

The Impacts of Natural Disasters on Power Systems: Anatomy of the Marmara Earthquake Blackout

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Abstract: An earthquake is an instantly occurring and unpredictable natural event. The potential and effects of earthquakes and other natural disasters on power systems are system faults. The faults are not only limited to the physical damage of power systems, but power quality disturbances may also take place. The Marmara Earthquake, which occurred in Turkey on Aug 17, 1999, caused death and catastrophe. After the earthquake, the Turkish Power System collapsed. This is the largest power blackout in Turkey in last twenty years. In this study, the impact of the Marmara earthquake on the Turkish power system are described and the Marmara Earthquake Blackout is examined in detail as regards the qualitative behavior of the power system.

Keywords: Power System Blackouts; Power System Disturbances; Overvoltages in Power Systems

1 Introduction

Disasters are sudden, uncontrollable, and mostly unexpected events. According to the source, the classification of disasters has two broad categories: as natural disasters and man-made disasters. A lot of disastrous events may be classified under the broad category of natural disasters, including earthquakes, hurricanes, tornados, avalanches, volcanic eruptions, landslides, floods, etc. On the other hand, terrorism, war, nuclear power plant accidents, and airplane crashes are examples of man-made disasters [1]. The impacts of natural disasters are often greatly prolonged and exacerbated by disruptions to critical infrastructure systems. Critical infrastructure includes the electric power system, water, and transportation [2].

The potential effects of earthquake and other natural disasters on the power system are system faults [3]. The faults are not only limited to physical damage of power systems, but power quality disturbances may also take place. They may cause

severe power outages. The definition of a power outage, measured by its duration, appears to be similar among countries. A customer interruption in the U.K. is defined as a power cut lasting more than 3 minutes, while it is 1 minute in Sweden and less than 5 minutes in the U.S. There is no official definition with regards to the size of blackouts. A large blackout could refer to incidents that affect over a million people in various locations [4].

Large blackouts are initiated by a single event that gradually leads to cascading outages and eventually to the collapse of the entire system [5]. They are more complex than smaller ones as they often involve cascading events in which the primary failure triggers a sequence of secondary failures that lead to a blackout in a large area of the grid [4]. Therefore, a cascading failure is the main mechanism of large blackouts [6].

Recent cascading failures in several power systems in the world require urgent attention. The US-Canada region failure during the August 2003 blackout affected 8 states in the U.S. and 2 provinces in Canada and left 50 million people in the dark. The Italian blackout of Sept 28, 2003 affected 57 million people. Around 19,000 MW of electricity load was lost over a 277,000 square kilometer area. The Scandinavian blackout of Sept 23, 2003 affected approximately 5 million people, cutting off around 3,000 MW of generating capacity in Sweden, and 1,850 MW in Denmark [4]. The US/Canada blackout, the Scandinavian blackout and the Italian blackout have shown that the technical issues related to power system security cannot be completely overcome. It is necessary to investigate the failure, to analyze the cause leading to the blackouts and to identify potential blackouts [7].

Over the last twenty years, there have been many significant blackouts for various reasons such as natural disasters, supply shortages, the restructuring of the electricity industry, etc. Apart from the news reported in the media, sources of information on blackouts are limited. However, anatomies of the blackouts have been studied by researchers in literature [2], [5], [7-12].

An earthquake with a moment magnitude of 7.4 on the Richter scale occurred on August 17, 1999 at 03:02 a.m. and affected the northwest of Turkey. The earthquake is called the Marmara Earthquake. After the earthquake, the Turkish Power System collapsed.

Although this was the largest power blackout in Turkey in last twenty years, the impacts of the earthquake on the power system and the causes of the large blackout have not been investigated in literature. The main goal of this paper is to investigate the Marmara Earthquake Blackout. The blackout is studied for its impact on the Turkish Power System in the context of the location and importance of the earthquake region and the theory of power system disturbances.

2 The Earthquake Region

On August 17, 1999 an earthquake with an epicenter near Izmit became the most terrifying disaster in recent Turkish history. The impact of the earthquake on the population and the economy was mainly felt in seven cities in the Marmara Region (Kocaeli, Sakarya, Yalova, İstanbul, Bolu, Bursa, and Eskisehir). The death toll was 18,373, another 48,901 people injured. Reportedly 93,000 housing units and 15,000 small business units collapsed or were badly damaged [13].

The Marmara Region, where the major impact of the earthquake occurred, is very important to the Turkish economy, both in terms of production and consumption capacities. This area accounts for 23% of the total population of Turkey. The seven cities, Kocaeli, Sakarya, Yalova, İstanbul, Bolu, Bursa, and Eskisehir, represent 33.4% of the Turkish GDP; further these cities produce 46.7% of total industry value added [14]. The Marmara region, mainly Kocaeli, Sakarya, and Yalova, is the center of the Turkish oil, textile, automobile, petrochemical, and tire industries. With an average income level per person that far exceeds the national average, the region also plays a very important role in terms of domestic consumption demand. Turkey main heavy industry is located in the Marmara Region. Figure 1 shows the location of the earthquake region on the map.



Figure 1
Location of the Earthquake Region

The region plays an important role regarding electricity consumption. At the end of 1999, the region used 32.2% of Turkey's electricity, which was 28 Billion kWh per annum [16]. In Table 1, the key indicators of the region are listed; the population, GDP and electricity consumption, and their percentages as a share of the total in Turkey.

Table 1
The Earthquake Region Indicators and Ratios in Turkey

City	Population	GDP (\$)	%	Consumption (MWh)	%
Bolu	554,473	184,628	1.0	730,288	0.8
Bursa	1,991,811	6,767,332	3.7	4,544,886	5.2
Eskisehir	662,599	2,275,641	1.2	849,913	1.0
Istanbul	9,382,894	40,506,151	21.8	16,509,300	18.8
Kocaeli	1,200,953	7,818,017	4.2	4,278,546	4.9
Sakarya	736,223	2,028,927	1.1	744,253	0.8
Yalova	166,617	715,127	0.4	595,927	0.7
Total	14,695,570	60,295,823	33.4	28,253,113	32.2

3 The Power System Characteristics

At the time of the Marmara Earthquake, the operational structure of the Turkish Power System was as follows. In 1999, TEAS (the Turkish Electric Generation Transmission CO.) was responsible for the generation and transmission of electricity throughout the country. Voltage levels of “National Grid Transmission System” were 154 kV and 380 kV. The length of the Turkish Power System transmission lines totaled 41,880 km, and the transformer capacities equaled 53,766 MVA, while 13,700 km and 18,470 MVA belonged to 380 kV [15]. An illustration of National Grid Transmission System for Turkey at 380 kV is displayed in Figure 2.

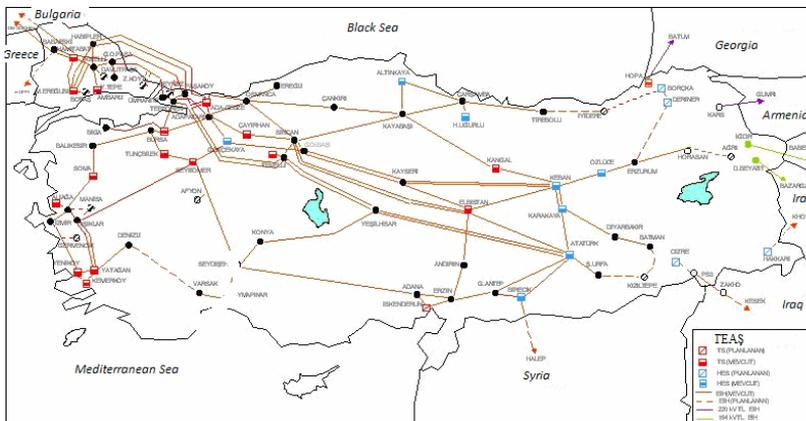


Figure 2
View of 380 kV Transmission System

The system was observed and managed by five regional operation divisions of National Load Dispatch Department. These were;

- Northeast Anatolia (NEA)
- Northwest Anatolia (NWA)
- West Anatolia (WA)
- Mid Anatolia (MA)
- Southeast Anatolia (SEA)

Each regional operation division was responsible in its region for load distribution and the operation of the interconnected system components. The operation divisions sent monthly reports to the National Load Dispatch Department. The connections among the regions are shown in Figure 3 [16].

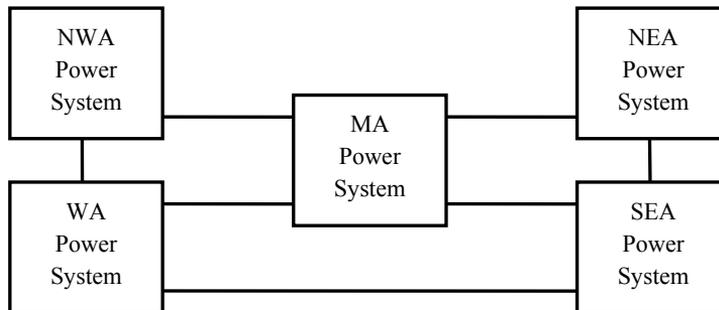


Figure 3
Connections among the Regions

In 1999, the installed power in Turkey was 26.1 GW. 60% was thermal, and 40% was from hydroelectric sources. 24.3% of the installed capacity came from lignite-fueled power plants. The most important of these were Afşin Elbistan (1,360 MW), Soma (1034 MW), Seyitömer (600 MW), Yatağan (630 MW), Yeniköy (420 MW) and Kemerköy (630 MW). Natural gas-fueled power plants, which accounted for the second major share in Turkey, produced 23.5% of installed capacity. The Power plants of Ambarlı (1,350 MW), Hamitabat (1,200 MW) and Bursa (1,432 MW) were natural gas-fueled power plants of the largest capacity [15]. All of them are in the Marmara region.

Figure 4 shows the monthly instantaneous peak loads for 1999. The instantaneous peak load of Turkish Power System was 18,938 MW at 17:30 on 8 December. Figure 4 also demonstrates the load distribution over the regions of the Marmara Earthquake, which was in month of August [15-17]. It was observed that the instantaneous peak load was higher in the earthquake region NWA than in the other regions.

Months	MW
January	17,137
February	17,392
March	17,671
April	16,320
May	15,758
June	16,042
July	17,088
August	17,063
October	16,063
September	16,818
November	18,170
December	18,938

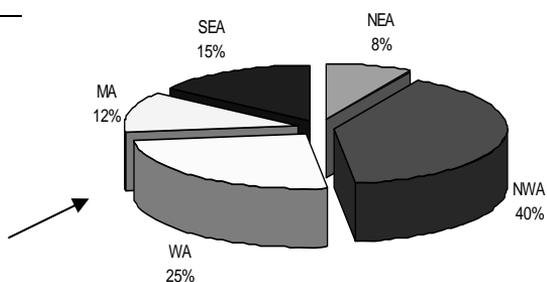


Figure 4

Monthly Instantaneous Peak Loads and load distribution over regions in August, 1999

Table 2 shows the hourly load values on the third Wednesdays of each month in 1999 [17]. In August, the minimum hourly load was 10,300 MW. Except in January, the minimum hourly load range was between 10,000 and 12,600 MW. However, the maximum load range was between 14,000 and 17,600 MW. As a result, the daily load fluctuation in 1999 was between 4,000 and 6,000 MW.

Table 2

The Hourly Load Values on the Third Wednesdays of Each Month in 1999

Date	The Hourly Load (MW)	
	Minimum	Maximum
20 January	8,300	12,200
17 February	11,300	16,800
17 March	11,600	17,600
21 April	10,400	15,400
19 May	10,000	14,000
16 June	10,400	15,300
21 July	11,200	16,200
18 August	10,300	16,000
15 September	10,500	15,000
20 October	10,250	16,400
17 November	11,750	17,750
15 December	12,600	17,750

4 The Earthquake Impact on the Power System

The Marmara Earthquake occurred on August 17 at local time 03:02 am. After the first shock, the Turkish Power System was badly affected and the system experience a blackout, except for some regions, WA and a region isolated from national grid, which were supplied by international connections (Bulgaria, Georgia and Iran) [16]. Therefore, except for WA, the thermal and hydroelectric power plants were out of service.

The time period of the minimum load drawn on the Turkish power system is usually between 02:00-07:00 am. This is a characteristic of Turkish power system. The Marmara Earthquake occurred during this period. Some of the daily load curves of August 1999 are presented in Figure 5 [17].

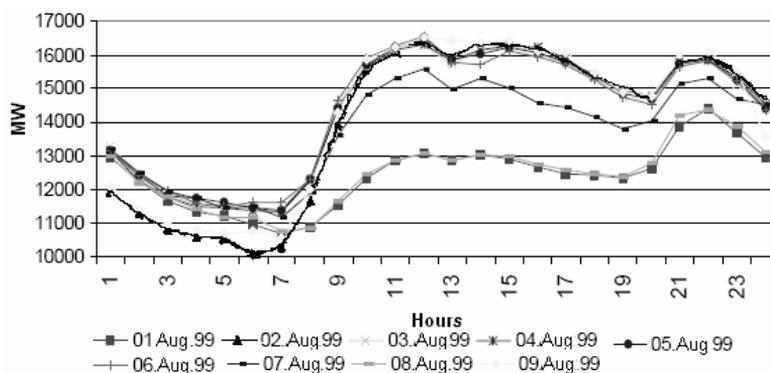


Figure 5
Daily Load Curves belonging to August 1-9, 1999

The generation-consumption balance of the regions on the day before the earthquake is given in table 3 [16]. NWA was the highest in both generation and consumption. In additional, WA was the region of second-highest consumption and was balanced in generation-consumption.

Table 3
Generation-Consumption of The Regions at the Time of Minimum Load on 16 August 1999 (MWh)

Region	Generation	Consumption
NWA	3,978	3,588
WA	2,234	2,574
SEA	2,622	1,420
MA	441	1,069
NEA	385	566
Total	9,682	9,217

At the time of the earthquake, the Turkish power system was supplied heavily by thermal plants. Figure 6 shows the power flow between the regions [18]. In general, the power flow of the Turkish power system is from the east regions, which have important hydroelectric power plants, to the west regions, where there are extensive industrial facilities. However, at the time of the earthquake, the power flow was not in that direction. The Marmara Earthquake occurred in the summer of 1999. The summer was dry, the water levels of the hydroelectric power plants were low, and the water was used for irrigation. At the same time, take or pay agreements had to be applied for natural gas power plants; therefore, the natural gas power plants were on service at the earthquake time.

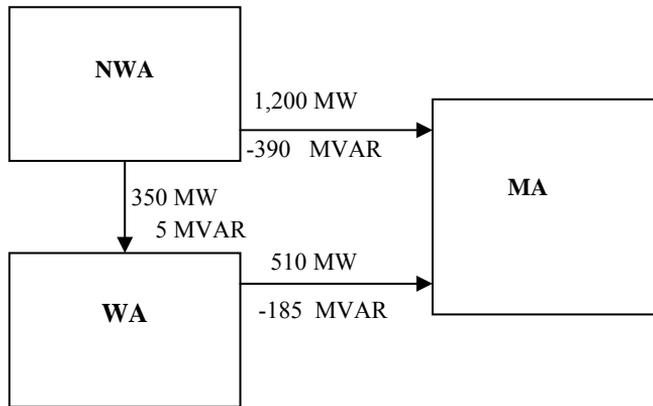


Figure 6

The Power Flow between the Regions at the Minimum Time Range on 17 August 1999

Consequently, the Marmara Earthquake occurred,

- at the time range of minimum load on the Turkish Power System;
- in Northwest Anatolia, which was the most developed region regarding the generation-consumption of electricity, industry and population density;
- during a situation when the power flow was to the east from the west.

When the earthquake occurred, the load of the NWA suddenly dropped. The region drew more than 35% of the total Turkey load. Excluding the isolated regions, the total drawn load of MA, NEA and SEA was roughly 4.0 GW. The load of WA was roughly 3.0 GW and 30% of the total drawn load of Turkey. Figure 7 shows the change to the system load during the earthquake [18]. Therefore, the load of the Turkish power system was suddenly rejected. As a result of disturbances to the power system, cascading failures occurred in the system.

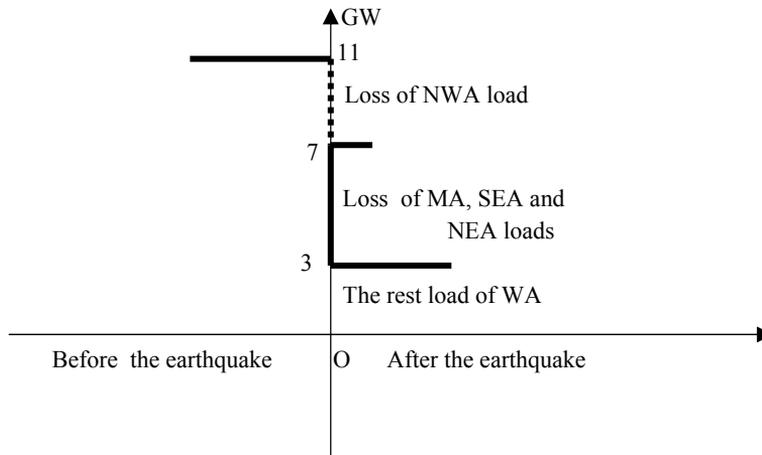


Figure 7

Sudden load reduction of Turkish Power System in the Marmara Earthquake

During the earthquake, the NWA power demand was covered by Hamitabat, Ambarli, and Unimar ve Bursa natural gas power plants. At the same time, the region exported power to MA. The power flow was roughly 1.2 GW [18]. The power connections were provided between NWA and MA by power transmission lines of 380 kV.

380 kV Osmanca and Adapazari transformer substations, which are located between NWA and MA regions, and power transmission lines of NWA region were affected by the earthquake. Therefore, transformer substations of NWA were switched off, and the region's load was suddenly lost.

The effect of a sudden loss of demand can develop the following possible results on the power system:

- System frequency rise,
- System voltage rise,
- Transmission overload,
- Transient instability,
- System oscillations.

These actions affect power system for particular instants. These time intervals can be from 1/10 seconds to seconds for system frequency and voltage; however, they can be from seconds to minutes for transmission overload and system oscillations [3].

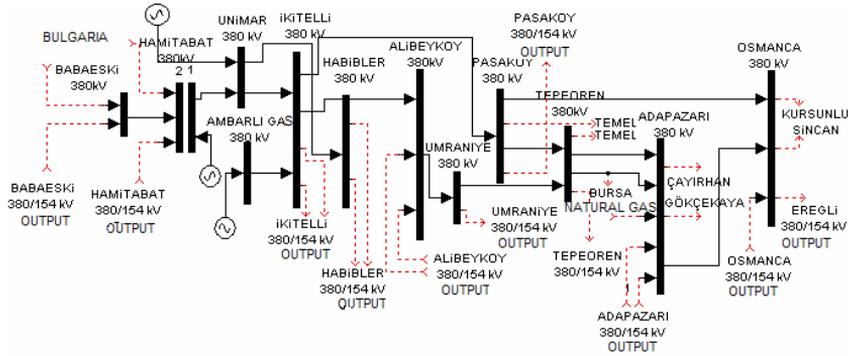


Figure 8

Power System of Northwest Anatolian Region (1999)

At the time of the earthquake, the NWA transmission and distribution lines were out of service because of pylon breaking and short circuits in the power lines. The substations in the severely affected earthquake regions were opened by buchholz relays. In addition, medium voltage and low voltage substations suffered damage. Consequently, immediately after the earthquake, the region load was rejected. At the same time, connection substations between NWA and MA suffered damage, when power was flowing from NWA to WA.

The rate of frequency change after the load rejection depends on the inertia constant and generation – load imbalance [19]. In other words, the power system frequency is directly related to the rotational speed of the generators supplying the system. There are slight variations in frequency as the dynamic balance between load generation changes. The size of the frequency shift and its duration depend on the load changes. Frequency variations that go beyond the accepted limits for normal steady-state operation of the power system can be caused by faults such as a large block of load being disconnected, or a large source of generation going off-line on the bulk power transmission system [20]. At the instance of the load rejection, the breaker opens and the current rapidly goes to zero. The voltage drop over the generator internal impedance becomes zero, as well, causing a sudden step change in generator output voltage amplitude and phase. When running as a generator connected to the grid, the electrical frequency of the generator is synchronized to the grid frequency [19].

After the blackout, the power system restoration started quickly and it was recovered between 03:30 and 08:30 am. Normal operating conditions of the power system were provided with the exception of the earthquake region. During the system restoration process, an aftershock earthquake occurred in Duzce at 08:54 am. Because of this earthquake, the 380 kV lines between MA and NWA went out of service. Therefore, the Turkish Power System was interrupted again, with the exceptions of the regions powered by international connections and the Black Sea region. At 14:00 pm of the same day, the power system recovered and put into

service at normal operating conditions except for the region seriously affected by the earthquake [18].

Conclusions

Earthquakes are natural, sudden, unpredictable, uncontrollable and short-lasting natural events with destructive effects. The earthquakes not only damage the power system, but also make disturbances on power system. An earthquake occurred on August 17, 1999 in Turkey, and the Turkish Power System was affected by this earthquake and the power system collapsed.

- The blackout affected the biggest industrial and electricity consuming region of Turkey.
- The earthquake occurred at the time range of the minimum load on the Turkish Power System while the power flow was to east from west and the power system was operated predominantly by thermal power plants.
- When the earthquake occurred, the region load, which was more than 35% of the total load in Turkey, was suddenly rejected.

Because of the effect of this sudden loss of demand and cascading failures, disturbances on the power system occurred. As a result of these disturbances, instant frequency and voltage increased and a large blackout happened on the Turkish Power System. After twelve hours, the Turkish Power System recovered to its normal operating conditions.

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