# Blackouts: Description, Analysis and Classification

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*Abstract:* - Thousands of disturbances occurred in the modern power systems every year in the world. Some of them led to blackouts. Large scale blackouts rarely happened in power systems, but they caused enormous economical and social damages. In order to prevent future blackouts, it is very important to review the previous large scale incidents and to draw their common characteristics. This paper analyzes some major blackouts in the world, classifies their features in each phase and summarizes their mechanisms.

*Key-Words:* - Blackout, power system control, power system stability, WAMS, FACTS.

## 1 Introduction

The system operator should ensure the security of his power system and transport stable energy to the customers. Blackouts, as disastrous phenomena in power systems, occur throughout the world. Small scale blackouts often happen, while large scale blackouts rarely occur. Large scale blackouts cause enormous economical and social damages. From 1965 to 2005, the largest scale blackouts happened in the Northeast of the United States and in the Canada on August 14, 2003, and in Italy on September 28, 2003. The first one affected approximately 50 million people in eight U.S states and two Canadian provinces. The economic losses were about $7 ~ $10 billion [1]-[2]. The second one affected about 57 millions people in Italy and 180 GW of load was interrupted [3]-[5]. This blackout in Italy is the largest one in Europe. Analyzing and studying the reasons and the mechanisms of blackouts would be the first step for blackout prevention.

This study investigated 37 blackouts [1], [5], [7], [8], [10], [11], [12], [13], [14], [15], [20], [21], [24], [25], [26], [27], [28] throughout the world, and tried to find their common characteristics. We introduced the divisions of the whole process and divided the progression of blackouts into several sequential phases. According to these different phases, the phenomena of those cited large scale incidents were compared, and it seems to exist some common characteristics. In this study, we highlighted the common mechanism of blackout by analyzing their progression.

## 2 Analysis of Blackouts

Blackouts seem to progress with some regularity. Previous studies showed that the progression of blackouts after the occurrence of initiating events could be divided into steady-state progression and transient progression [6]. In our study, the progression of 8 blackouts [1], [5], [7], [8], [10], [11], [24], [26], from which detailed information are available, were investigated. The results suggested that the progressions of blackouts can be divided into several phases. The diagram shown in Figure 1 clearly describes these phases which are precondition, initiating events, cascade events, final state and restoration. Among these five phases, cascade events can be further divided into three phases in the process of some blackouts: steady-state progression, triggering events and high-speed cascade. A high-speed cascade usually follows the critical point -- the occurrence of triggering events. But, not all of the blackouts have all the phases listed above. For example, the steady-state progression was skipped in some previous blackouts. In these cases, the initiating events were also the triggering events that started the high-speed cascade. For the blackout in Croatia on January 12, 2003, the initiating event at 16:43:58 triggered the high-speed cascade, and the blackout happened within 30s (Fig.4) [8].

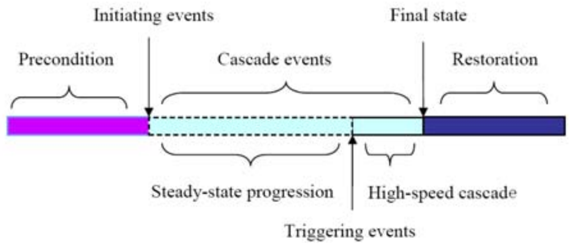

Fig.1. Phases of Blackout

In the following sections, the blackouts will be discussed according to these sequential phases.

## 2.1 Precondition

37 previous blackouts [1], [5], [7], [8], [10], [11], [12], [13], [14], [15], [20], [21], [24], [25], [26], [27], [28], which have comparative detailed information, were collected in this study. Different preconditions happened in these blackouts, but we can classify these blackouts according to their common characteristics. The classification is carried out as follows:

1. System condition is stressful in summer peak and winter peak.

The table 1 shows that 13 blackouts happened in summer peak and 11 blackouts in winter peak. Moreover, 64.9% of the blackouts (24/37) happened in summer peak and winter peak when there was a high electrical demand and 35.1% of the blackouts (13/37) happened in normal system condition.

2. Aging equipments

The Russia power system was ever a system with high security. No blackout happened from 1975 to 2005 [9]. However, a blackout occurred in Moscow on May 25, 2005, because more than 70% of the Moscow 220kV power substations were working over their life time, and such system became unstable during the emergency condition.

3. Inadequate reactive power reserve

Inadequate reactive power reserve was the reason of the blackout in Northeast United States and Canada on August 14, 2003 and in France on December 19, 1978. Reactive power is related to the voltage. Lacking of reactive power decreased the flexibility of voltage control, which may increase the risk of voltage collapse.

4. Some important equipment out of service

Before the blackout in Athens and Southern Greece on July 12, 2004, one 125 MW generating unit in Peloponnesus (Megalopolis) and one generating unit in Northern Greece were out of service. This led the system to a stressful condition [10].

Table 1
Blackouts in summer and winter peak

| Blackouts in Summer peak | Blackouts in winter peak |
|---|---|
| 07/1978, New York's suburbs | 09/11/1965, United States |
| 1987, Japan | 19/12/1978, France |
| 24/08/1994, Italy | 01/1981, Idaho, Utah and Wyoming, United States |
| 08/06/1995, ISRAEL power network | 27/12/1983, Sweden |
| 02/07/1996, 14 states in the United States | 12/01/1987, France |
| 07/08/1996, Big Rivers Electric Corporation, United States | 12/03/1996, Florida, United States |
| 10/08/1996, California Pacific Northwest | 01/1998, Canada, New York and New England |
| 26/08/1996, New York, Unite States | 12/1998, San Francisco, California Bay Area |
| 07/1999, New York City | 01/12/2003, Southeastern Massachusetts from New Bedford to Provincetown to the islands |
| 14/08/2003, United States and Canada | 12/01/2003, Southern part of Croatia and a part of Bosnia Herzegovina |
| 28/08/2003, South London | 14/12/1994, Arizona and Washington state United States |
| 05/09/2003, West Midlands | |
| 12/07/2004, Athens and Southern Greece | |

5. Natural reasons such as wind, thunderstorms, fog, geomagnetic disturbances, fire, etc.

Before the blackout in the United States on April 16, 1996, the area had an unusually high amount of dust and soot from prairie fires due to drought conditions. This increased the possibility of flashovers [11].

The voltage collapse in Quebec in 1989 was caused by the side effects of a geomagnetic storm during a period of heightened solar activity [12].

## 2.2 Initiating events

Initiating events were various in different blackouts. These events can directly cause blackout or can worsen the system condition which may indirectly lead to blackout. Short-circuit, overload, protection hidden failure are the usual initiating events, and other events such as loss of generator sometimes can also be initiating events. The initiating events of some blackouts, of which related information could be obtained, are described in Table 2.

Table 2
Initiating events of blackouts

| Blackouts | Initiating events 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 09/11/1965 United States | | √ | √ | |
| 07/1978 New York | | | √ | |
| 27/12/1983 Sweden | | √ | | |
| 08/06/1995 ISRAEL | √ | | | |
| 12/03/1996 Florida | | √ | | |
| 16/04/1996 Unite States | √ | √ | | |
| 02/07/1996 United States | √ | | | |
| 10/08/1996 California Pacific Northwest | | √ | | |
| 26/08/1996 New York | | | √ | |
| 21/09/1996 Allegheny | | | √ | |
| 11/03/1999 Brazilian | √ | | | |
| 12/01/2003 Croatia | √ | | √ | |
| 14/08/2003 Northeast United States and Canada | √ | | | |
| 28/08/2003 London | | | √ | |
| 23/09/2003 Eastern Denmark and Southern Sweden | | | | √ |
| 28/09/2003 Italy | √ | √ | | |
| 12/07/2004 Athens and Southern Greece | | | | √ |
| 14/03/2005 South Australia | √ | | | |
| Total : 18 | 8 | 6 | 6 | 2 |

1- Short-circuit, 2- Overload, 3- Protection hidden failure, 4- Loss of power plants.

## 2.3 Cascade events

The cascade is a dynamic phenomenon. It can be triggered by the initiating events. These initiating events can cause power oscillations and voltage fluctuations which may result in high currents and low voltages. The high currents and low voltages can be detected by other lines and be treated as faults. The lines and the generators can trip to protect themselves from damage, which may lead more and more lines and generators to become out of order. Besides power oscillations and voltage fluctuations, line overloads also can cause cascade. When a line is tripped, due to an overload, the neighbor lines can become overload and be tripped [2].

By analyzing some important blackouts [1], [5], [7], [8], [10], [11], [24], [26], we can divide the period of cascade events into steady-state progression and high-speed cascade (Fig.1). In the period of steady-state progression, the progression of the cascade events is slow, and the system can keep balance between the generation and the consummation. During this period, the major incident is the cascade overload. Because of the slow speed of the worsening of the situation in the period of steady-state progression, it may be a good opportunity for the system operator to take actions to stop the spread of the cascade overload and then, prevent the occurrence of blackout. While the triggering events have triggered the high-speed cascade, the balance between the generation and the consummation may be broken, series of system equipments may be tripped rapidly, and system collapse can happen in a very short time. In the period of high-speed cascade, it is generally too late for the system operator to take actions to stop the rapid progression of blackout.

The period of cascade events was studied by analyzing the accumulated number of the tripped lines, transformers and generators in this period. Data of the United States Blackout on August 14, 2003, the Italy Blackout on September 28, 2003 and the Croatia Blackout on January 12, 2003 were cited to describe the progression of blackout during the cascade.

In the United States Blackout on August 14, 2003, the triggering event was the tripping of the East Lima-Fostoria Central 345-kV line at 16:09:06, and this event caused large power oscillations through New York and Ontario into Michigan. The high-speed cascade was triggered and led to blackout (Fig.2).

In the Italy Blackout on September 28, 2003, we can clearly see the period of steady-state progression and the period of high-speed cascade (Fig.3). The triggering events tripped the Mettlen – Airolo 220kV line and Sils- Soazza line in Switzerland at 03:25:21. These triggering events directly led to 17 lines tripped within 21 seconds.

In the Croatia Blackout on January 12, 2003, the steady-state progression was skipped (Fig.4). The initiating event, which was also the triggering event, triggered the high-speed cascade, and blackout happened within 30 seconds.

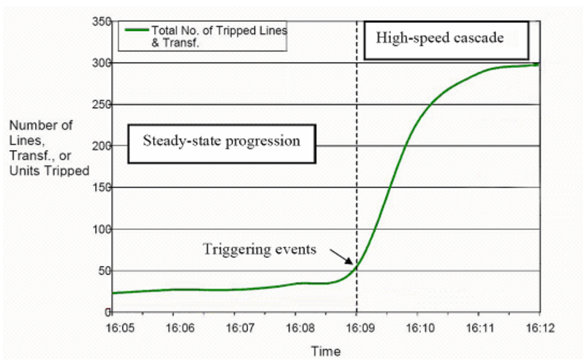


Fig.2. Accumulated Line and Generator Trips during the Cascade in the United States Blackout on August 14, 2003 [1]

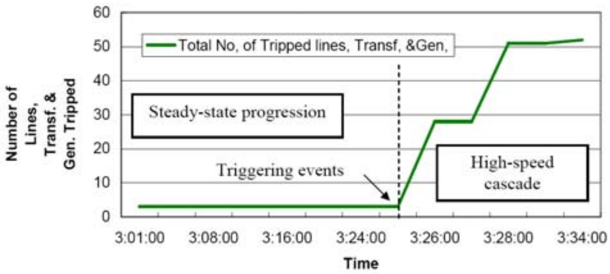


Fig.3. Accumulated Line and Generator Trips during the Cascade in the Italy Blackout on September 28, 2003 [Data from reference 3]

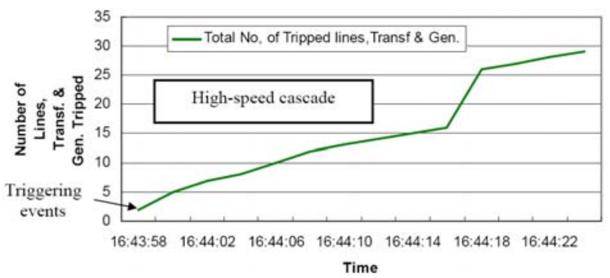


Fig.4. Accumulated Line, transformer and Generator Trips During the Cascade in Croatia Blackout on January 12, 2003 [Data from reference 8]

The duration of the periods of steady-state progression, high-speed cascade and restoration of 7 blackouts was listed in Table 3.

Table 3
Period of the blackouts

| Blackouts | Steady-State progression | High-speed cascade | Restoration |
|---|---|---|---|
| 14/08/2003 United States and Canada | 1 h | 5 min | ~24 h |
| 28/09/2003 Italy | 20 min | 2.5 min | 20 h |
| 12/01/2003 Croatia | / | 30 s | -------- |
| 14/03/2005 South Australia | / | 6 min | 1.5 h |
| 12/07/2004 Greece | 13 min | 2 min | --------- |
| 02/07/1996 United States | / | 60 s | --------- |
| 10/08/1996 United States | 1 h 38 min | 7 min | -------- |

-------- Unavailable data

From the Table above, we can find that

1) The progression of the high-speed cascade is very fast. Numerous of lines and generators can trip in several seconds or several minutes. It's a too short time for system operators to take effective actions to stop the cascade. If we want to stop the blackout, we need to take adequate actions before the period of high-speed cascade.

2) In some blackouts, the period of steady-state progression was skipped. After the initiating event happened, the system quickly went into the period of high-speed cascade. This kind of blackout is more difficult to stop because of its rapid progress.

## 2.4 Blackout Incidents

From available data, some serious incidents in 10 blackouts from 1965 to 2005 were analyzed in this study. (Table 4)

Table 4
Blackout Incidents

| Blackouts | Blackout Incidents 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 9/11/1965 United States | | | √ | | |
| 19/12/1978 France | √ | | √ | | |
| 2/7/1996 United States | √ | | √ | | |
| 07/08/1996 United States | √ | | √ | | |
| 12/01/2003 Croatia | | | | √ | |
| 14/08/2003 Northeast United States and Canada | √ | | √ | | |
| 23/09/2003 Eastern Denmark and Southern Sweden | √ | | √ | | |
| 28/09/2003 Italy | | √ | √ | | √ |
| 12/07/2004 Athens and Southern Greece | √ | | | | |
| 14/03/2005 South Australia | | | | | √ |
| Total : 10 | 6 | 1 | 7 | 1 | 2 |

1- Voltage collapse , 2- Frequency collapse , 3- Cascade overload, 4- System unsymmetrical, 5- Loss of synchronism.

Referring to Table 4, voltage collapses (6/10) and cascade overloads (7/10) happened with a higher frequency in these blackouts. It suggests that voltage collapse and cascade overload are the major incidents in the progression of blackouts. Finding out effective methods to avoid voltage collapse and cascade overload in emergency condition might be a good way to stop most of progressions of blackouts.

The system separation is also a blackout incident, but it is a consequence of the incidents that are represented in Table 4.

We have identified the phases of blackout, analyzed the phenomena occurred in these phases and found some common characteristics of blackouts. But how did the blackout progress in each phase? In the next part, the mechanisms of blackouts will be analyzed.

# 3 Mechanisms of Blackouts

The power system may enter into an emergency condition due to some critical events that may happen in the system. Usually, the system can be pulled back to normal condition by its protection and control system. But, sometimes, the system can not return to normal condition in good time and some new events can trigger the cascade incidents, which may interact and rapidly worsen the situation. Finally, blackout can happen.

In this study, we analyzed the mechanisms of 8 blackouts of which we could get detailed information [1], [5], [7], [8], [10], [11], [24], [26]. Combined with a previous study, which suggested a common generic scenario of cascading processes for blackouts [9], we describe the mechanism of blackouts in the Fig.5.

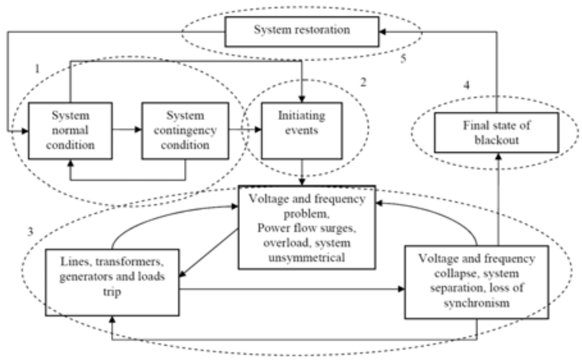


Fig. 5. Mechanism of Blackouts [9].
1. precondition 2. initiating events 3. cascade events
4. final state 5. system restoration

## 4 Conclusion

Large scale blackout caused enormous economical and social damages. To prevent blackout, above all we must well know the previous blackouts and find their characteristics. In this study, by analyzing 37 previous blackouts, we divided the progression of blackout into five phases: precondition, initiating events, cascade events, final state and restoration. During the period of cascade events, the triggering events follow the period of steady-state progression, and the triggering events, being a critical point, lead to start the high-speed cascade. In some blackouts, the period of steady-state progression was skipped and the initiate events became the triggering events. According to the available data from the 37 blackouts, we found that 35.1% of the blackouts happened in system normal condition; the period of steady-state progression is long (t >10 min), while the period of high-speed cascade is very short (several seconds < t < 10 min), and the blackout usually happened quickly after the high-speed cascade was triggered. So, we suggested that effective actions should be taken before the triggering events happened, because when the high-speed cascade has been triggered, the situation can become uncontrollable and the blackout can happen within a very short time. According to the analysis of 10 blackouts (from which detailed information was available) from 1965 to 2005, voltage collapse and cascade overload, which happened with a higher frequency, can be considered as the major incidents in blackouts. Mechanisms of blackouts have been also studied in this paper and this analysis will lead us to propose some recommendations to prevent blackouts in further works, using new technologies like FACTS (Flexible AC Transmission Systems), WASM (Wide Area Measurement System), etc.

*References:*


[1] NERC Steering Group, *Technical Analysis of the August 14, 2003, Blackout: What Happened, Why, and What Did We Learn?*, Report to the NERC Board of Trustees July 13, 2004.

[2] *Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations*, U.S.-Canada Power System Outage Task Force April 2004

[3] Corsi, S.; Sabelli, C, General Blackout in Italy Sunday September 28, 2003, h.03:28:00, *Power Engineering Society General Meeting, 2004*. IEEE 6-10 June 2004 Page(s):1691 - 1702 Vol.2

[4] Berizzi, A, The Italian 2003 blackout, *Power Engineering Society General Meeting, 2004*. IEEE 6-10 June 2004 Page(s):1673 - 1679 Vol.2

[5] *Interim Report of the Investigation Committee on the 28 September 2003 Blackout in Italy*, UCTE 27 October 2003

[6] James D. McCalley, *Operational defense of power system cascading sequences: probability, prediction, & mitigation*, PSerc Seminar, 7 October, 2003

[7] *Power System Incident 14 March 2005 Final Report*, National Electricity Market Management Company Limited ABN 94 072 010 327

[8] N.Dizdarevic, M.Majstrovic, *Causes, analyses and countermeasures with respect to blackout in Croatia on January 12, 2003,* The CRIS International Workshop on Power System Blackout, May 3 -5, 2004, Lund, Sweden

[9] Yuri V. Markov, Viktor I. Reshetov, Blackout Prevention in the United States, Europe, and Russia, *Proceedings of the IEEE* , Vol. 93, No. 11, November 2005.

[10] Costas Vournas, *Technical Summary on the Athens and Southern Greece Blackout of July 12, 2004, August 2004* http:// www.pserc .org/Greece_Outage_Summary.pdf

[11] *1996 System Disturbances Review of Selected 1996 Electric System Disturbances in North America,* North American Electric Reliability

Council Princeton Forrestal Village 116-390 Village Boulevard Princeton, New Jersey 08540-5731 August 2002

[12] Novosel, D.; Begovic, M.M.; Madani, V, Shedding light on blackouts; *Power and Energy Magazine, IEEE,* Volume 2, Issue 1, Jan-Feb 2004 Page(s):32 – 43

[13] Hain, Y.; Schweitzer, I, Analysis of the power blackout of June 8, 1995 in the Israel Electric Corporation, *Power Systems, IEEE Transactions*, Volume 12, Issue 4, Nov. 1997 Page(s):1752 – 1758

[14] OFGEM, *Report on support investigations into recent blackouts in London and west midlands* Volume 1, main report, OFGEM, February 2004.

[15] OFGEM, *Report on support investigations into recent blackouts in London and west midlands* Volume 2, Supplement report, protection commissioning & performance OFGEM, February 2004.

[16] Jim Y Cai, zhenyu Huang, John Hauer, Ken Martin, Current status and Experience of WAMS implementation in North America ,2005 *IEEE/PES Transmission and Distribution Conference & Exhibition: Asia and Pacific Dalian, China,* 15-18 August, 2005.

[17] Carson W. Taylor, Dennis C. Erickson, Kenneth E. Martin, Robert E. Wilson, Vaithianathan Venkatasubramanian, WACS – Wide-area stability and voltage control system: R&D and online demonstration, *Proceedings of the IEEE*, VoL. 93, No.5, May 2005.

[18] Marek Zima, Mats Larsson, Petr Korba, Christian Rehtanz, Goran Andersson, Design aspects for wide-area monitoring and control systems, *Proceedings of the IEEE*, VoL. 93, No.5, May 2005.

[19] Narain G. Hingorani, Flexible ac transmission, *IEEE spectrum,* April 1993.

[20] Gregory S. Vassell, Northeast Blackout of 1965, *Power Engineering Review*, IEEE, Volume 11, Issue 1, January 1991 Page(s):4

[21] Massoud AMIN, North America's electricity infrastructure, *Security & Privacy Magazine, IEEE,* Volume 1, Issue 5, Sept.-Oct. 2003 Page(s):19 – 25

[22] G. Andersson, P. Donalek, R. Farmer, N. Hatziargyriou, I. Kamwa, P. Kundur, Causes of the 2003 Major Grid Blackouts in North America and Europe, and Recommended Means to Improve System Dynamic performance, *IEEE Transactions on Power System*, Vol 20, No.4, November 2005.

[23] G.T.Heydt, C.C.Liu, A.G.Phadke, V.Vittal, Solution for the Crisis in Electric Power Supply, *IEEE Computer Applications in Power 2001*, Volume 14, Issue 3, July 2001.

[24] Ekrft System, *Power failure in Eastern Denmark and Southern Sweden on 23 September 2003 Final report on the course of events*, Ekrft System 4 November 2003

[25] RTE, *Mémento de la sûreté du système électrique* edition 2004, RTE 2004

[26] Interstate Renewable Energy Council, *CHILE – Power Blackout Hits Most of Country*, http://www.solarstorms.org/Chile2002.html, 7, November 2003

[27] Power Systems Engineering Research Center, *Resources for Understanding the Moscow Blackout of 2005*, http://www. pserc.org /MoscowBlackout.htm

[28] Filho, V.X.; Pilotto, L.A.S.; Martins, N.; Carvalho, A.R.C.; Bianco, A., Brazilian defense plan against extreme contingencies, *Power Engineering Society Summer Meeting, 2001. IEEE*, Volume 2, 15-19 July 2001 Page(s):834 - 839 vol.2