation.

The main identified regulatory deficiencies and the necessary regulatory actions to solve these failures are presented hereinbellow. Furthermore, for additional clarity deficiencies were classified in five main thematics: Human factors, Information systems, System restoration, Maintenance, and Planning and operation.

A. Human Factors (HF)

1) Training Regulatory Deficiencies

No reference to the control center operator training, the obligatory existence of a training program and a permanent training record. Also the amount of annually training and its duration, trainers qualifications, the training subjects, and the evaluation procedures to verify the knowledge assimilation by the operators need to be regulated.

Likewise the use of tools such as Operator Training Simulators (OTSs) to allow the operator to face emergency conditions, and the use of simulator models that match the real time conditions have to be regulated.

In addition the regulation of periodic visits of the operators to the national control center complemented with visit to other countries control centers is advisable. The sharing of knowledge and experiences with other operators should be addressed too.

2) Staff Certification Regulation

The regulation shall establish certification procedures for the control center operators involving the approval of a proficiency test certifying their capability to handle reliability related issues.

B. Information Systems Regulation (IS)

1) State Estimator and Contingency Analysis

The regulation shall establish the obligatory use of state estimator and contingency analysis in real time as basic analysis tools of the National Dispatch Center, modeling the entire Colombian system plus international interconnections to the necessary extent allowing monitoring the elements of the Venezuela and Ecuador networks that could directly impact the Colombian system reliability. The model must be timely updated.

The state estimator observability shall be system wide and it shall run every thirty seconds or faster.

2) Screens

The regulation shall mention the requirements that the control centers must meet about visualization screens to allow operators to easily detect changes in the power system state.

3) Alarms

The regulation shall address the requirements that must be met by the alarming systems, indicating the existence of a notification mechanism to the operators in case the main alarming system fails, as well as the means to easily identify the equipment with problems and the alarms priority scheme.

The number of alarms to be handled by the system under the most severe emergency must also be established.

4) Continuous Upgrade of IT Systems

The regulation shall establish the convenience to use emerging technologies such as Synchronized Phasor Measurements as a means to improve system reliability, provided a benefit-cost study demonstrates the applicability of systems such as WAMS (Wide Area Measurement Systems) in the country, [19]-[24], enhancing the grid real time monitoring.

C. System Restoration Regulation (SR)

1) Restoration Plan

Although the regulation establishes that the control centers follow a restoration scheme, it shall further indicate the periodic verification of such a scheme, and the need to train the operation personnel in its implementation.

2) Relays Operation During the System Restoration

Although the regulation indicates that synchronism checking relays have to be installed to supervise the automatic reclosing and manual closing, it shall also establish the adjustments of these relays to avoid potential problems during reclosing.

The regulation must establish the periodic review of the constrains regarding phase angles preventing the line reclosing during emergencies addressing the adjustment of the synchronism checking relays, and the required alternative means to allow the direct closing of critical interconnections to maintain stability during emergencies.

3) Black Start and House Load Operation

Although the regulation includes the capacity of starting from collapse conditions among the services that generators may provide, it shall also address the need to have sufficient number of units to restore the system in case of a large event, and shall also determine suitable locations. The periodic obligatory evaluation of this capacity shall also be regulated.

In case the installed units with the black start capability is not enough for fast restoration after a major incident, contracts with generators shall be made to guarantee the availability of this service.

D. Maintenance Regulation (M)

1) Vegetation Management

Although the regulation indicates that the transmission line maintenance must guarantee the safe and reliable operation during their guaranteed life time, it shall be specific about the periodic maintenances required to insure security distances. A program of vegetation management with the regularity of these maintenances shall be formulated.

2) Relay Maintenance

The regulation indicates that the adjustment and maintenance of the protection relays for the line bays are the transmission utility responsibility, as well as the tests for the protection relays to verify their correct operation. However it has to address the obligatory requirement of the periodic maintenance of the protection relays, their calibration and settings and the documentation of such maintenance for both generators and transmission companies.

E. Planning and Operation Regulation (PO)

1) Reactive Power Management and Voltage Control

The regulation shall establish system bus voltages during contingency situations, and consider load shedding to avoid voltage collapses. These actions shall be included in the emergency system operation procedures.

It shall also indicate the planning by zones of reactive reserves, and the reactive power be generated near consumption points. In case that reactive reserves are limited in some zones, an available option is to attract investments in new generation facilities by regulatory incentives.

2) Emergency Plans

The regulation shall mention the need to develop an obligatory emergency plan and that the operation demonstrate compliance with the performance plan for emergencies.

3) Manual Load Shedding

The regulation shall indicate procedures for an obligatory manual load shedding plan be applied during emergency cases.

4) Distance Protection Relays

Although the regulation establishes that the currents and impedances seen by the neighboring relays must not cause the outage of additional elements, it is not specific about the technical requirements that the distance protection relays must meet.

The regulation shall establish the minimum value of the current detected by relays in zone 3 so that they do not act during overloads during emergencies. Another option to prevent undesirable operation of these relays is to link them with information obtained from remote sites confirming the action as necessary.

5) Electrical Islanding

The regulation shall indicate the controlled separation of the system in electrical islands with enough generation during serious emergencies, preventing as far as possible the amount of affected customers and reducing the service restoration time. It must establish to carry out studies to define the separation criteria, the number of islands, the opening points, and the approaches for re-synchronization.

6) Security Criterion (N-1)

The regulation indicates that deterministic or probabilistic methods can be used for the evaluation of the reliability criteria, and that for the reliability analysis by deterministic methods the N-l criterion be used.

The regulation shall indicate that the operation procedures and the training address multiple contingencies, and the convenience to review the N-1 criterion for the Colombian power system. It shall also address the requirements for new ties with other countries, and the analyses required to determine meeting reliability criterion of N-2 or N-3.

7) Dynamic Models

The regulation shall indicate the obligatory nature of periodic tests to generation units upon failures to know their dynamic behavior.

The generation unit dynamic models must be carefully established with the purpose of reviewing, validating and updating their dynamic characteristics, since they must consider the variation of their behavior during any operating condition.

8) Interruptible Customers

The regulation shall specify measures of demand management during emergencies to improve system reliability, establishing measures such as agreements with interruptible customers, to put them in practice during emergency situations.

9) SCADA and Communication Security

The regulation shall establish the obligatory nature to implement the necessary measures to maintain the security in the SCADA system, and in the communications, preventing the accesses of non-authorized operations to the SCADA systems. This shall include the handling of users authentication, passwords, use of security related hardware and software with firewalls and on-line detection of computer system virus.

V. Conclusions

One of the aspects analyzed in this study is to characterize the blackouts about their incidence and their effect on the electrical systems and the affected customers. Indicators have been calculated that allow to compare blackouts with practical measuring units. In this form a "ranking" of blackouts can be started to record them in the future.

The proposed color code to classify the blackouts respect to the relation between their Severity and the Percentage of the Affected Population, helps to visualize the level of importance of each blackout with respect to the selected indices. This color code could be adopted in a global map in which the most prone zones to this type of phenomena could be shown.

The compilation of information made about the main blackouts that have occurred worldwide, allows to establish the importance that those incidents had for their respective systems, and helps to understand their causes in order that preventive measures be taken to avoid them or to quickly restore the systems.

The common causes for the referenced blackouts have shown commonalities that also illustrate potential remedies. The compiled information for the time the operators had to react confirms that some of these blackouts could had been avoided by taking the appropriate timely actions.

The case of the Colombian regulation analysis shows that deficiencies exist. The methodolgy followed could be easily extended to the analysis of any country. The paper suggests a classification of relevant matters that could be adopted in a standardized approach to this type of studies.

The human factor impact on system reliability is heavy. Unfortunately, this importance is not reflected in the Colombian regulation, where training or certification processes are not established.

A key factor to avoid the occurrence of blackouts is that operators have sufficient high quality information about the system state. Deficiences about some aspects related to information systems, specially about the tools of network analysis, visualization screens, and alarms have been detected.

The actions taken to prevent blackouts are as important as those actions that must be planned for the cases in which they can not be avoided. In this respect, restoration plans are critical.

Counting on suitable maintenance procedures and to implement them appropriately is fundamental to prevent blackouts, given that it has been demonstrated that they are related to the main detected causes. Improvements in relation to the vegetation trimming, and maintenance of protection relays are mandatory.

In order to guarantee the proper system operation and to avoid the occurrence of blackouts, it is necessary to suitably carry out the network planning and operation. The N-1 criterion, and the operation of distance protection relays are crucial in this respect. Likewise, the separation of the system in electrical islands, the manual load shedding, and the emergency plans, with adequate generation unit dynamic models are required.

The new emerging systems based on technologies such as the Synchronized Phasor Measurements are the future for real time system monitoring and control. They shall be addressed in regulations for further improved reliability.

VI. Acknowledgment

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