European Network of
Transmission System Operators
for Electricity

Report on Blackout in Turkey on 31st March 2015

– Final Version 1.0 –

Project Group Turkey

21 September 2015

Content

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1. Executive Summary

After the major disturbances in Western Europe in 2003[1] and in 2006[2], the disturbance of March 31st 2015 was the third serious event in the **C**ontinental **E**uropean (CE) System within the last 15 years. All these three events had similar characteristics such as high corridor loading, underfrequency load shedding and non-conform power plant behaviour with respect to abnormal frequency deviations.

However, thanks to the measures taken at the Turkey-ENTSO-E CE interface, the 31st of March event mainly affected Turkey and had no impact on the system operation of the rest of the interconnected system. The blackout did not disturb Turkey's neighbours and the disturbance was kept inside of the Turkish power system.

Even for Turkey, the total system black-out had only minor negative effects as most of the critical infrastructure equipment possesses its own emergency power supply, and the power system restoration process was finished in a quite short time. It was reported that e.g. mobile communication in Turkey was functional at all times during the blackout and airport traffic was not affected either.

General System Conditions Before the Blackout

Due to the spring water regime hydro power plants with and without dams were running at full load, especially in Eastern Black Sea region, and Southern and Eastern Anatolia. This situation led to a generation pattern in the Turkish power system in which a lot of power plants which are located in Western Anatolia were not in operation. As a result, the 400 kV lines which connect the East to the West of Turkey were heavily loaded.

The peak load in the Turkish system traditionally occurs during the summer period, and the maintenance works before the peak period are mostly scheduled during the spring when the loads are relatively low.

The main system East to West transmission corridor was weakened due to the outage (for maintenance purposes) of four important 400 kV lines and of all (16) series capacitor (SC) banks.

Sequence of Events

The sequence of the events is shown in Figure 1. Prior to the blackout, four 400 kV long transmission lines (marked in black colour in Fig.1) were open in the central section of the 400 kV East to West transmission corridor of Turkey. The parallel lines in service were carrying around 4700 MW over a very long distance. At first, the Osmanca – Kursunlu line (marked [1] in Fig.1), carrying 1127 MW/1237 MVA, tripped on overload. This event initiated the loss of synchronism between the Eastern and the Western subsystems of Turkey, with the fast consequential tripping (in 1.9 sec.) of all the parallel lines (marked with numbers in Fig.1) by the line distance protection relays. As a consequence, the Eastern and Western Turkish subsystems were separated.

The Western subsystem, with a pre-disturbance load of 21870 MW and import from Bulgaria of around 500 MW, underwent a power deficit of 4700 MW (i.e. 21%). This sudden imbalance caused the loss of synchronism with the CE power system and the separation from it by tripping of the three interconnection lines with the Bulgarian and Greek grids by the out-of-step function of the corresponding tie-lines protection relays approximately 1 sec. after the separation of two subsystems in Turkey. During the frequency drop from 49 Hz to 48.4 Hz the underfrequency load shedding relays disconnected about 4800 MW of load, supplemented by the disconnection of 377 MW of load by the CE-TR interface Special Protection System (SPS). After a short stabilisation of a few seconds the frequency, however, continued to decay due to the tripping of several generators at frequencies above 47.5 Hz which is the frequency level specified by the Turkish Grid Code for generators to remain connected for at least 10 minutes. This caused the collapse of the Western subsystem in around 10 sec.

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The Eastern subsystem, with a pre-disturbance load of about 11080 MW, remained with a surplus of generation of approx. 4700 MW (~ 42%). In spite of the disconnection of several generators on overfrequency it also collapsed within a few seconds.

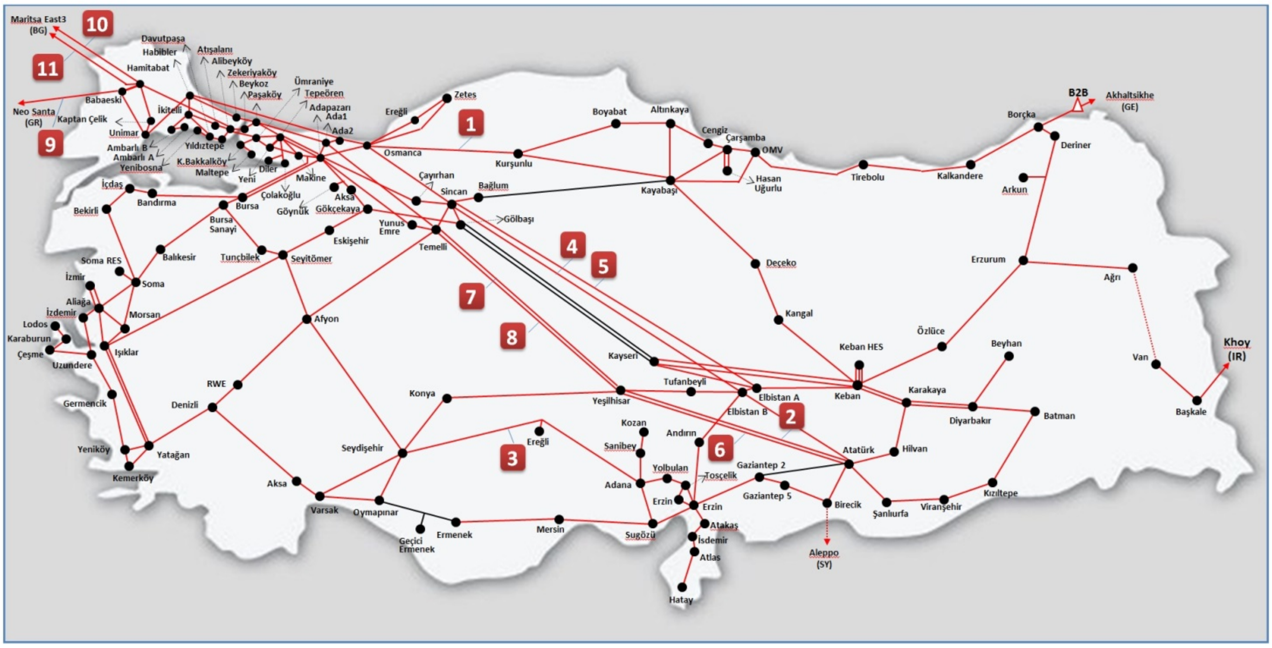

Figure 1: Turkish transmission system map with sequence of events

Main Causes

1. The four 400 kV lines out of service in the critical central section of the East to West corridor line system (three for construction works of new assets; one for maintenance), the long transmission distance (1300 km from the remote Coruh river hydroelectric power plants (HPPs) of the North – East to the major load area of Istanbul), and the out of service of all the series capacitors resulted in a high East to West transfer impedance. In this grid situation, with high hydroelectric generation in the East and relatively high power transmission to the West, the system was not compliant with the (N-1) dynamic security criterion. The tripping on overload of the line with the highest load initiated angular instability and consequently system separation.
2. Prior to the blackout there was no adequate awareness about the importance of the series capacitors for angular stability of the system operation condition.
3. Although the Turkish 400 kV grid is equipped with a protection system that is in line with international standards, the effect of the distance relay settings on the line that tripped first was not correctly evaluated.
4. During the frequency decay transient after the separation of the Western subsystem from CE power system several large thermoelectric generators were disconnected at frequencies higher than the 47.5 Hz, which is in contradiction to the specification by the Turkish Grid Code.
5. Owing to the less than satisfactory recorded stability of several power plants during the severe electromechanical transient, a larger amount of load shedding by the underfrequency relays would have been needed to compensate the irregular early disconnection of generators.

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6. Regardless from the system configuration and specific load flow prior to the March 31st events in the Turkish power system, the quite huge imbalance of respectively 21% and 41% between load and generation in the Western and Eastern Turkish power subsystems, remains a challenge which is hard to manage. Current protection schemes in use in these power systems are possibly not suitable for saving the system during such extreme imbalances.
7. The exceptional exceedingly large weakening of the East to West corridor line system, in particular in the Central – Northern section, and the effect of all the Series Capacitors (SC) banks out of service, have not been correctly evaluated for the 4700 MW to be transmitted from East to West on March 31st. TEIAS' latest load flow and angular stability calculation analyses have shown that the East to West transmissible power with all the 400 kV lines and SCs banks in service is up to about 8000 MW, in compliance with the (N-1) steady state and dynamic security criteria specified by ENTSO-E for the CE system.

Critical Factors

In addition to the main causes described above, the following two factors contributed in a negative way to the event evolution.

1. Reliable on-line automatic contingency analysis and off-line angular stability analysis were not yet available in the National Control Centre (NCC).
2. Not enough attention was paid in the NCC with respect to the angular stress in East-West direction throughout the Turkish grid.

System Restoration

The restoration plan of TEIAS is prepared to be started by dividing the system in 9 isolated islands each related to the one of her 9 Regional Control Centres (RCCs). During the restoration, the bottom-up and top-down approaches were applied in parallel by getting electrical energy from Bulgaria 18 minutes after the blackout starting the recovery of the Trace region, and then synchronizing it with the region of Northwest Anatolia RCC, as well as by initiating black starts in the other regions . At 11:11 (CET), one and a half hour after the blackout, 50% of the Thrace region was already energised. The final synchronisation of East and West and thereby of the complete Turkish power system to the ENTSO-E CE power system took place at 400 kV Kayseri Substation (Mid Turkey) at 16:12 (CET). At that moment, 80% of the Turkish grid was already energized (approximately 6.5 hours after the blackout). The energising of the remaining feeders was done gradually according to the starting-up of the available power plants.

Conclusions and Recommendations

Based on the detailed analysis of the current available information the following recommendations are given:

1. Improve coordination for scheduled outage planning and maintenance planning in order to avoid the overloading of the crucial Turkish East-West transmission corridor
2. Improve the contingency analysis tools, accelerate the process of installing the on-line (N-1) contingency analysis
3. Improve dispatcher training and coordination with asset management with respect to awareness of critical voltage phase differences
4. Improve sensitivity with respect to the correct usage of the existing series capacitors within the East-West transmission corridor

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5. Reassess the amount of load participating in the underfrequency load shedding schemes, by careful consideration of potential voltage challenges during load shedding
6. Request all the power plants to remain connected to the grid in the frequency ranges specified in the National Grid Code.
7. Analyse the current distance protection settings for the main transmission lines and the coordination with the related SCADA system databases

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2. Introduction

Background

On 31st March 2015, the Turkish power system was affected by a serious incident, originating from the tripping of a heavily loaded 400 kV transmission line, which led to the disconnection of the Turkish power system from the ENTSO-E CE grid and eventually resulted in a blackout. This event is the most severe disturbance in the Turkish power system since 17th August 1999, when a large-scale earthquake caused a blackout. The analyses were drafted using high-resolution measurements recorded in Phasor Measurement Units (PMUs) and power quality devices which are installed in most of the Turkish transmission system substations. The blackout occurred 12 seconds after the initial event.

Source of Data and Information

The analysis is mainly based on WAM measurements as well as on information from TEIAS PMU devices, high resolution measurement from ESO EAD, Swissgrid WAM measurements, and SCADA recordings with respect to the CE-TR link. SCADA recordings from TEIAS and different power plant operators were also acquired as well as steady-state snapshot files reflecting the Turkish power system situation before the event.

Project Group Turkey

The ENTSO-E Project Group for the interconnection of Turkey to the Continental European power system (PG Turkey) was established in 2006 in order to work out detailed technical conditions and measures for this interconnection, in accordance with the relevant ENTSO-E rules. PG Turkey worked on open timeline under the mandate of Regional Continental Europe (RG CE and elaborated a comprehensive document entitled “Contractual Agreement” which includes all technical, organisational and legal issues needed as preconditions for the interconnection of the Turkish Power System to the Continental European synchronous area. The interconnection was achieved on 18th September 2010 and then operated during a trial period. The Contractual Agreement reflects the results and the recommendations of the complementary steady-state and stability studies and was signed on 18th December 2009 by the following TSOs: HTSO (now IPTO Greece), ESO EAD (Bulgaria), Amprion (Germany), Transpower (now TenneT TSO GmbH, Germany), and TEIAS (Turkey). PG Turkey is responsible for the management of the overall process of the contract execution regarding deadlines and administrative aspects, and was monitoring the implementation of the measures stated in the Contractual Agreement, the mandatory final tests of the Turkish Power System, and the trial parallel operation.

After the successful trial operation, Turkey’s interconnection with ENTSO-E CE power system has been turned into a permanent connection, by signing the Long Term Agreement between TEIAS, ENTSO-E RGCE TSOs, and ENTSO-E.

After the blackout, PG Turkey was asked by ENTSO-E to prepare a comprehensive report with the aim of finding out the root causes of the blackout and to elaborate and prepare corresponding recommendations.

PG Turkey includes representatives of TSOs from Greece, Bulgaria, Switzerland, Serbia, France, Germany, Italy, and Turkey.

This Final Report presents facts and analyses of the root causes of the disturbance as well as final conclusions and recommendations.

ENTSO-E as Standard Setting Organization and TSO Co-ordination Platform

ENTSO-E, the European Network of Transmission System Operators, represents 41 electricity transmission system operators (TSOs) from 34 countries all over Europe. ENTSO-E was established and given legal mandates by the EU legislation. ENTSO-E promotes closer cooperation across Europe's TSOs to support the implementation of EU energy policy and achieve Europe's energy & climate policy objectives which are changing the very nature of the power system.

ENTSO-E contributes to the achievement of these objectives mainly through:

- the drafting and implementation of network codes;
- the development of pan-European network plans (TYNDPs);
- the technical cooperation between TSOs and between TSOs and DSOs;
- the publication of outlook reports for electricity generation;
- the publication of fundamental data on the EU electricity markets;
- the coordination of R&D plans.

ENTSO-E is the focal point for all technical, market and policy issues relating to TSOs and the European network, interfacing with power system users, EU institutions, regulators and national governments. Through its work, ENTSO-E helps to build the world's largest electricity market, the benefits of which will not only be felt by the energy sector, but also by Europe's overall economy, today and in the future.

ENTSO-E, as the association of European electricity TSOs with key legal mandates from the EU institutions, aspires to become the professional body which European and national policy makers, regulators and market participants ask for competent guidance and which offers pro-active suggestions and objective assessments of technical, market and policy issues related to the European electricity systems. ENTSO-E will take the TSO perspective at European level and will create value for society at large.

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3. Evolution of the System Conditions During the Event

System Conditions Before the Blackout

The day of the blackout was an ordinary working day in spring, no extreme weather conditions. System load at 09:00 CET was 32200 MW. However, several lines were not in service, which are listed in Table 1.

Table 1: Scheduled line outages of the TR transmission system

Line Name	# in Appendix-1	Explanation
Kayabasi-Baglum 400 kV TL	1	To move shunt reactors and series capacitors protection system into a new building
Golbasi-Kayseri Southern 400 kV TL	2	To allow connection of new PPs in Anatolia region and also to reinforce the existing corridor with a double circuit line
Golbasi-Kayseri Northern 400 kV TL	3	To allow above mentioned work for safety reasons
Oymapinar-Ermenek 400 kV TL	4	Due to fault

The situation before the event is given in Appendix-1. Already open lines are illustrated in black colour.

Four 400 kV long **t**ransmission **l**ines (TLs) (with a length ≥ 265 km) were out of service, three of them only due to interference with the construction works of new transmission infrastructures. These 4 TLs are all in the central part of the corridor line East to West transmission system of Turkey. Prior to the blackout the total power flow from the East to the West in the other TLs in service in the same transmission section was 4700 MW, with all the series capacitor banks out of service (by-passed) and non-uniform power flow in the TLs, reportedly: 1168 MW in the Kursunlu – Osmanca TL; 884 MW in the Adana – Seydisehir TL which has twin bundle conductors; the other lines, all with triplet bundle conductors, were moderately loaded (470 to 625 MW). The voltages and reactive power flows were in normal limits.

The 220 kV and 400 kV lines which were in maintenance before the blackout in southeast Europe are shown in Figure 2. The topology of the network, i.e. scheduled outages, was agreed among all South Eastern TSOs according to the standards of the RG CE Operation Handbook. This procedure includes - besides other procedures - the (N-1) security of the interconnected system. However, each TSO is only responsible for the security of its own area and, consequently, a complete (N-1) security analysis is performed mainly for the own power system.

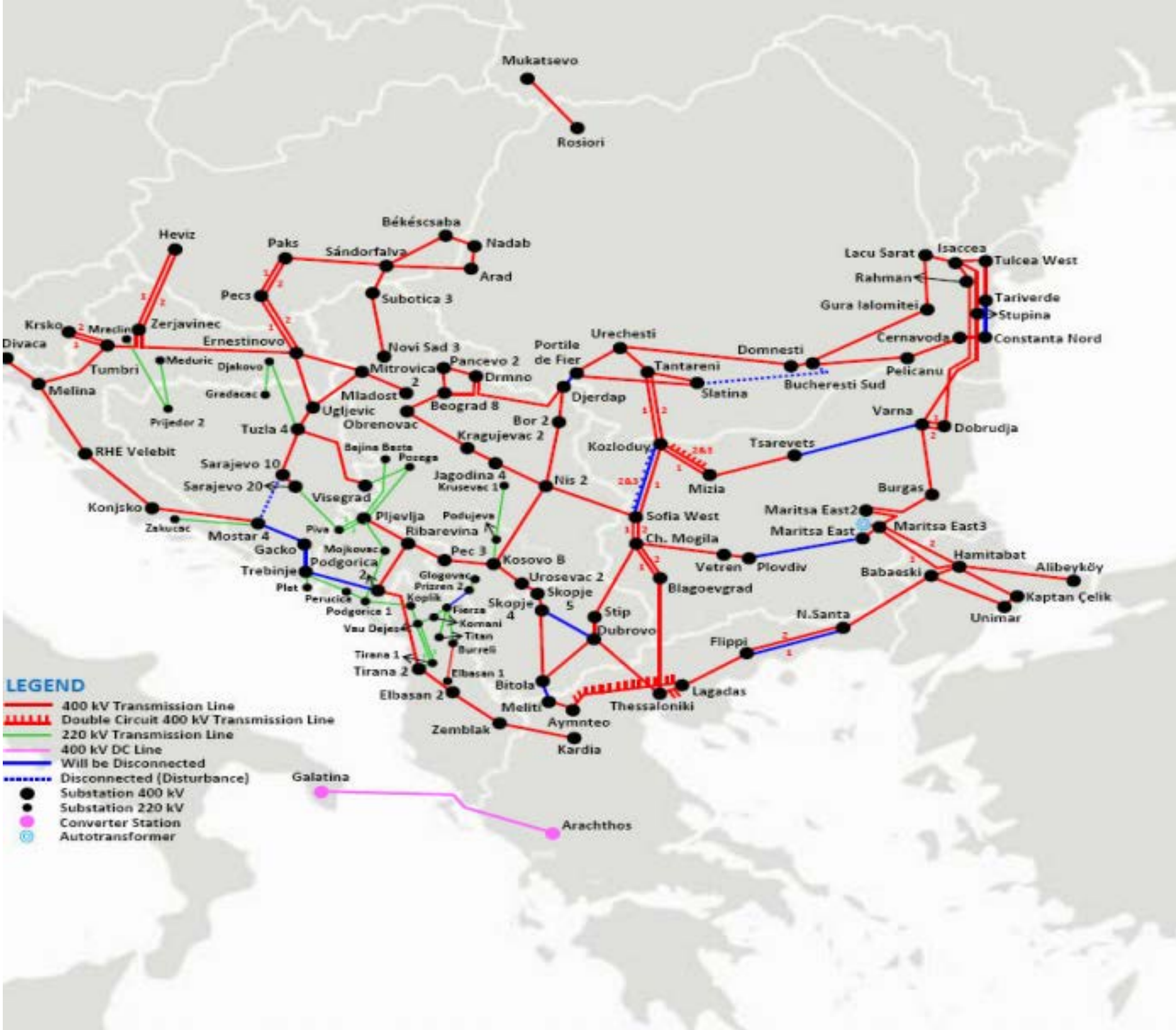

Figure 2: South East CE Transmission System with scheduled outages included

List of the lines in maintenance before the blackout, according to the maintenance schedules of the SEE region which are close to Turkey, is given in the Table 2 below:

Table 2: List of lines out of service before the blackout (scheduled outage) of SE CE transmission system

Line Name	Start Date&Time (CET)	End Date&Time (CET)	Daily/Permanent
IPTO internal TL 400 kV Nea Santa-Filippi 1	25-02-2015 06:30	09-04-2015 14:00	Permanent
MEPSO internal TL 400 kV Dubrovo – Skopje 4	23-03-2015 08:00	27-03-2015 17:00	Daily
Interconnection TL 400 kV Djerdap (EMS) – Portile de Fier (TEL)	23-03-2015 06:00	05-04-2015 08:00	Permanent
Interconnection TL 400 kV Meliti (IPTO) – Bitola (MEPSO)	30-03-2015 08:00	03-04-2015 16:00	Permanent
ESO internal TL 400 kV Maritsa East – Plovdiv	30-03-2015 07:00	03-04-2015 16:00	Daily
ESO internal TL 400 kV Tsarevets – Varna	30-03-2015 08:00	07-04-2015 16:00	Daily
ESO internal TL 400 kV Kozloduy – Sofia West, Line 2&3	30-03-2015 07:00	09-04-2015 15:30	Cancelled

Due to the spring water regime, hydro power plants with and without dams were running at full load, especially in Eastern black sea region, and Southern and Eastern Anatolia. This situation led to a generation pattern in the Turkish power system in which a lot of power plants which are located in Western Anatolia and close to the load centres were not in operation. As a result, 400 kV lines which connect west and east were heavily loaded.

Reportedly, the total pre-disturbance load of the Western subsystem was 21870 MW and the sudden generation deficit (loss of import from the East) was ~ 4700 MW, i.e. 21%.

The peak load of the Turkish system traditionally occurs during the summer period, and the maintenance works before the peak period were mostly scheduled during the spring period when the system load is relatively low.

Factual Sequence of the Events

The factual sequence of the events is given in Table 3. The time stamps are based on **C**entral **E**uropean **T**ime (CET).

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Table 3: Sequence of events

#	Line/Event	Delta (sec)	Time (h:min:sec:hsec) in CET	Active Power (MW)	Reactive Power (MVAr)	Voltage (kV)	Current (A)	Comments
1	Kursunlu-Osmanca	0	09:36:09:418	1127	510	393	1816	Tripped
2	Ataturk-Yesilhisar Kuzey (North)	1.566	09:36:10:984	600	531	333	1400	Both Ataturk - Goksun SKM section and Goksun SKM - Yesilhisar sections of the Ataturk - Yesilhisar (North) TL open.
3	Seydisehir-Adana	1.597	09:36:11:015	867	697	296	2163	Tripped
4	Sincan-Elbistan B	1.724	09:36:11:142	613	587	246	1992	Tripped
5	Sincan-Elbistan A	1.786	09:36:11:204	422	1054	303	2160	Tripped
6	Ataturk-Yesilhisar Guney (South)	1.825	09:36:11:243	484	1154	355	2060	Both Ataturk - Goksun SKM section and Goksun SKM - Yesilhisar sections of the Ataturk - Yesilhisar (South) TL open.
7	Temelli-Yesilhisar (North)	1.835	09:36:11:252	348	1035	315	1980	Tripped
8	Temelli-Yesilhisar (South)	1.899	09:36:11:317	51	1391	346	2300	Tripped
9	Babaeski(TR)-Nea Santa (GR)	3.023	09:36:12:441	440	265	130	2333	Tripped
10	Hamitabat(TR)-Maritsa East 3 (2)	3.024	09:36:12:442	335	230	130	2828	Phase A opens at 9:36:12:267
11	Hamitabat(TR)-Maritsa East 3 (1)	3.110	09:36:12:528	631	300	165	2036	Tripped

The Kursunlu-Osmanca TL was tripped by the intervention in the Osmanca substation of the 5th zone of one of the distance relays (a BBC electronic analogue relay) that operates as an under-impedance starter set for pick-up at 125 Ω primary impedance (10 Ω secondary impedance) for tripping with a time delay of 2 seconds. In the steady state operation, with the recorded line voltage of 393 kV, i.e. of 226.9 kV$_{rms}$ phase-to-ground, the 5th zone intervened at the current of 226900 V/125 Ω = 1816 A. With normal voltage operation (380 kV to 420 kV), the 5th zone impedance starter picks-up at a current from 1755 A to 1940 A according to the line operation voltage in the moment of pick-up.

It should be noted that, under normal circumstances, the loading of the Kursunlu-Osmanca TL is generally much lower than recorded on March 31st.

Details on the line tripping are the following:

At 09:36:09:418, Kursunlu-Osmanca 400 kV line was tripped due to a relay action (impedance) on the line (it corresponds to 1820 A according to its settings). This line was loaded at 1127 MW (1816 A) prior to the trip (instantaneous values at the tripping moment). This event is illustrated in Appendix-2 together with the high-resolution measurement of the voltage and the current on the line.

At 09:36:10:984, Ataturk-Yesilhisar Kuzey (North) 400 kV line was tripped. This line was loaded at 600 MW (1400 A) prior to the trip (instantaneous values at the tripping moment). This event is illustrated in Appendix-3 together with the high-resolution measurement of the voltage and the current on the line.

At 09:36:11:015, Seydisehir-Adana 400 kV line was tripped. This line was loaded at 867 MW (2163 A) prior to the trip (instantaneous values at the tripping moment). This event is illustrated in Appendix-4 together with the high-resolution measurement of the voltage and the current on the line.

At 09:36:11:142, Sincan-Elbistan B 400 kV line was tripped. This line was loaded at 613 MW (1992 A) prior to the trip (instantaneous values at the tripping moment). This event is illustrated in Appendix-5 together with the high-resolution measurement of the voltage and the current on the line.

At 09:36:11:204, Sincan-Elbistan A 400 kV line was tripped. This line was loaded at 422 MW (2160 A) prior to the trip (instantaneous values at the tripping moment). This event is illustrated in Appendix-6 together with the high-resolution measurement of the voltage and the current on the line.

At 09:36:11:243, Ataturk-Yesilhisar Guney (South) 400 kV line was tripped. This line was loaded at 484 MW (2060 A) prior to the trip (instantaneous values at the tripping moment). This event is illustrated in Appendix-7 together with the high-resolution measurement of the voltage and the current on the line.

At 09:36:11:252, Temelli-Yesilhisar North (Kuzey) 400 kV line was tripped. This line was loaded at 348 MW (1980 A) prior to the trip (instantaneous values at the tripping moment). This event is illustrated in Appendix-8 together with the high-resolution measurement of the voltage and the current on the line.

At 09:36:11:317, Temelli-Yesilhisar Guney (South) 400 kV line was tripped. This line was loaded at 51 MW (2300 A) prior to the trip (instantaneous values at the tripping moment). This event is illustrated in Appendix-9 together with the high-resolution measurement of the voltage and the current on the line.

After this event, the Turkish power system was split into 2 areas: east and west

At 09:36:12:441, Babaeski (TR)-Nea Santa (GR) 400 kV interconnection line was tripped with activation of "voltage phase angle difference" protection in Nea Santa (GR). This line was loaded at 440 MW (2333 A) prior to the trip (instantaneous values at the tripping moment). This event is illustrated in Appendix-10 together with the high-resolution measurement of the voltage and the current on the line.

At 09:36:12:267, circuit breaker of Hamitabat (TR)-Maritsa East 3 (BG) interconnection line 2 (in Hamitabat SS) opened the Phase A contact. According to the findings from the relay records, this opening was caused by wrong contact assignment. At 09:36:12:442, Hamitabat (TR)-Maritsa East 3 (BG) interconnection line 2 was tripped due to the activation of "out-of-step" relay protection at Maritsa. This line was loaded at 335 MW (2828 A) prior to the trip (instantaneous values at the tripping moment). This event is illustrated in Appendix-11 together with the high-resolution measurement of the voltage and the current on the line.

At 09:36:12:528, Hamitabat (TR)-Maritsa East 3 (BG) interconnection line 1 was tripped due to the activation of "out-of-step" relay protection at Maritsa. This line was loaded at 631 MW (2036 A) prior to the trip (instantaneous values at the tripping moment). This event is illustrated in Appendix-12 together with the high-resolution measurement of the voltage and the current on the line.

After this event, the Turkish power system was separated from ENTSO-E CE synchronous area.

Recordings of all ESO (Bulgarian TSO) interconnections during the disturbance are given in Appendix-13 to Appendix-15. The peak value of the active power was 2220 MW over BG-TR line 1&2.

The sequence of the events seen from Maritsa East 3 (BG) is given in Table 4 below:

Table 4: TR-BG line separation sequence of events(East European Time stamps, EET)

No	Time (EET)	Actions
1	10:36:11:742	Start of overloading protections – 1400 MW/8 s.
2	10:36:12:263	Trip of BG-TR 2 phase L1 (phase A) in Hamitabat s/s
3	10:36:12:266	Start of out of step protections (PSP) of BG-TR 2
4	10:36:12:276	Start of out of step protections (PSP) of BG-TR 1
5	10:36:12:445	Trip of phases L2 and L3 from main 1 distance protection (REL 521) of BG-TR 2 in Maritza East 3. 1830 ms later phases L2 and L3 are tripped in Hamitabat TPP
6	10:36:12:531	Three phase trip of BG-TR 1 in ME3 s/s by main 2 distance protection (7SA522) of BG-TR 1. 58 ms later BG-TR 1 line is three phase tripped in Hamitabat TPP
7	10:36:12:653	Start of overvoltage protection of TL 400kV ME3-ME2 in ME3 s/s, switched shunt reactor 1 in the substation

Appendix-14 and 15 show rms voltage and current recordings of the last two line disconnections and reflect the dramatic and fast loss of synchronism of the Western Turkey power system.

Power plants in the east of Turkey were disconnected due to high frequency while power plants in the west of Turkey were disconnected due to low frequency. A few power plants are given below in Table 5 and their location on the Turkish grid is given in Appendix-16.

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Table 5: List of some power plants which were disconnected from the grid

Power Plant Name	Installed Capacity (MW)	Power output prior to disturbance (MW)	Technology	# in the map, see Appendix- 16	Part of Turkey after split	Cause of disconnection from grid (Reported by the PP Owners)	Disconnection time (CET) (Reported by the PP Owners)
Erzin DGKC	2x300+315	460	Combined Cycle	1	East	High frequency	09:36:30
Atlas TES	2x600	900	Thermal	2	East	High frequency	09:36:30
Sugozu TES	2x650	1040	Thermal	3	East	Low frequency	09:36:34
Ataturk HES	8x300	520	Hydro	4	East	Over speed	09:36:12 (1st unit) 09:36:24 (2nd unit)
Birecik HES	6x112	530	Hydro	5	East	High frequency	09:36:20
Temelli DGKC	2x265+240	620	Combined Cycle	6	West	Low frequency	09:36:12
Bekirli TES	2x600	1150	Thermal	7	West	Bus voltage drop to 0	09:36:28
Adapazari DGKC	2x (2x256+279`	1460	Combined Cycle	8	West	Low frequency	09:36:22
Gebze DGKC	2x256+279	720	Combined Cycle	9	West	Low frequency	09:36:20 (1st block) 09:36:21 (2nd block)
Izmir DGKC	2x (2x256+279)	1430	Combined Cycle	10	West	Low frequency	09:36:21 (1st block) 09:36:22 (2nd block)

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The graphs of the above mentioned power plants outputs taken from SCADA is given through Appendix-17 to Appendix-26

Current load shedding scheme in Turkey is given in Table 6 below:

Table 6: Load Shedding Scheme and shed load in Turkey

Step	Threshold (Hz)	Region	West Island Rated Load (Design) (MW)	Total design value in West Island (MW), (% to the reference day load)	West Island Real Sched Load (MW), (% to the reference day load)	East Island Rated Load (Design) (MW)	Total design value in East Island (MW), (% to the reference day load)	East Island Real Sched Load (MW), (% to the reference day load)
1	49	Thrace	236.8	1706.6 (5.2 %)	1641 (5.0 %)			
2	48.8		368.1					
3	48.6		568.6					
4	48.4		533.1					
1	49	Northwest Anatolia	445.9	2027.9 (6.2 %)	1018 (3.1 %)			
2	48.8		443.4					
3	48.6		578.5					
4	48.4		560.1					
1	49	West Anatolia	244.3	1891.3 (5.8 %)	1059 (3.2 %)			
2	48.8		436.5					
3	48.6		498					
4	48.4		712.5					
1	49	Southwest Mediterranean	130.5	666.5 (2.0 %)	516 (1.6 %)			
2	48.8		121.7					
3	48.6		209					
4	48.4		205.3					
1	49	Middle Anatolia	373.3	1427.6 (4.4 %)	583 (1.8 %)	57.1	336.6 (1.0 %)	204 (0.6 %)
2	48.8		144.6			114.3		
3	48.6		415.9			42.6		
4	48.4		493.8			122.6		

1	49	Northeast Anatolia				53	234.2 (0.7 %)	242.2 (0.7%)
2	48.8					47		
3	48.6					55.2		
4	48.4					79		
1	49	East Anatolia				18.8	176.7 (0.5 %)	0 (0%)
2	48.8					77		
3	48.6					61.2		
4	48.4					19.7		
1	49	Southeast Anatolia				196.8	1337.4 (4.1 %)	683 (2.1 %)
2	48.8					353.1		
3	48.6					292.2		
4	48.4					495.3		
1	49	Southeast Mediterranean				184.7	1846.3 (5.6 %)	1148.1 (3.5 %)
2	48.8					590.5		
3	48.6					575.5		
4	48.4					495.6		
		TOTAL		**7719.9 (23.5 %)**	**4817 (14.7 %)**		**3931.2 (12.0 %)**	**2277.3 (6.9 %)**

According to the Turkish Grid Code in force, the underfrequency load shedding relays should be technically able to start in 100-150 milliseconds when the system frequency drops to the determined level. Sensitivity of the low frequency relays should not exceed 0.05 Hz.

Summarising, the current load shedding scheme for the Turkish power system is based on a load shedding ratio of 35.5% with respect to the reference load after reaching the last underfrequency load shedding stage of 48.4 Hz. The slightly different percentages of load shedding reached on March 31st result due to a system loading difference to the reference load. It can also be assumed that all available underfrequency load shedding load was activated or, with other words, the total amount of load to be automatically shed reached its maximum level during the event.

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4. Technical Analysis of the Events

Loss of Angle Stability, System Split and Disconnection from CE

The tripping of the line Osmanca-Kursunlu due to distance protection (it corresponds to 1820 A according to its settings) caused a loss of angular stability and a loss of synchronism within the Turkish power system. The divergence of voltage phase angle between eastern and western part of the Turkish system caused increasing currents on the remaining east-west interconnection lines. According to ordinary function of distance line protection devices, all lines within the east-west cross section were tripped in close sequence and finally the Turkish system split. The power flow from eastern to western part of the Turkish system was interrupted and the eastern part islanded with high power surplus and frequency increase. During the transient phase, also loss of synchronism occurred between the Western part of the Turkish system and ENTSO-E **C**ontinental **E**uropean (CE) Power System leading to the separation of the western part of the Turkish system from CE. The islanding of the Western part caused a loss of power infeed from the eastern part of the Turkish system (≈ 4700 MW) and a loss of power import from CE (≈ 500 MW) and thus a sudden high power deficit and frequency decrease.

Tripping of Generation Units and Loss of Frequency Stability

With around 4700 MW, i.e. 21% (loss of import from the East) generation deficit the frequency drop should expectedly have been stopped by the underfrequency load shedding (UFLS) relays which disconnected, from 49.0 Hz to 48.4 Hz, approx. 4800 MW of load (calculated in the status prior to the blackout). The UFLS was supplemented by the disconnection of 377 MW of load by the SPS in Hamitabat. The frequency, however, continued to decrease due to the tripping of several generators at frequencies > 47.5 Hz, which is the frequency level specified by the Turkish Code[3] for generators to remain in service during at least 10 minutes. This caused the total system collapse after about 10 seconds.

The irregular disconnection of steam and gas turbine–generators at frequencies higher than the lower stipulated value reportedly contributed to blackouts in the past in other countries, see /1-2/. SCADA recordings of different power plants of the Turkish system document a too early disconnection of generation units from the transmission system with respect to frequency deviations from the rated values.

Reports on blackouts show that these irregular tripping of steam turbine-generators (STs) and of gas turbines (GTs) has been caused by various electrical, mechanical and thermal reasons, in particular:

- Setting of under frequency generator protection relays by the IPPs at frequency > 47.5 Hz
- Overvoltage or decay of voltage at generator terminals exceeding the limits specified in the Grid Code, or the setting of the over- and-undervoltage protection relays precautionary in a too narrow band.
- Loss of field of synchronous generators, not capable of continuous operation near the underexcitation limit which was specified for the thermoelectric units at a power factor of 0.95, at full generator load.
- For units performing the primary frequency control, disconnection of STs by the undertemperature-underpressure protections and of GTs by the inlet overtemperature protection. These tripping may occur due to ST or GT too large step increase of MW output, as a reaction to a large decrease of system frequency. It is recommended adjust the ST governor limiters to limit the step change of steam valves opening to about 10% of ST rated power. Similarly, the GT governor limiters should be adjusted to prevent an excessive increase of inlet flue gas temperature and the consequential automatic trip of GT.

Power Plant Behaviour

According to the Turkish Grid Code in force, the power plants must remain connected to the transmission grid for at least the time given in Table 7 in the specified frequency ranges:

Table 7: Power plant connection requirements for the Turkish power system

Frequency Range	Minimum duration
51,5 Hz ≤f≤ 52,5 Hz	10 minutes
50,5 Hz ≤f< 51,5 Hz	1 hour
49 Hz ≤f< 50,5 Hz	Permanent
48,5 Hz ≤f< 49 Hz	1 hour
48 Hz ≤f< 48,5 Hz	20 minutes
47,5 Hz ≤f< 48 Hz	10 minutes

According to the Turkish Grid Code in force and in line with the Figure 3, the units should have the capacity to:

– generate constant active power output for the system frequency changes within the range 50.5 to 49.5 Hz, and
– generate active power at a level higher than the linear characteristic values for system frequency changes within the range 49.5 to 47.5 Hz
– in the case that the grid frequency is in the range of 49.5 Hz – 50.5 Hz, the output power should maintain 100% constant value and no more than 1 % output power drop should occur against every additional 1 % frequency drop. This requirement applies to any ambient temperature under 25 ^{0}C (77 ^{0}F) for the gas turbines.
– Necessary measures should be undertaken to ensure that the active power output of the gas turbines, due to turbine speed reduction by decrease of the system frequency, does not drop below the linear characteristic shown in the figure.

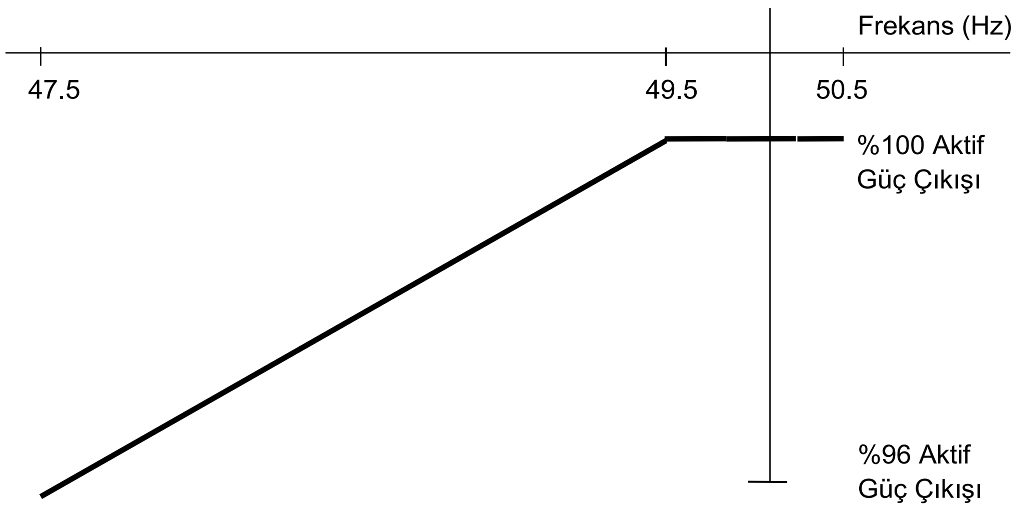

Figure 3: Output power requirement against frequency. (The x-axis represents the frequency in Hz, whereas the y-axis represents the percentage of the active power output of the unit)

According to the Turkish Grid Code in force, speed governor must meet the following minimum requirements;

- Speed governor must be able to control the active power output of the unit within the operating interval in coordination with other control equipment and in accordance with the adjusted operating parameters,
- Speed governor should be able to keep the frequency between 47.5 and 52.5 Hz when the system area in which the unit is connected is disconnected from the transmission system as an island but the unit continues to feed the demand. However, this should not cause the output power to go below the designed minimum output level of the unit.

With a few exceptions for old coal power plants, speed controller droop in the Turkish power system is 4%. Dead band is set to zero (0) in all power plants except in large hydro power plants with long penstock where the dead band is 200 mHz. The list of those large power plants is as follows:

- Atatürk HPP
- Karakaya HPP
- Keban HPP
- Altınkaya HPP
- Berke HPP
- Sır HPP
- Borcka HPP
- Gokcekaya HPP
- Hasan Ugurlu HPP
- Birecik HPP
- Oymapinar HPP

On 31st March 2015, the thermoelectric generators may have been disconnected for the above listed reasons or, however, also by other protections of the electrical and thermal generation cycles, including the loss of synchronism because the Western subsystem was affected by large frequency and voltage swings. However, this is a subject of detailed power plant owner and power plant operator analysis.

The system frequencies during the blackout are depicted in Figure 4 and Figure 5, respectively.

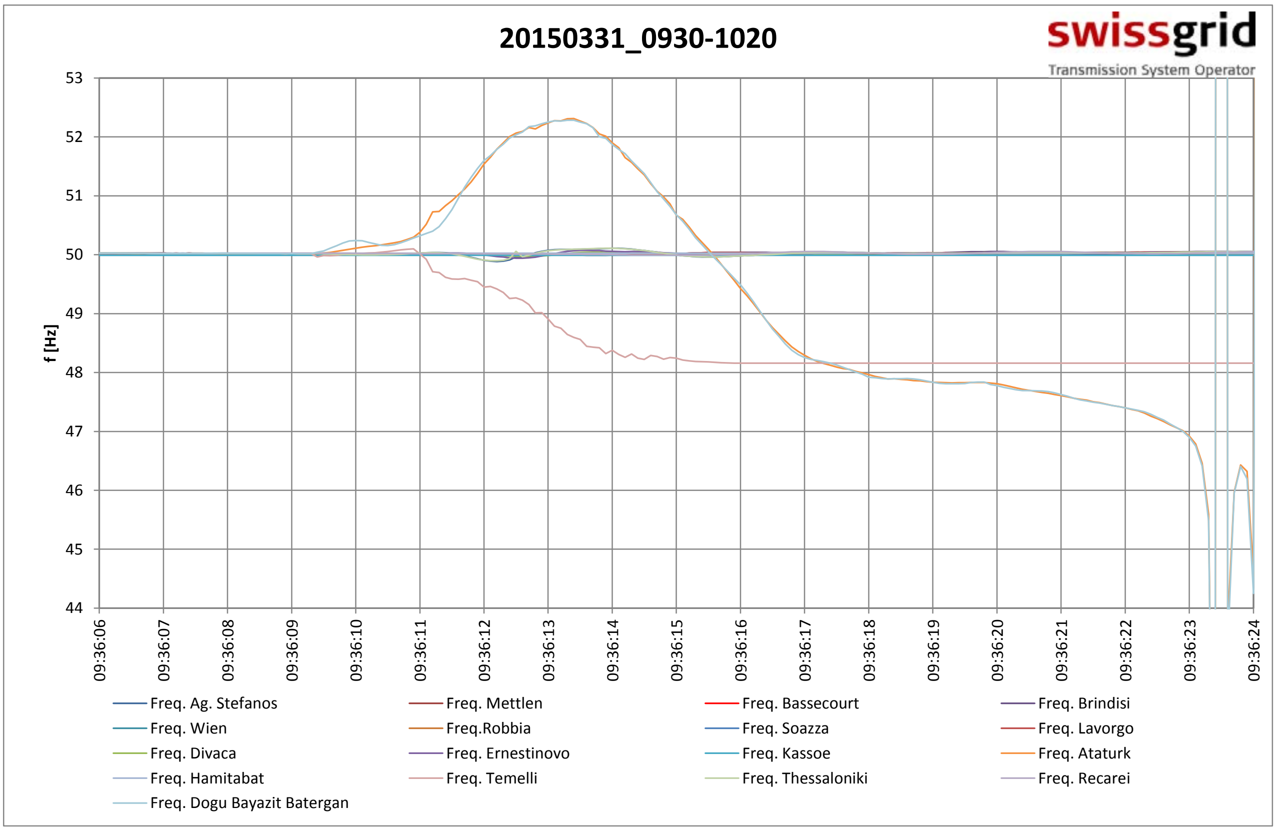

Figure 4: CE power system frequencies during complete blackout sequence

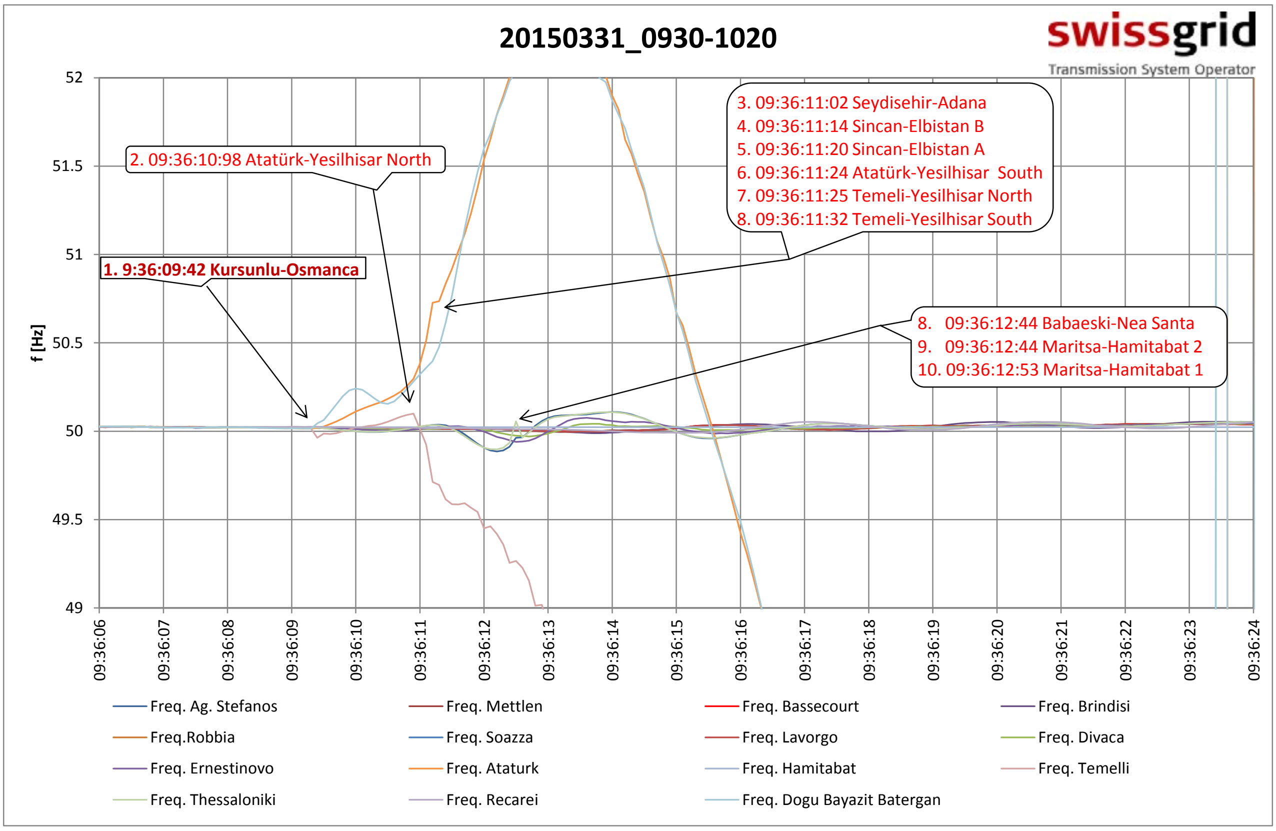

Figure 5: CE power system frequencies during system separation

The Eastern power excess area (Dogu Bayazit & Atatürk) started accelerating up to 52.3 Hz with gradients of about 1 Hz/s. The Dogu Bayazit area seemed to be more weakly interconnected, but remained connected to the Atatürk island. At the same time the region around Temelli substation in the western part of Turkey was firstly accelerated too and remained synchronised with the system for a few seconds longer until 9:36:11 CET when in that island, due to power deficit, the frequency decreased with a gradient of about 500 mHz/s. At 9:36:13 CET, at a frequency value of 48.2 Hz, the recordings stopped to be consistent in the underfrequency island. At 9:36:23 CET the initially overfrequency east island collapsed at underfrequency values less than 47.0 Hz

Dynamic Model Calculation Results

Based on the experience of the CE dynamic model setup procedures, a dynamic model of the Turkish power system for the time of the event was created. This model is mainly based on the system snapshot from 9:00 CET and all the dynamic information already acquired for the CE dynamic model.

With the help of the existing WAM measurements, see Figure 6, a final model check and fine-tuning was possible.

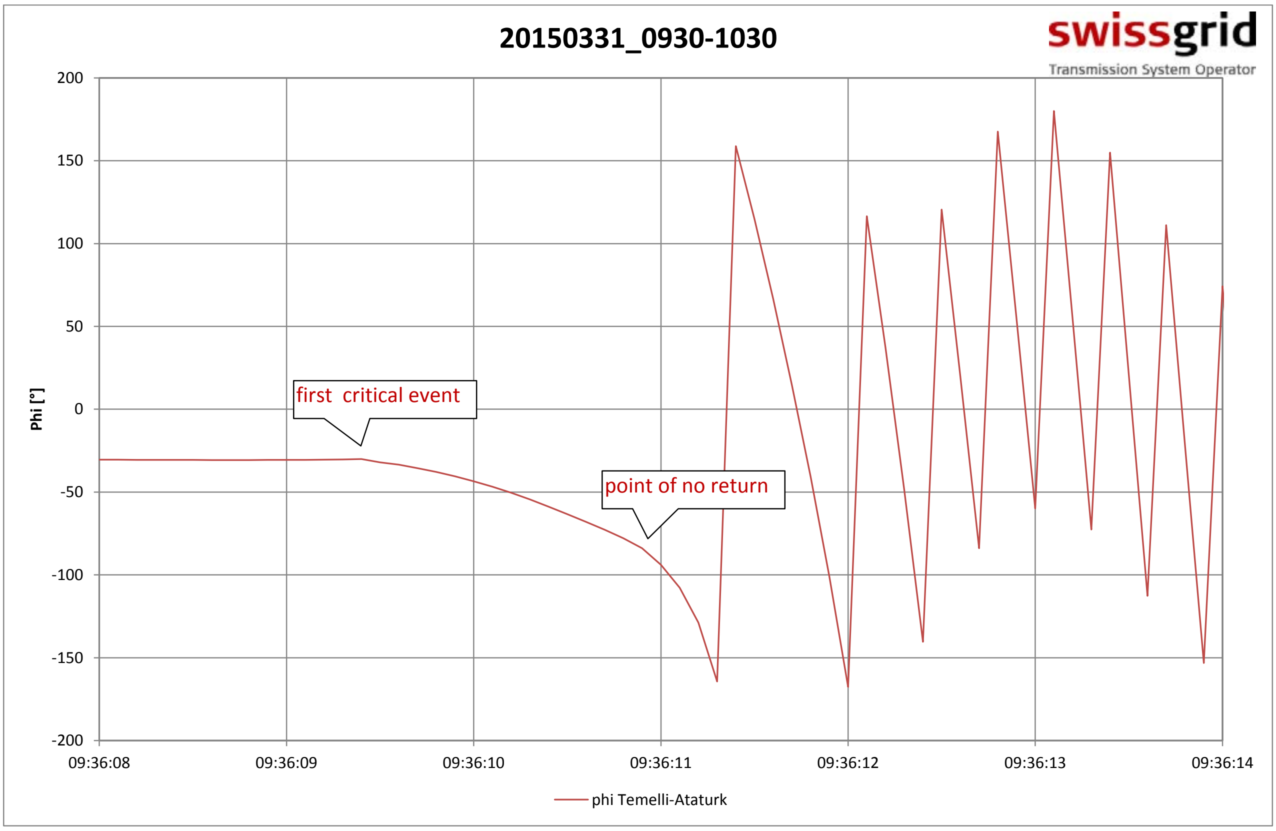

Figure 6: Voltage phase angle difference during angular instability

In Figure 6 the angular displacement between the main generation area (Atatürk) and the main consumption area (Temelli) is shown with focus on the time between the opening of the first line (first critical event) and the second line after 1.6 seconds (point of no return).

The simulation results of this dynamic behaviour are represented in Figure 7; it is worth while noting that angle differences before the first line tripping are in proximity of the static stability limit (blue horizontal lines). That means that after the first line separation the stability of the Turkish system was lost as the voltage phase difference between the two substations one of the Eastern and one of the Western areas reflects the resulting asynchronous operation of both areas.

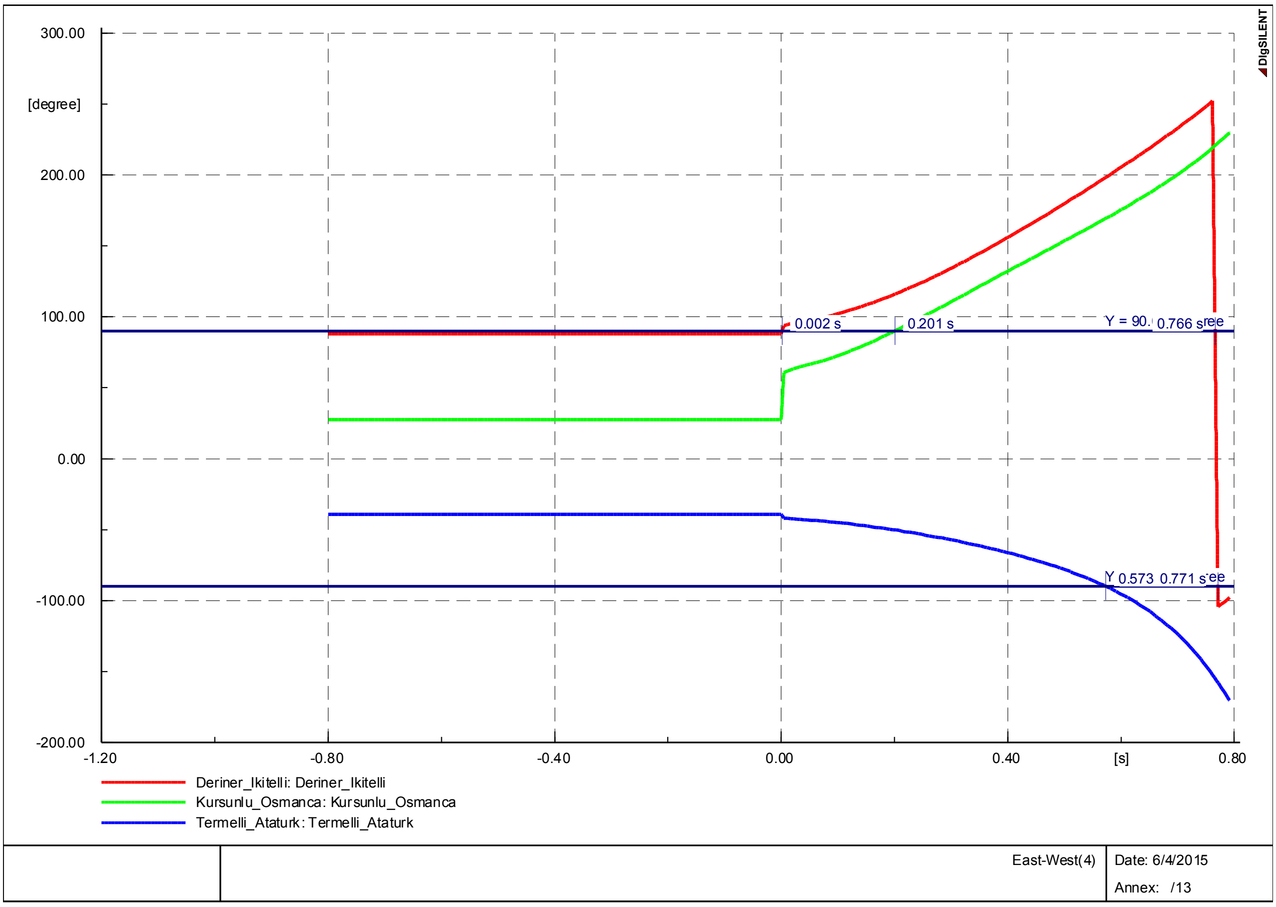

Figure 7: Dynamic model simulation results for angular instability process

Modal analysis with the dynamic model is able to reproduce the critical dynamic system situation before the first event mainly reflecting the highly unfavourable rotating mass distribution in the east-west, longitudinally too weakly connected system.

By implementing a standard distance protection device in the dynamic model, the opening scheme of the second transmission line can easily be reproduced, see Figure 8; the simulation confirms the correct intervention of protections due to the out of step of the two electrical areas.

Some additional considerations can be extracted from the simulation calculations. The overfrequency transient in the eastern part of Turkey reached critical values, over 51 Hz, after in around 1 second; it is clear that only emergency control could react (Fast valving for thermal steam power plants, overspeed control for hydro, load droop anticipator for combined cycle plants). Additional investigations are recommended to check the correct behaviour of these controllers, taking into account, however, that the transient is particularly severe and hard to be controlled.

Priority should, of course, be given to grid operation analyses and rules aiming at eliminating the risk of events as the one of March 31st. A quickly and simply implementable measure is the continuous monitoring in the National Control Centre (NCC) of the sum of the active power flows in the 400 kV lines of the East-to-West central transmission section, for fast actions by the operators on duty if the total power flow happens to approach or exceed the pre-calculated acceptable value, in particular for the line contingency operation.

Opposite problem is in the western area, where the underfrequency transient could be managed by load shedding relays; in this case, the key role is played by tripping of generation plants that causes following phenomena:

1. Increase in imbalance which is in conflict with load shedding
2. Loss of reactive power control and increase of cascading tripping of additional generators due to the overvoltage and "apparent" loss of field on machines.

In conclusion, it can be stated that the dynamic phenomena that occurred in the Turkish power system in the morning of March 31st 2015 can transparently be reproduced and consequently explained in detail.

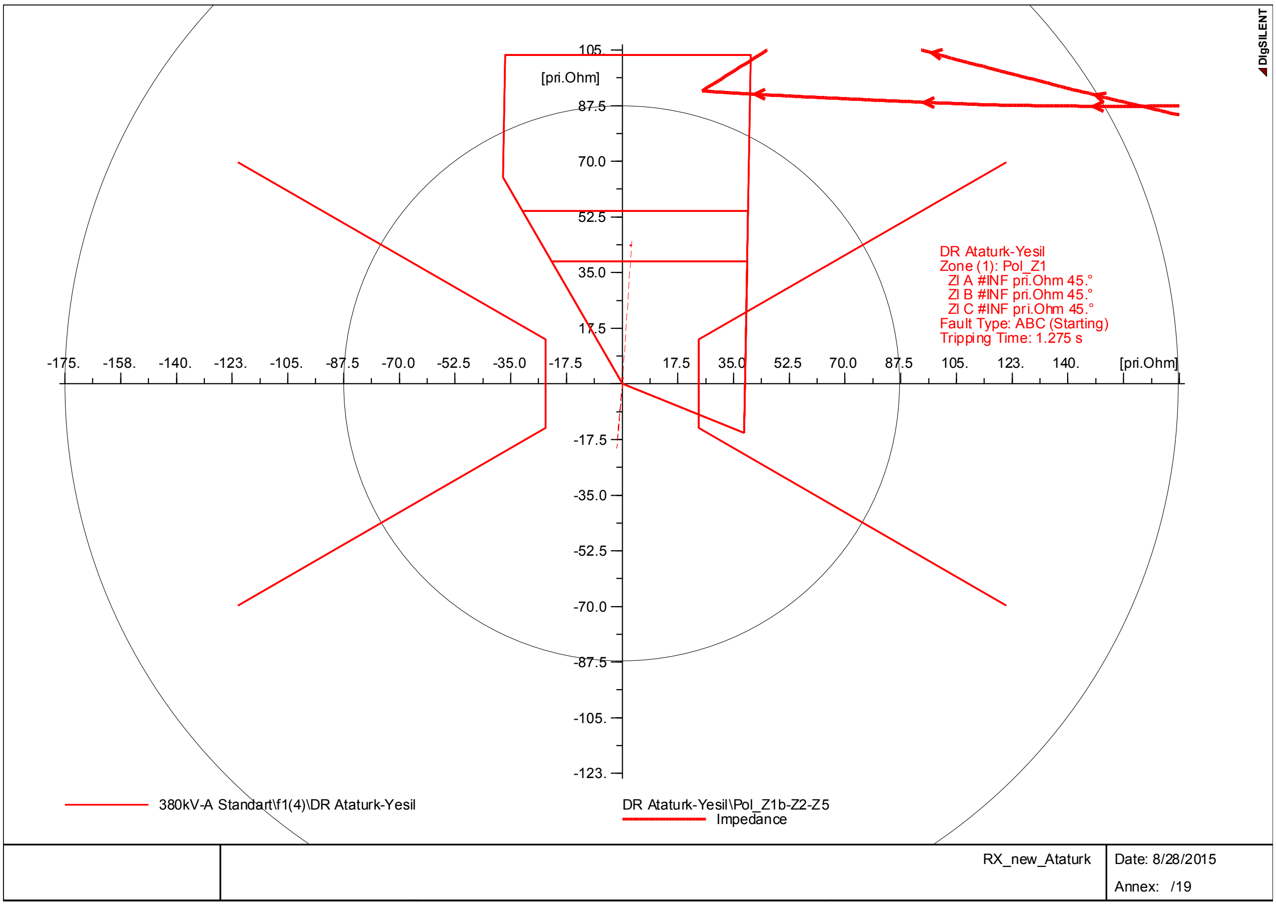

Figure 8: Simulation of distance protection triggering scheme for Atatürk-Yesilhisar North line

In addition, the case of the similar incident was checked, that occurred the day before, on 30th of March; this case shows that the initial voltage phase angle differences between eastern and western Turkey were smaller. The angle differences were not that critical and the simulation of the line opening consequently does not result in out of step. This means that, due to different power flow and area configurations on the day before, the system was much more robust.

5. System Status and Activated Defence Schemes

As one of the measures for the connection of the Turkish power system to the CE power system, a dedicated interface special protection scheme (SPS) was designed and installed at Hamitabat substation for the operation of the related three interface lines.

Brief Description of the SPS in Service in Turkey in the Interface with the Bulgarian and Greek Systems:

The SPS design and technical specification are reported in ref.[4] . The implemented hardware and software that have been in service since 2010 are described in ref. [5].

The dynamic analyses of the whole CE power system interconnected with the Turkish system showed that the particular longitudinal configuration of the system with Turkey located in the tail, the size of the Turkish System (peak load is ~ 43000 MW) and the relatively high transfer impedance across the Balkan countries, yield a very long inter-area electromechanical oscillation period of the Turkish generators against the Central-Western Europe generators (~ 7.5 sec., i.e. frequency ~ 0.13 Hz). On the other hand, a sudden load/generation imbalance occurring in Turkey is made-up by 80-85% from the kinetic energy of the rotating masses of Turkish generators and the primary reserves of the Continental European system entering into the Turkish system. This may cause a large unscheduled power flow to or from Turkey via the Balkan countries before this imbalance is reduced by activating the secondary and tertiary reserves of the Turkish system.

The sudden load/generation imbalances occurring anywhere in Turkey are quantitatively detected by the measurement and fast on-line calculation of the following quantities that are up-dated at a time interval < 100 ms:

- Algebraic sum of the active power flows on the three 400 kV interconnection lines: $\Sigma P(t)$ (positive if exported).
- Rate of change of $\Sigma P(t)$ averaged during the last 1.5 sec.: $[d\ \Sigma P(t)/dt]_{1.5"}$, and relevant sign.

The monitoring of the sudden load/generation imbalances occurring anywhere in Turkey in the three 400 kV interfacing lines has allowed the application of a “response-based” SPS (much simpler and more reliable in a large system than the “event-based” SPSs).

In order to counteract the propagation of the disturbances from Turkey to the Balkan countries, the SPS uses 24 pairs of $\Sigma P(t)$ and $[d\ \Sigma P(t)/dt]_{1.5"}$ thresholds to initiate, by means of transfer tripping on optical ground wires (OPGWs), the following:

- Load shedding (LS) in altogether 15 154/34.5 kV and 400/34.5 kV substations; this happens in 1 or 2 or 3 blocks of ~ 500 MW each at peak load, according to the amount of sudden generation loss, the number of interconnection lines in services, and actual system load in Turkey (higher or lower than 27000 MW).
- Generation dropping (GD) in 6 power plants (3 hydroelectric and 3 thermoelectric); this happens in 1 or 2 or 3 blocks each of ~ 500 MW according to the amount of loss of load, the number of interconnection lines in service, and actual system load in Turkey. The status of operation (in or out of service) and MW output of the generating units are continuously monitored via OPGWs in order to allow disconnection of the desired amount of generation, with priority given to generators in three large hydroelectric power plants if detected to be in service.

The long period of the inter-area oscillation (~ 7.5 sec.) allows up to 2 sec. for the efficacious completion of the loss of load or generation dropping from the moment of the disturbance.

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The Master Programmable Logic Controller of the SPS is installed in the Hamitabat 400 kV substation; a slave unit is installed in the Babaeski 400 kV station, interconnected via OPGWs.

The SPS performs the followings additional functions:

- A back-up overload protection which detects also the large but slow loss of generation and initiates load shedding for preventing separation of Turkey from the rest of ENTSO-E system by the overload protection installed in Maritza (Bulgaria).
- Detection of the inter-area oscillations with alarms or, as last line of defence, tripping of the three 400 kV interconnection lines if the thresholds are exceeded.
- Tripping of the 400 kV interconnection line with Greece if Turkey remains connected to CE only via this line and active power flow exceeds the set threshold.

Settings of the Hamitabat SPS are given in Appendix-27.

As shown below in Figures 9 to 11, Turkey was isolated from ENTSO-E Grid by activation of protections on the Bulgarian and Greek side. Owing to the exceedingly large deficit of generation in Turkey, which caused loss of synchronism with the CE system, the SPS did not have the capacity to prevent the separation of the Turkish system.

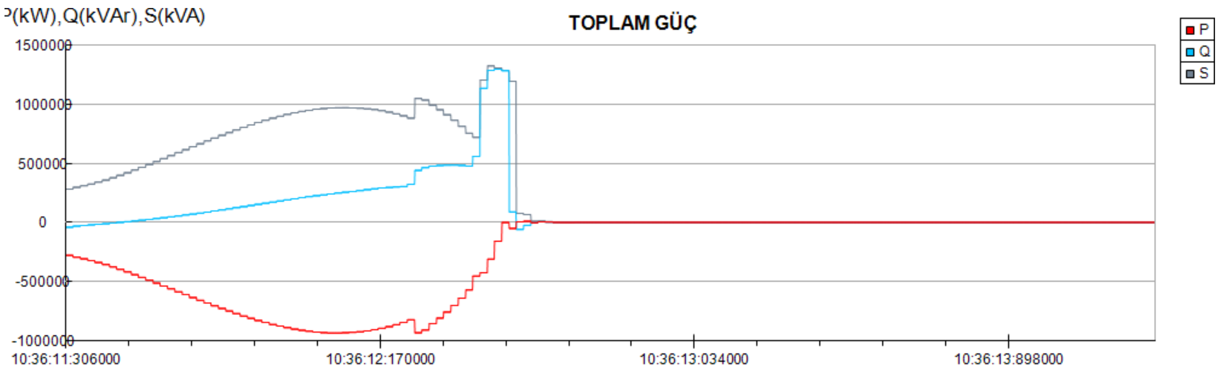

Figure 9: Hamitabat (TR) - Maritsa East 3 (BG) line-1, EET time stamps

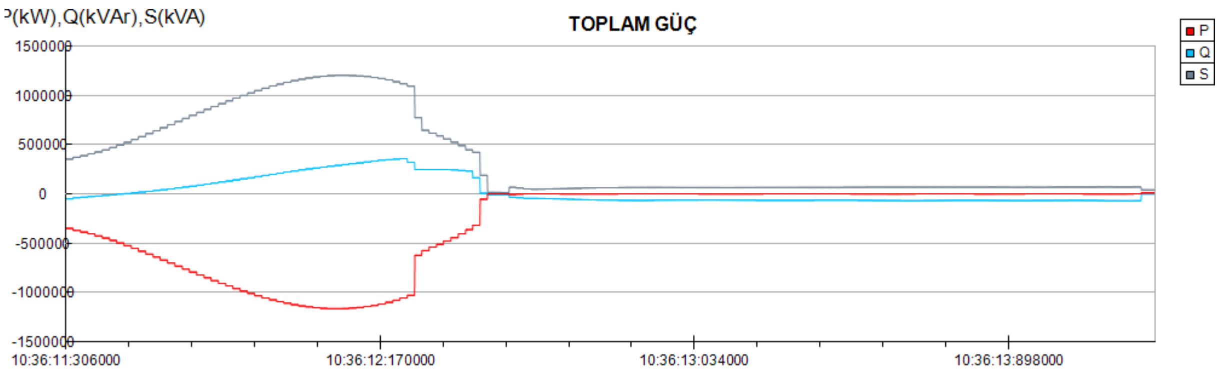

Figure 10: Hamitabat (TR) - Maritsa East 3 (BG) line-2, EET time stamps

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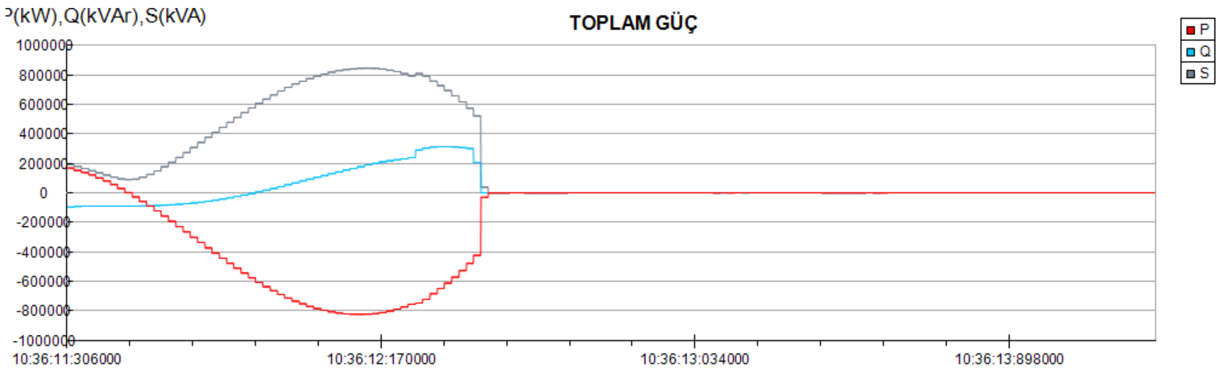

Figure 11: Babaeski (TR)-Nea Santa (GR) line, EET time stamps

Overfrequency Generation Shedding and Underfrequency Load Shedding

After the system split, in the East Island approximately 14000 MW of generation was lost due to overfrequency.

The loads that were shed by SPS and underfrequency relays are given in Table 8:

Table 8: Loads shed by SPS & UFLS Relays on 31st March

Region	West Island		East Island	TOTAL
	SPS	UFLS		
Thrace	252 MW	1641 MW		1893 MW
Northwest Anatolia	125 MW	1018 MW		1143 MW
West Anatolia		1059 MW		1059 MW
Southwest Mediterranean		516 MW		516 MW
Middle Anatolia		583 MW	204 MW	787 MW
Northeast Anatolia			242.2 MW	242.2 MW
East Anatolia			0	0
Southeast Anatolia			683 MW	683 MW
Southeast Mediterranean			1148.1 MW	1148.1 MW
TOTAL	**377 MW**	**4817 MW**	**2277.3 MW**	**7471.3 MW**

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6. Power System Restoration Process

Restoration Scheme

After the blackout the restoration plan was started immediately. The restoration plan of TEIAS is prepared to be started by dividing the system into 9 isolated islands; actually these are the 9 Regional Control Centres (RCCs). The procedure is to start simultaneously in each island with black-start capability power plants distributed all over the Turkish Grid and complete the whole ring in coordination with the National Control Centre (NCC). Both bottom-up and top-down approaches were applied during the restoration, by getting electrical energy from Bulgaria, starting the recovery of the Trace region, and then synchronizing it with the region of Northwest Anatolia RCC, as well as by initiating black starts in the other regions. Each RCC has at least 3 restoration paths (some regions have 4 paths) and each path includes generators with black start capability.

Sequences of Restoration

Using TEIAS-ENTSO-E CE interconnection, the Thrace region (European part of Turkey) started restoration by closing Hamitabat (TR) - Maritsa East-3 (BG) Line 2 and supplying the electrical energy to Hamitabat (TR) and Ambarli (TR) Natural Gas Combined Cycle Power Plants (NGCC PPs). The connection to the Central European system was used to energise the Thrace region at 9:54 CET, half an hour after system separation.

After starting up of several power plants in the European part of Turkey, the 400 kV tie-lines connecting European and Asian Part of Turkey were closed at 11:11 (CET). At that moment, 50% of the Thrace region was already energised.

Black Sea and east part of Turkey restored their systems and synchronised with each other at 11:30 (CET).

The North East part which was energised from Thrace region was synchronised with West Turkey.

Afterwards the Middle Anatolia which feeds a big part of Ankara city was connected to the ENTSO-E system.

The final synchronisation of East and West and thereby to ENTSO-E CE took place at 400 kV Kayseri Substation (Mid Turkey) at 16:12 (CET). At that moment, 80% of Turkey was already energised. The energising of the remaining feeders was done gradually according to starting up of the power plants.

Percentage of the total restoration is given in Table 9:

Table 9: Total restoration time

Time (CET)	Percentage of system load restored
09:36	Blackout
12:00	20%
14 :30	50%
16:12	80%
18:30	95%

At 18:32:17 (CET) 400 kV Erzurum-Ozluce tripped. The Black Sea SPS was put out of service during restoration process in order to prevent unnecessary tripping. Due to loss of overproduction in the region, the SPS at Hamitabat shed 980 MW load from Turkish EPS (step 1, 2, and 3) and then the Turkey-CE interconnection lines were tripped. The re-synchronisation with CE took place at 18:36 (CET).

Recordings from the second disturbance which occurred during the restoration at 18:32:17 (CET) is shown on the next two figures (Figure 12 and Figure 13). Only the overloading protections reacted – 1400 MW/8 s which tripped the two interconnection lines between Bulgaria and Turkey. The summary peak value of the active power over BG-TR lines 1&2 was 2332 MW. The Hamitabat SPS dP/dt and P pick-up thresholds were exceeded for the disconnection of all the 3 blocks of load, and also the SPS 1300 MW – 3.5 sec. overload threshold were exceeded, but the load shedding was not activated for reasons that have not been reliably identified.

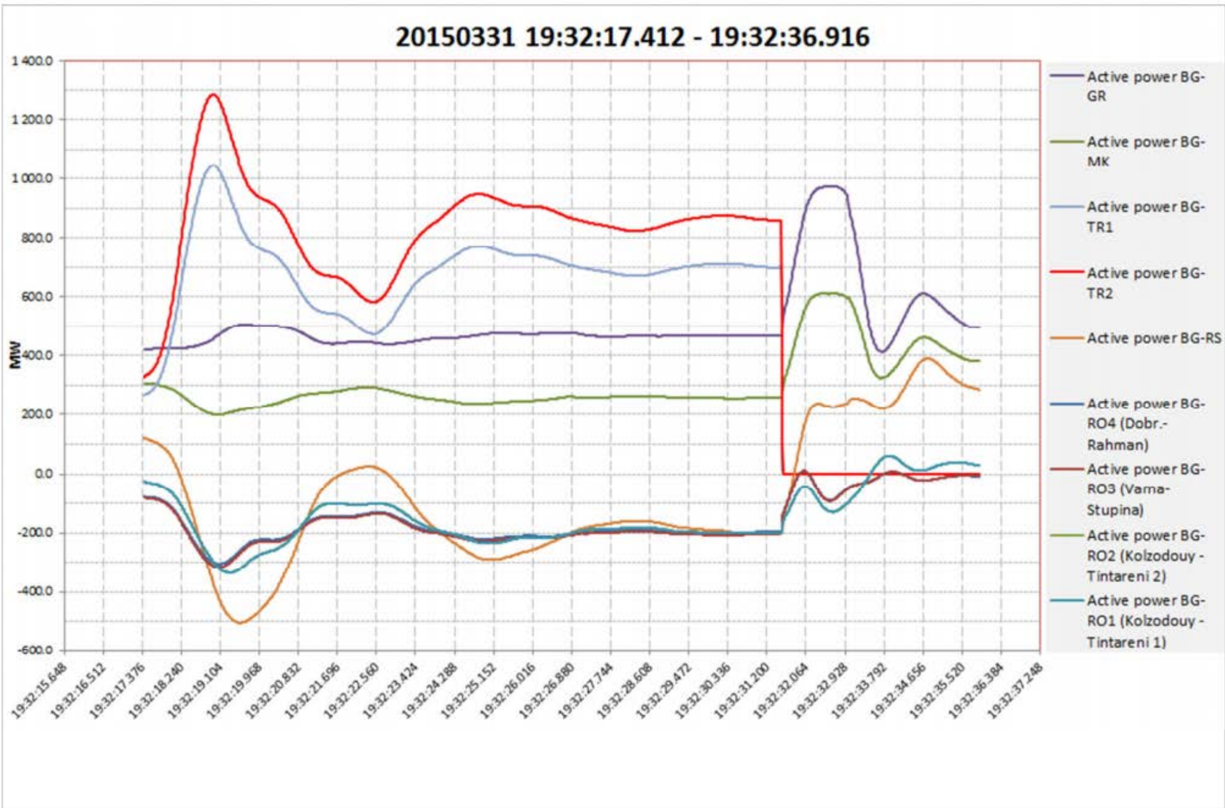

Figure 12: Disconnection of TR power system after the end of the restoration process, EET time stamps

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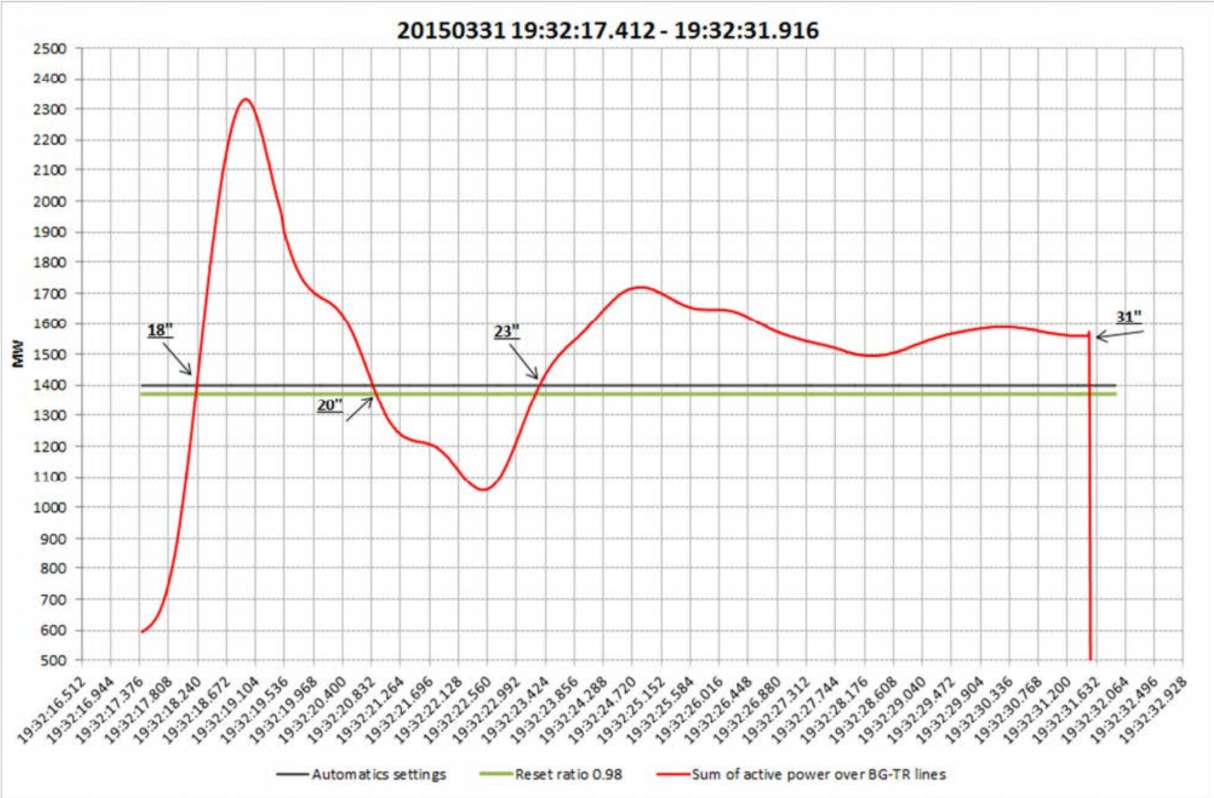

Figure 13: Overload protection activation during TR system separation, EET time stamps; summary flow over BG-TR lines 1&2

During the first and second disturbance active and reactive power swings of generators in the whole of the Bulgarian grid were observed. The deviation of the machines in TPP ME3 was around 135 MW (rated active power 227 MW).

The system frequencies during the TR evening island operation are shown in Figure 14.

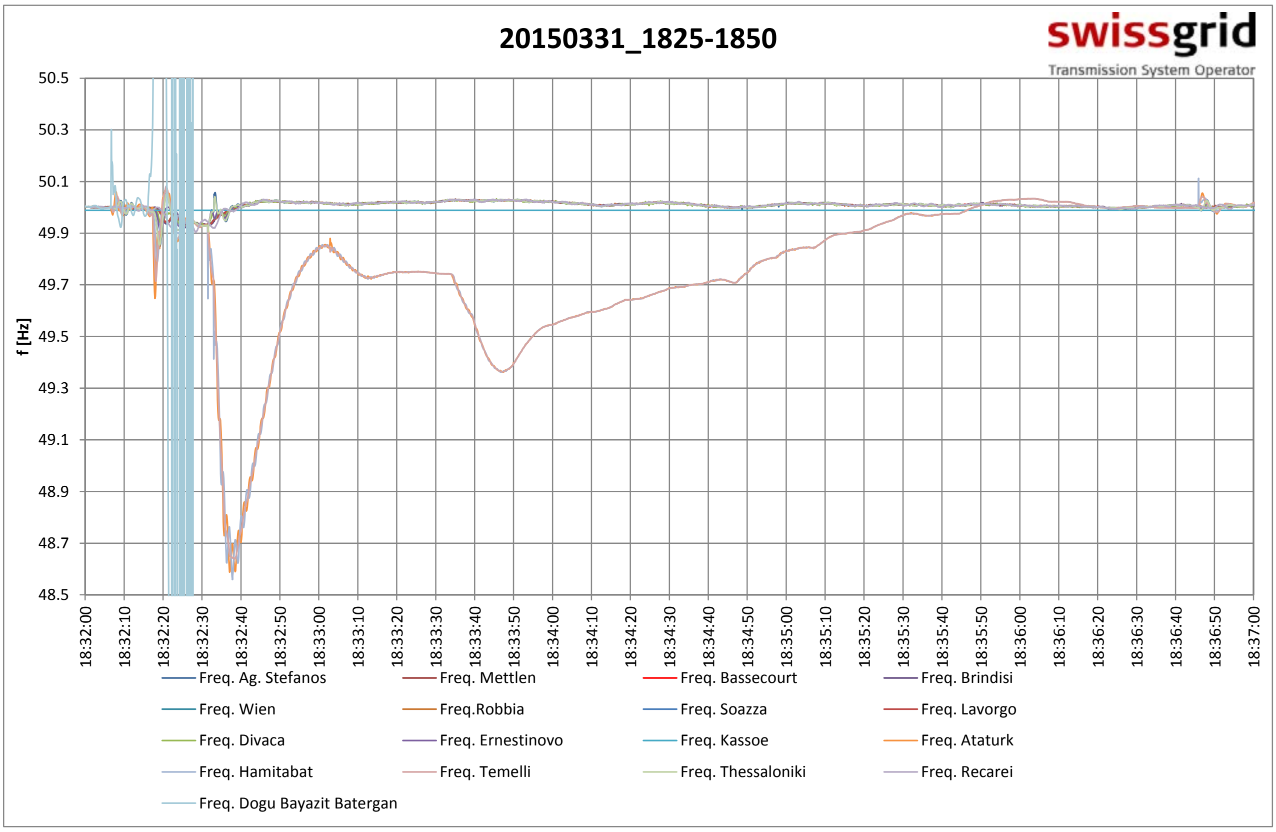

Figure 14: Frequencies during evening TR island system operation, CET time stamps

7. Analysis of Main Causes

As in previous similar blackouts of large power systems in industrialized countries, the total systems collapse was caused by a fast sequence of events involving the transmission, the generation, the protection-control and operation-supervisory subsystems, with shared responsibilities.

400 kV Transmission Lines Out of Service

Four 400 kV long **t**ransmission **l**ines (TLs) (with length ≥ 265 km) were out of service, three of which owing only to interference with the construction works of new transmission infrastructures. These 4 TLs are all in the Central part of the corridor line East to West transmission system of Turkey. Prior to the blackout the total power flow from the East to the West in the other TLs in service in the same transmission section was 4700 MW, with all series capacitor banks out of service (by-passed) and non-uniform power flow in the TLs, reportedly: 1168 MW in the Kursunlu – Osmanca TL; 884 MW in the Adana – Seydisehir TL which has twin bundle conductors; the other lines, all with triplet bundle conductors, were moderately loaded (470 to 625 MW).

Owing to the many long TLs out of service, the long transmission distance (up to 1300 km from the remote Deriner hydroelectric power plant (HPP) in the North East to the major load area of Istanbul), and the above reported undesirable non uniformity of power flow in the other TLs, the national system was not in (N-1) secure state with respect to angle stability. This situation occurred in spite of the advantage given by the multiple transfer technique (stabilizing support of the generators which are in service in intermediate points along the transmission route). The results of steady state load flow calculations in the contingency analysis, which were reportedly verified by the NCC prior to the blackout, show no line overloading and no undervoltage in case of (N-1) contingencies.

In very highly meshed grids with short transmission distances this (N-1) steady state security criterion allows maximum loading of the lines. On the other hand, in case of long distance transmission (N-1) contingencies, the loss of angle stability requires accepting line loadings below steady state (N-1)-security limits. Angular stability analyses are therefore necessary for critical operation conditions. Simple indicators of critical system conditions that could have been evidenced by the load flow contingency analysis for the system status prior to the blackout are discussed in Appendix-28 of this report.

However, it should be noted that TEIAS do not have yet a complete on-line (N-1) contingency analysis process in operation. The current procedure is based on hourly snapshots and during the time of the event there was one of the daily highest load increase gradients observed. That means that the last (N-1) hourly contingency analysis results might have been based on a less loaded system as during the blackout.

The Tripping of the Osmanca – Kursunlu 400 kV TL

Review of recording of relay operation shows that the Osmanca – Kursunlu TL, which was reportedly steadily carrying ~ 1800 A prior to the blackout, was reportedly tripped by the 5th zone of the TL distance protection relays in Osmanca at 09:36:9 CET. The reasons of the tripping are reported in section "Factual sequence of events" of Chapter 8. This setting was not known to the operational department. At the moment of tripping, 2 sec. after pick-up of relay 5^{th} zone, the line currents were 1820 A and voltage was 393 kV:

– The TL has a length of 206 km and is equipped with triplet bundle ACSR conductors Code Cardinal which have a continuous current carrying capacity of 2350 A (i.e. 1628 MVA at 400 kV) in the most unfavourable ambient conditions ($t_{amb.}$ = 45°C; $t_{cond.}$ = 80°C; air motion of 0.5 m/sec; solar radiation of 900 W/sqm). It is reported that the 5^{th} zone of the relay was set, as specified in previous paragraph, because the operation current is limited to this value by the rated current of the disconnector of the Osmaca substation (DSs).

The limiting components for the current limit of TLs are by rule the line conductors, the up-rating of which would be very difficult and expensive and, on the other hand, is not necessary in case of triplet bundle conductors of this TLs in Turkey. On the other hand, however, old line terminal apparatuses of relatively modest cost, such as the DSs, should be timely up-rated regarding their maximum admissible current up to no less than the thermal limit current of the conductors. Up-rating to no less than the line conductors thermal capacity may be necessary also for the terminal apparatuses (DSs, current transformers, circuit breakers, line traps, substation accessories) of other TLs in Turkey that are or can be heavily loaded in contingency operation.

The unjustified tripping of healthy TLs, generators, and transformers by the protection relays has invariably been one of the causes of the blackouts of large power systems, in particular the tripping of TLs by the 3rd zone of the distance relays on overloads detected by the relays as TL 3-Phase faults. A modern rational overload protection of TLs is briefly described in the following:

– Let us assume that the 400 kV terminal apparatuses are rated at not less than the current carrying capacity of the line conductors, with some margins for the temporary overloading. Then the physical quantities to be maintained within the admissible limit are the actual temperature of the TL conductors and compression joints, as well as the conductor extra sagging that can cause flashovers to vegetation or to other infrastructures beneath the TL, or can be dangerous for people and animals.

  Conductor temperature of TLs exposed to overloading can be continuously calculated by modern digital distance relays. A precautionary approximation is usually obtained by providing to the relay the information on the actual line current and the ambient temperature measured at the line ends, by precautionary assuming absence of wind (air motion of only 0.5 m/sec) and full sun radiation (say, 900 W/sqm) in the day hours and no radiation during the night.

  The conductors of the 400 kV TLs in Turkey generally carry currents lower than their thermal limit. TLs are, therefore, operated with conductor temperature much lower than the security limits relevant for the integrity of the TL and for avoidance of dangerous extra sagging. On the other hand, the ambient temperature is generally lower or much lower than +45°C. Therefore, owing to the thermal capacity of conductors, the TL can generally be largely overloaded in emergency operation during at least 20-30 minutes before reaching the conductor limit temperature. This leaves time to the operators on duty for eliminating the overload by re-dispatching of generation, and/or modifying the network operational configuration, and/or shedding some loads. In case of overload, the relay should display the time available before reaching the limit temperature; this time setting need to be continuously up-dated according to actual TL current.

– The TL current overloads should be monitored and activate alarms to the Regional Control Centre (RCC) and to the National Control Centre (NCC) by the SCADA systems. The physical presence in Turkey of operators around the clock in the 400 kV substations is an effective additional mean to guarantee that the overloads will not be overlooked by the RCCs and NCC.

– It is worthwhile to point out that if the Osmanca – Kursunlu line had not been tripped, the blackout would not have occurred although the system was operated in critical conditions.

– It should be noted that, under normal conditions, the loading of the Kursunlu-Osmanca TL is generally much lower than recorded on March 31st when the very exceptional high loading was caused by the out of service for the purpose of construction works of three long 400 kV TLs in the Northern part of the middle section of the East to West corridor line transmission system, whereas the system was operated with high hydroelectric generation in the Eastern Black Sea region.

– The other TLs listed in Table 3 were tripped rapidly by the out-of-step tripping function of the distance relays. The fast tripping was of course mandatory when, at first, the Eastern and Western subsystems lost synchronism and, shortly thereafter, when the Western Turkish system lost synchronism with the CE power system. The recorded transient line voltages and currents at the moment of tripping are reported in the Appendixes-2 through Appendix-15. In the specific conditions of March 31st, the out-of step protections correctly tripped the long lines in substations located not far from the electrical centre of the transmission system during the power swings.

- Although the tripping of the Kursunlu-Osmanca 400 kV TL initiated the blackout, the protection system cannot be considered responsible for the event. As discussed elsewhere in this report, the root causes were the number and location of long 400 kV TLs out of service in the critical transmission section, combined with the out-of-service of all the 16 series capacitor banks.
- The Turkish transmission system is equipped with state-of-the-art protection equipment; in most of the double TLs one circuit is operated with PLC telecommunications and the other one with OPGWs; generally, distance relays of different manufacturers are applied at each 400 kV end; duplicated DC batteries and battery chargers; duplicated tripping coils of the circuit breakers; duplicated protection and tripping circuits. As of 2015, the vast majority of the distance relays is numerical. The 400 kV underground cable TLs are protected also by the differential schemes. The 400 kV substations are equipped with circuit breaker failure protection and bus-bar differential protection. The protection operation statistical recording of the 400 kV TLs and substations shows a very high rate of fast fault clearing, also compared to other national 400 kV grids.

Series Capacitors of 400 kV TLs

Reportedly, all the 16 **s**eries **c**apacitor (SC) banks of the Turkish 400 kV grid were out of service (by-passed) prior to the blackout (three of them were at Kayabasi SS which was under refurbishment process, two of them were in the opened lines Golbasi-Kayseri North & Golbasi-Kayseri South-, SC in the line Sincan-Elbistan A was faulted). SCs were installed for increasing the transmissible power at the steady state and angular transient stability limits from the power plants of the South-Eastern regions to the load areas of the West of Turkey, and also for controlling the sharing of the power flows among the old 400 kV TLs equipped with twin bundle (2 x 546 sqmm) conductors and the later built TLs with triplet bundle (3 x 546 sqmm and 3 x 726 sqmm) conductors.

A load flow analysis run for the much weakened grid topology prior to the blackout (from a snapshot of SCADA) shows that if all the SCs had been in service, except the SC on the Kayabasi – Kursunlu TL, the current in the Kursunlu – Osmanca TL would have been ~ 1570 A. The tripping of this TL, which initiated the blackout, would not have occurred. An analysis also shows that the current flow in the SCs, if they had been in service at the time of the blackout, would have not exceeded their rated current, and the currents in all the 400 kV TLs would have been lower than their thermal limits.

Overcrossing of Existing 400 kV TLs by New 400kV TLs

The simultaneous out-of-service of both the South and North Kayseri – Golbasi 400 kV TLs on the same corridor has reportedly been justified by crossing the construction works on the new Golbasi – Kirikkale TL above the North Kayseri – Golbasi TL combined with re-building the last 10 km section of the South Kayseri – Golbasi TL to a double-circuit TL.

Analyses show (see also section of this report on the Contingency Analysis) that, with the South Kayseri – Golbasi TL in service, the tripping of the Kursunlu – Osmanca TL, that initiated the blackout, would have not occurred.

State Estimation Function of EMS system

The State Estimator of the system is reportedly not in operation in the NCC. As a consequence, other important network applications such as real-time contingency analysis are also not available and instead of this a temporary solution with corresponding off-line calculation based on hourly snapshots is currently in use.

At present, around 500 substations and power plants are monitored by NCC and RCCs in real-time by means of the existing SCADA of the Energy Management System (EMS) system. However, due to the current insufficient observability of real-time data in certain parts of the Turkish power system, the current version of the State Estimator is not yet completely functional. By the completion of the SCADA/EMS System Upgrade Project NCC will be able to run the State Estimator and other important Energy Management System (EMS) applications.

The following Energy Management System (EMS) generation control and network applications are available in the TEİAŞ existing SCADA/EMS System:

- Network Topology Processing
- State Estimator
- Load Flow
- Contingency Analysis
- Short-Term Load Forecasting
- Automatic Generation Control
- Reserve Monitoring
- Interchange Transaction Scheduler
- Dispatcher Training Simulator

However, Load Flow, Dispatcher Training Simulator, Contingency Analysis etc. applications cannot be exploited in the TEİAŞ existing EMS System since they require the State Estimator output as an input, which is expected to be in normal operation by the end of 2015.

One of the important applications used in the existing SCADA/EMS System is AGC. The AGC function interacts with the AGC interface (Plant Controllers, PLCs) at power plants. The AGC interfaces at the power plants control the generating units under their control by distributing set-point signals sent by the AGC program at TEIAS NCC/ENCC (National Control Centre & Emergency National Control Centre). All EMS programs used at NCC will be also functional at ENCC.

Similar Incident on 30th March 2015

It should be noted that very similar load conditions existed one day before the black out (i.e. on 30th March 2015), and the system survived after a similar fault. Although the total loads were similar, the generation pattern on 30th March 2015 was different.

The total generations for 30th and 31st March 2015, between 9 and 10 a.m. CET is given in Table 10.

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Table 10: Total Generation in Turkey

Technology	Total generation (MW) on 30th March 2015 09:00-10:00 (CET)	Total generation (MW) on 31st March 2015 09:00-10:00 (CET)
Import	**856**	842
Lignite	3333	3022
Hard Coal	4586	3770
Fuel Oil	541	562
Diesel	0	0
Geothermal	46	46
Natural Gas	10251	9921
Hydro	12248	13656
Wind	550	640
Export	362	331
TOTAL	**32773**	**32128**
TOTAL load shed	**4527 MW (14%)**	**7471 MW (23%)**

On 30th March 2015 (one day before the blackout) at 09:35 CET (almost at the same time as on 31st March), due to several 400 kV TL tripping, a regional, small part of the system at the south of Turkey was isolated from the main power system. This situation is illustrated in Appendix-29.

The green framed region got isolated. This sub-system had 2580 MW generation surplus which is simply the sum of the loading of three 400 kV TLs which were exporting power from this region. In the appendix-29, the load flows on the East-West Corridor and the tripped lines can be seen. The tripping of two 400 kV TLs Erzin - Gaziantep (940 MW) and Andirin - Elbistan B (930 MW) which were feeding the East-West corridor caused a decrease of the East to West power transfer. The sum of the power transfer by the East-West Corridor was 3710 MW before the incident. With the splitting of the region in the south, 2580 MW of net generation was lost in the main part of the system. SPS at Hamitabat intervened and shed 1210 MW of load, which was a correct action. The logic controller had enough time to intervene before the Turkish system split from the CE system though, but this load shedding could not prevent the separation from CE

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because the generation deficit exceeded the capacity of the SPS. The action of load shedding by the SPS together with UFLS relays stopped the frequency drop at 48.6 Hz.

The total load shed on 30th March is given in Table 11.

Table 11: Loads shed by SPS & UFLS Relays on 30th March

Region	SPS (MW)	UFLS (MW)	TOTAL (MW)
Thrace	931	759	1690
Northwest Anatolia	276	632	908
West Anatolia	0	455	455
West Mediterranean	0	268	268
Central Anatolia	0	206	206
Black Sea	0	96	96
Southeast Anatolia	0	560	560
East Mediterranean	0	193	193
East Anatolia		0	0
TOTAL	**1207**	**3169**	**4376**

Comparing to the 30th March situation, the generation pattern on 31st March led to a higher east-west power flow. The load flow on 31st March between east and west is illustrated in Appendix-30.

As it can be seen, the total east-west power flow on 31st March 2015 was 1000 MW higher than on 30th March 2015.

Summarising by comparing the Turkish power system morning situation of March 30th and March 31st the following can be concluded:

- The East-West transmission system corridor was weakened in the same way on both days due to system operation with 4 open out of 11 main 400 kV east-west interconnection links and out of operation of all corridor serial capacitors.
- However, on March 31st, due to 1000 MW higher flow, the east-west voltage phase angle prior the event was significantly higher already exceeding the related stability limit after the first line trip. Dynamic calculations with the March 30th system pre-loading conditions reflect the fact that the stability limit was fulfilled even if one additional corridor line had been lost.
- Further, the sequence of events on March 30th was quite different and triggered in an early stage the interface special protection scheme with corresponding load shedding. In addition, a local system separation in the southern area occurred which also contributed to the overall system stabilisation.
- Finally, due to the more moderate resulting imbalance between generation and consumption in the western part of the Turkish power system on March 30th, the underfrequency load-shedding scheme was able to save the system by activating three out of four load shedding stages. Consequently, the

analysis confirms that on March 30th the system was operated with a sufficient dynamic stability margin, able to resist to a severe transient. On March 31st, however, as confirmed by simulations and data analysis, the Turkish power system was at the stability limit and a small disturbance was sufficient to drive the system to collapse.

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8. Analysis of Other Critical Factors

Originally, the Turkish transmission infrastructure had the function to form the essential backbone for the security of supply in Turkey. For this purpose the system has been developed over the last 50 years with a view to assure a sustainable and secure system operation. However, a fundamental change of paradigms took place during the past one or two decades. Although the European transmission infrastructure, including Turkey, is able to provide mutual assistance and to ensure a high level of security of supply at reasonable costs, the system has become the platform for electricity market and is more and more loaded by growing market driven power flows across the continent. Market developments result in higher cross-border and long-distance energy exchanges (with short term commercial objectives). Other cross-continental power flow result from the fast and successful development of regional intermittent renewable energy generation with low in-feed predictability (wind power). These developments were not taken into account in the original system design. Against this background, the day-to-day grid operation has become much more challenging and the system has to be operated closer to its limits.

Due to environmental reasons and public resistance, the development of the transmission system is more and more delayed. Many ENTSO-E TSOs face significant difficulties to build new overhead lines due to long authorization procedures and regulatory regimes.

Transmission System Maintenance and Operation

For 20 years, thanks to rapid development of the country and continuous urbanization, Turkey has been facing rapid load-growth. This situation led to fast development of new power plants and, consequently, there had been a strong need to construct high voltage grid lines to cope with this growth. The new power plants that were connected to Turkish transmission system during the last 2 years have an installed capacity higher than 12 GW, which is higher than the generation capacity of some of ENTSO-E TSOs. TEIAS is investing hundreds of millions of euros to cope with this development and make sure that the power system is sound and reliable. In order to execute the necessary construction works it is sometimes necessary to de-energize the existing lines for the purpose of creating stronger lines on the same corridors. As it can be seen further in this report, this situation was valid also on the Blackout day.

All this forces TEIAS to operate the system closer to its limits as given by the current security criteria based on system physics and technical capabilities of the components. Consequently, there are often situations within sufficient security margins so that critical and unforeseeable events might lead to endangered system conditions with severe consequences.

Contingency Analysis

It is worth of mentioning that on day D-1 (30th March 2015) TEIAS modelled its own network for every hour of the day D before giving permission for finalization of the maintenance program. These models also included the market results which contain a large generation penetration in the eastern part of the grid and relatively low generation penetration in the west. TEIAS checked each hour of the anticipated system operation against compliance with the (N-1) security principle. TEIAS also developed a software package which is installed in the National Control Centre allowing the dispatcher to do automatic (N-1) check for each hour. None of the above mentioned security checks revealed any overloading on a line or any voltage problems.

The evaluation by NCC operators of the (N-1) dynamic security of critical transmission/generation operation conditions requires, however, the acquisition by the NCC of a reliable system dynamic model and of analysis expertise. For this reason, TEIAS did not perform dynamic security evaluations for the day D.

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9. Measures, Recommendations and Conclusions

Main Causes,

Main causes of the blackout can be summarized as below:

1. The four 400 kV lines out of service in the critical central section of the East to West corridor line system (three for construction works of new assets, one for maintenance), the long transmission distance (1300 km from the remote Coruk river hydroelectric power plants (HPPs) of the North – East to the major load area of Istanbul), and the out of service of all the series capacitors, resulted in a high East to West transfer impedance. In this grid situation, with high hydroelectric generation in the East and relatively high power transmission to the West, the system was not compliant with the (N-1) dynamic security criterion. The tripping on overload of the mostly loaded line initiated angular instability and consequently system separation.
2. Prior to the blackout there was no adequate awareness about the importance of the series capacitors for angular stability of the system operation condition.
3. Although the Turkish 400 kV grid is equipped with a protection system that is in line with international standards, the effect of the distance relay settings on the line that tripped first was not correctly evaluated.
4. During the frequency decay transient after the separation of the Western subsystem from CE power system several large thermoelectric generators were disconnected at frequencies higher than the 47.5 Hz, which is in contradiction to the specification by the Turkish Grid Code.
5. Owing to the less than satisfactory recorded stability of several power plants during the severe electromechanical transient, a larger amount of load shedding by the underfrequency relays would have been needed to compensate the irregular early disconnection of generators.
6. Regardless of the system configuration and specific load flow prior the March 31st events in the Turkish power system, the quite huge imbalance of respectively 21% and 41% between load and generation in the Western and Eastern Turkish power subsystems remains a challenge which is hard to manage. The resulting high frequency gradients of 500 mHz/s to 1000 mHz/s have driven the power system above a manageable operation margin. Current protection schemes in use in these power subsystems are possibly not suitable for saving the system during such extreme imbalances.

Short Term Measures

The followings measures have already been implemented or will be soon completed:

- Careful check of compatibility with the (N-1) system operation security requirements of the 400 kV TLs and substations which are planned to be put out of service for maintenance or construction works.
- The on-line display in the NCC of the electrical angles of the 400 kV busbars is on the way to be implemented.
- Improvement of TL overloading monitoring in RCCs and NCC
- Changes of the directional comparison teleprotection from blocking scheme to transfer tripping scheme or differential protection were appropriate.
- All the 16 series capacitor banks should always be in service.
- The owners of the large generating units which tripped during the blackout at frequencies higher than 47.5 Hz have been invited to apply the necessary corrective actions in conformity with the Turkish National Code. Checks of implementation are being made by TEIAS.
- The amount of load subject to automatic load shedding by the underfrequency relays is being gradually increased to a total of 41% at peak load, in 5 steps of 7% to 10% each. Pick-up frequencies are 49 Hz, 48.8 Hz, 48.6 Hz, 48.4 Hz and 48.2 Hz.

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- In several substations the 400 kV disconnectors, current transformers, circuit breakers and line traps are being up-rated step-by-step from 1600 A to 3150 A.
- Verify the characteristics of intervention of protections of TLs. Replace in the 400 kV grid the still in service old analogue distance relays with numerical relays with polygonal characteristics and load encroachment capability, more robust in case of transient overload. Check on conventional steam power plants the reaction of thermal system to fast underfrequency transients, introducing, if necessary, gradient limitations on the governors in order to avoid trips.

Medium Term Measures

- Build the planned new 400 kV TLs for re-instating the (N-1) system security in the power exporting regions where, at present, the system is not compliant with this criterion due to recently commissioned new power plants (Eastern Black Sea, Southern Marmara Sea, and Adana regions)
- Implement the on-line contingency analysis in the NCC, with monitoring not only the grid component overloading and voltage limits violation, but also the electrical angles of critical 400 kV busbars
- Implement in the NCC a reliable system dynamic model and expertise for running in short time intervals the angular stability analysis for critical contingencies, with the initial load flow continuously up-dated from the SCADA/State Estimator.
- Complete the SCADA/EMS System Upgrade Project, in addition to the classical SCADA/EMS functions. An Operator Desk for Wind Energy Resources and related functions will be added at NCC and ENCC. By means of this new application the following features will be available: generation curtailment, wind energy forecast and curtailment of wind generation – if required for security reasons, and static analysis and dynamic analysis.
- Identify the reasons which caused on March 31st the disconnection of generating units at frequencies > 47.5 Hz and request the power plant owners to apply corrective actions.
- Perform periodical full load rejection test of the steam generating units, to secure that the vast majority of them remain in service supplying their auxiliary services for at least 1 hour.
- Avoid as far as possible the crossing of existing 400 kV TLs with new 400 kV TLs.

Recommendations

Recommendations which can be quickly implemented at no-cost or minimal cost are summarized below:

- The number of 400 kV TLs put simultaneously out of service in the same transmission section should be checked to be compatible with the preservation not only of the (N-1) steady-state security but also of the (N-1) dynamic security of operation.
- Improve the overload monitoring and protection of the 400 kV TLs. Take advantage of the overloading capacity of the 400 kV TLs according to the thermal inertia of conductors. The 3rd impedance zone of distance protection relays should be set such as not to trip TLs on overloads interpreted as 3-phase short circuits. The short time delay tripping by the 5th zone under-impedance starters should be disabled
- If the PLC telesignals cannot be warranted to be dependable, TEIAS may consider the change of the blocking scheme to the transfer tripping or to the differential protection. This change is justified in the 400 kV stations where the tripping of healthy TLs by the blocking scheme has more dangerous consequences for system operation than the possible delayed tripping of the faulty TL by the non-telecommunication assisted impedance zone of the transfer tripping scheme.
- During the critical operation conditions, keep in operation the series capacitors (SCs) in all the 400 kV TLs except in exceptional location(s), if any, where bypassing might be justified for not overloading the SCs or TLs.
- Improve the dispatcher training with elements of critical system conditions, critical angle differences. Improve the system operation coordination with respect to awareness for critical voltage phase differences. Improve the awareness of the correct usage of the existing series capacitors within the East-West transmission corridor.

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- Avoid the crossing between the existing and new planned 400 kV TLs, unless it is physically unavoidable. It is advised that some crossings already implemented and the crossings included in the project of some new TLs should be as far as feasible eliminated.
- Operate the State Estimator in the NCC and enhance the on-line and off-line computation capacity by including, as soon as possible, the transient stability analysis. As a first priority, activate a dependable (N-1) automatic on-line contingency analysis in NCC. Provide, as soon as possible, the NCC with a reliable dynamic system model and expertise for running the transient stability analysis in short time intervals (say, every 15 minutes) for selected critical contingencies, starting from the snapshot of system load flow. Although this functionality is requested by the CE power system, the current operation with the still offline (N-1) contingency analysis is one of the temporary admitted exceptions.
- Identify and eliminate as far as feasible the causes of the abnormal disconnection at frequencies > 47.5 Hz of the synchronous generators during system disturbances.
- Periodical tests of generator should be performed and certified, for securing compliance with the above requirements and for fast system restoration after a blackout. The steam generating units should undergo successfully a load rejection test at full load, and remain in service supplying their auxiliary services for at least 1 hour.
- In absence of the dynamic analysis capability in the NCC, take advantage of the identification of criticalities with the load-flow contingency analysis for detecting risky system operational conditions (voltage phase angle difference check). An estimate of the too risky contingency operational conditions (probable non-compliance with the (N-1) dynamic security) can be done by using some indicators resulting from the load flow contingency analysis. Such indicators are commented in Appendix-28 for the operational status prior to the blackout on 31st March. A few CE transmission system operators have already implemented within their on-line contingency analysis process, on top of the thermal loading check, also a related voltage phase angle difference check. The principle of this additional loop is to verify if the voltage phase angle difference during opening of lines does not exceed the corresponding transmission line synchro-check setting.
- Although this does not refer to normal operation conditions in Turkey, it is suggested to all TSOs to evaluate if tripping the excess of generation with maximum intervention time of 500-600 ms by a dedicated SPS on a critical electrical section where high electrical flows take place could save the risky area in case of transients.

Conclusions

A lesson has been learned from each of the past blackouts in the industrialized countries, which helps to make the transmission system more robust in the future.

A large electric power system is the most complex existing man-made machine. Although the common expectation of the public in the economically advanced countries is that the electric supply should never be interrupted, there is, unfortunately, no collapse-free power system. The long transmission distances in Turkey and the location of its power system in the Eastern tail of the Continental European system, with international interconnection only in the North-West border, put Turkey in a more critical condition than the other national systems of the Continental Europe.

It is known that at present the transmission system of Turkey has some deficiencies in a few regions (Southern Marmara Sea, North-Eastern Black Sea, and Adana) owing to construction delay of long time ago planned new TLs. However, at national level, the East to West transmission system is robust and adequate. The operation prior to blackout with four long critical TLs and all the SCs out of service was an exceptional severe multiple contingency which cannot be covered in system planning.

The restoration time after the blackout on 31st March 2015 was shorter than it has been reported in case of other blackouts of large power systems in industrialized countries. It was satisfactory. Experience has however shown that the restoration is speeded-up if the disconnected thermoelectric generating units remain in service supplying their auxiliary services (load rejection capability). This event has demonstrated

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that managing an imbalance ratio of 21% (of peak load) between far located areas can lead to serious challenges up to total system blackout if the transmission system from the East to the West of Turkey is weakened by putting out of service several 400 kV TLs and series capacitors. One of the key messages is that in such a case the system separation due to angular instability with 10-40 deg./s results in very high frequency gradients of 500 mHz/s – 1 Hz/s. This risk can be mitigated in different ways:

- Reduce the transfer ratio below 21% by accepting e.g. only 15%
- Increase the fast reaction ability for overfrequency and underfrequency disconnection of generating units
- Increase the amount of underfrequency load shedding
- For fast counteracting sudden large loss of generation and import resulting in high rate frequency decay it is possible to activate, besides the conventional underfrequency load shedding, one or two additional frequency decay rate load shedding steps, e.g. one step with pick-up very tentatively at – 0.4 – 0.5 Hz/s if simultaneously the frequency is ≤ 49.7 Hz (the settings can be chosen by reviewing the frequency recordings following the loss of generation and loss of synchronism in Turkey).

However, as usual, a percentage of non-conform disconnections will have to be accepted. It is recommended to always have more than a sufficient amount of load participating in the underfrequency load shedding scheme. It is recommended to perform additional studies in order to:

- Evaluate the effect of voltage increase during and due to increase of load shedding
- Identify critical transmission corridors on which corrective Defence Schemes could improve system security.

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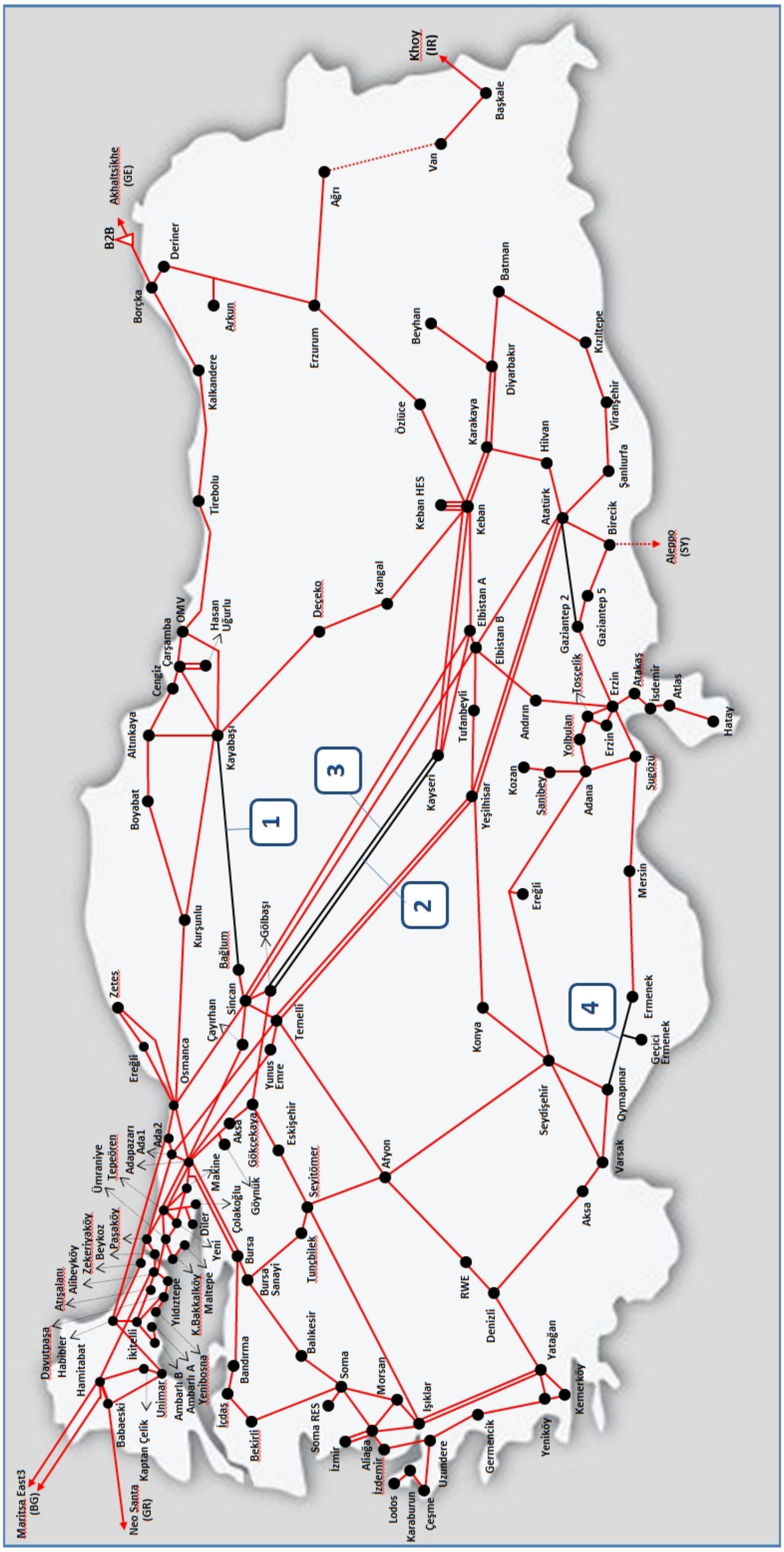
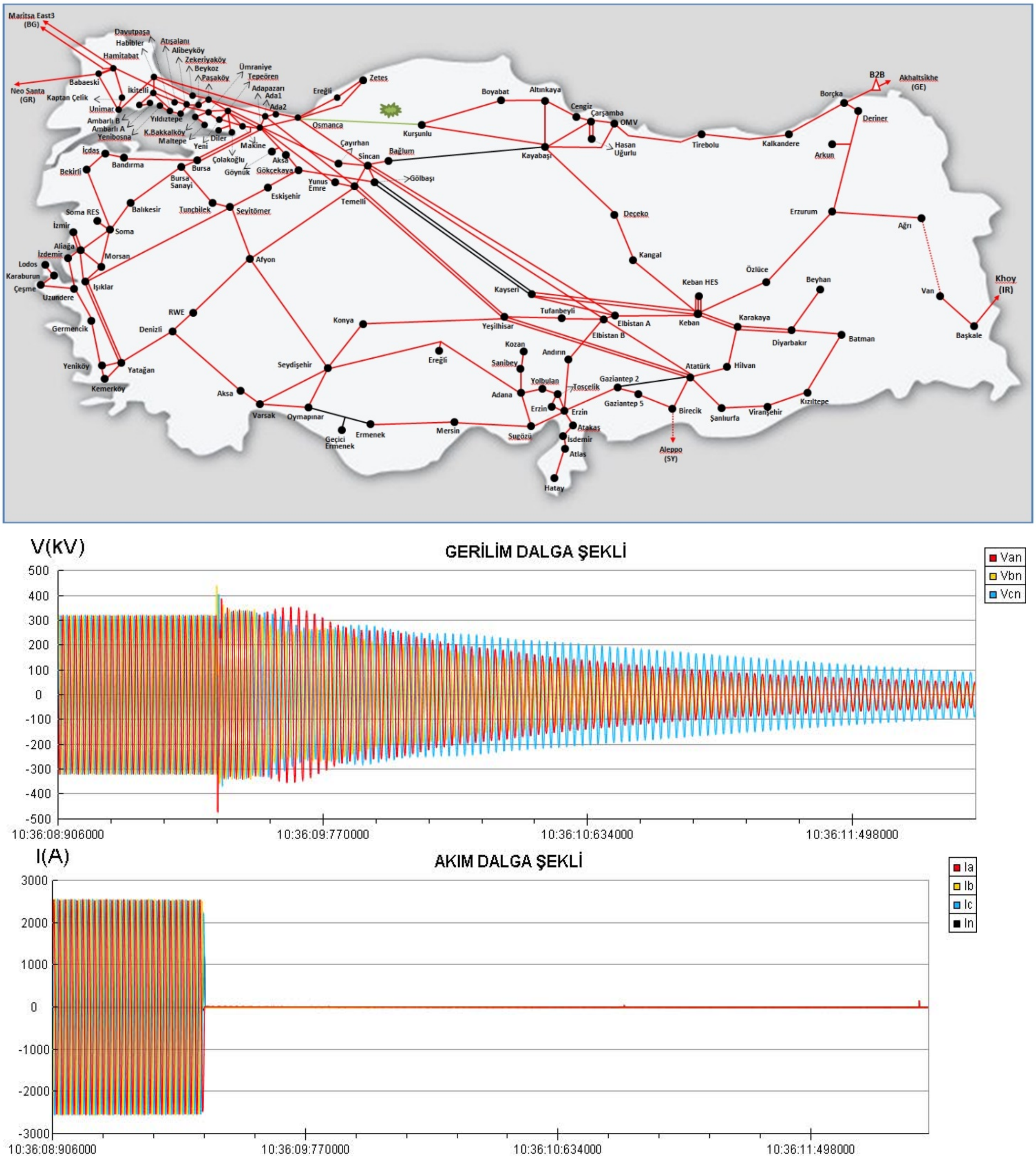
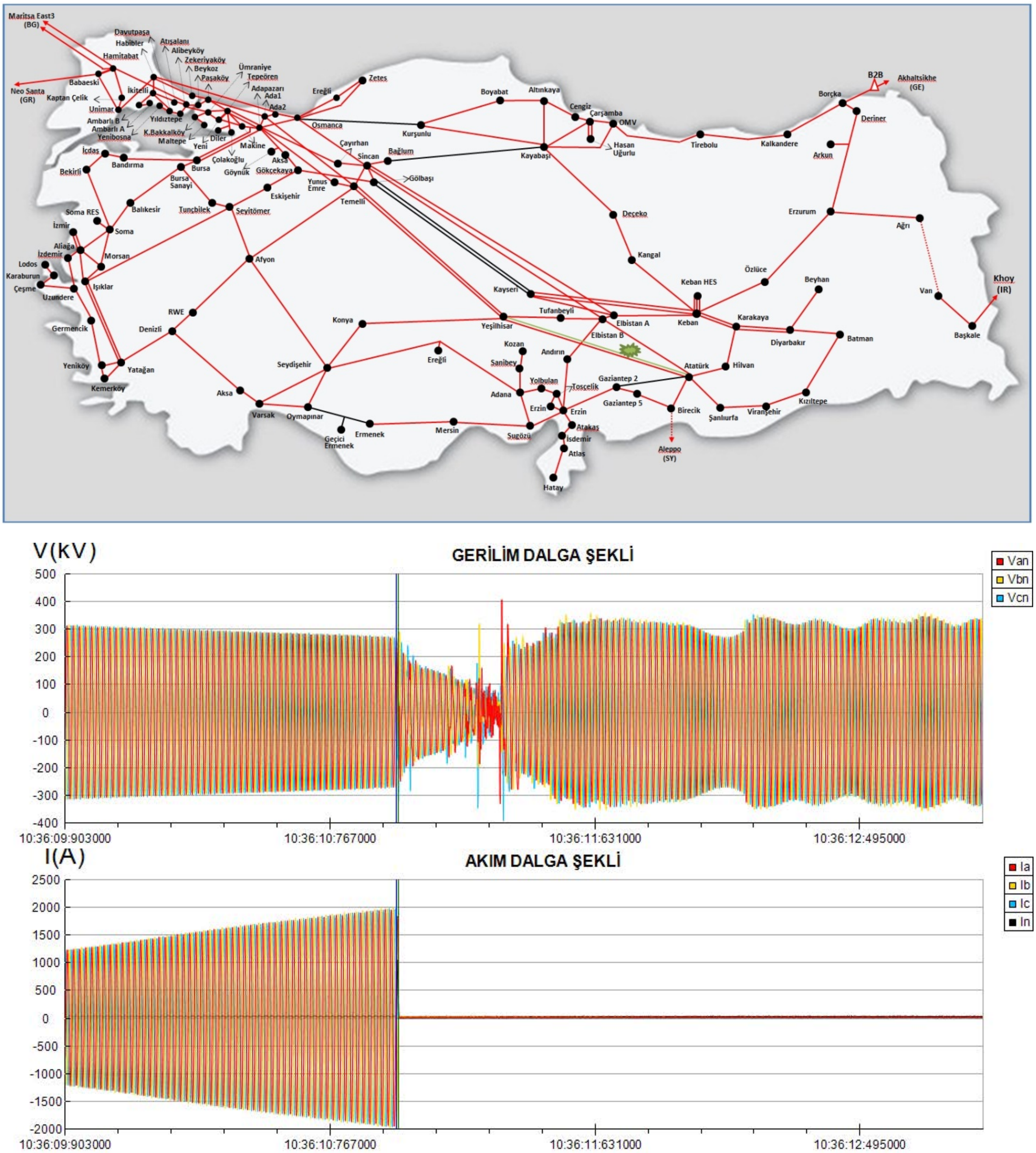
10. Appendices



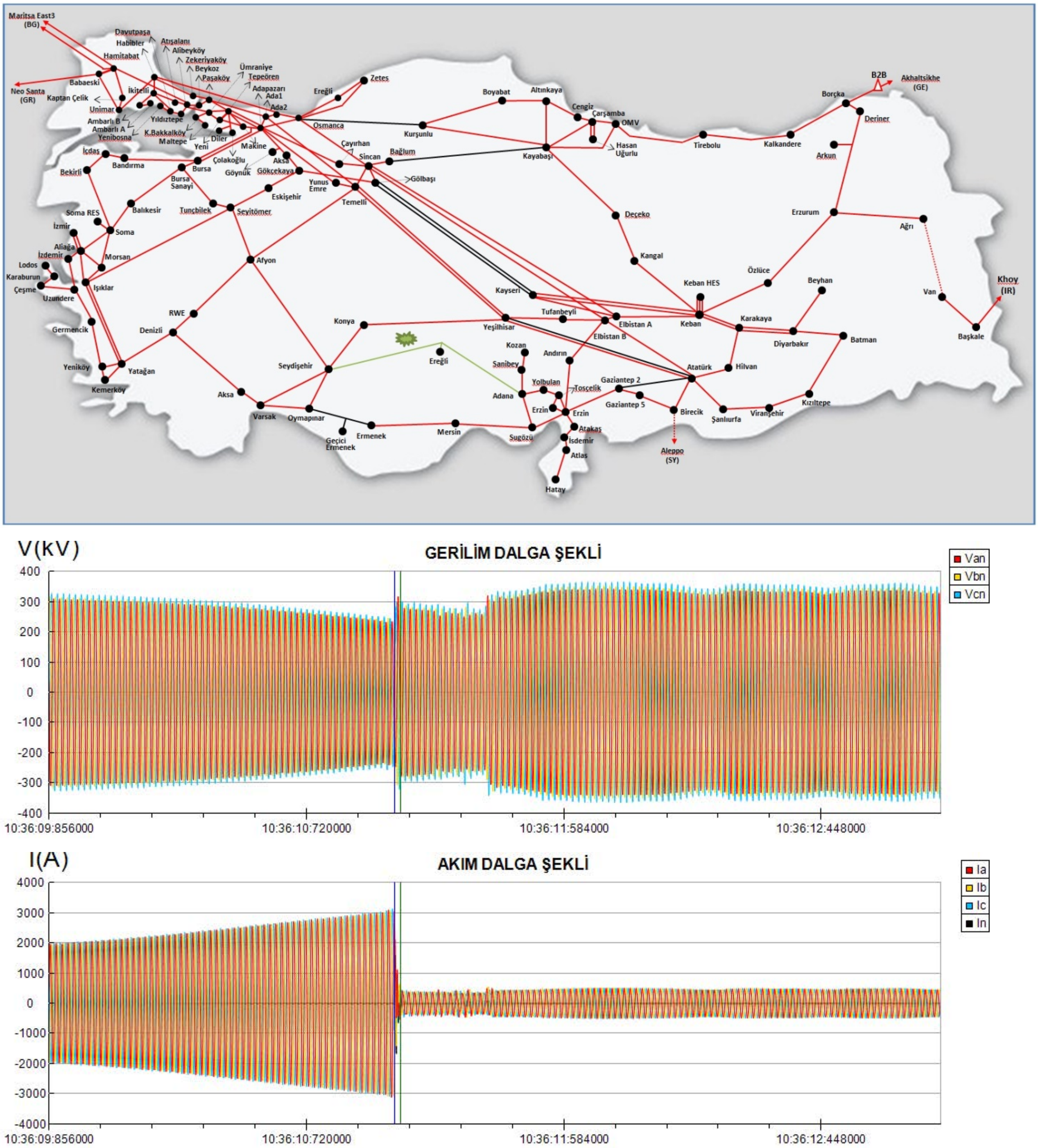
Appendix- 1: Situation before the disturbance



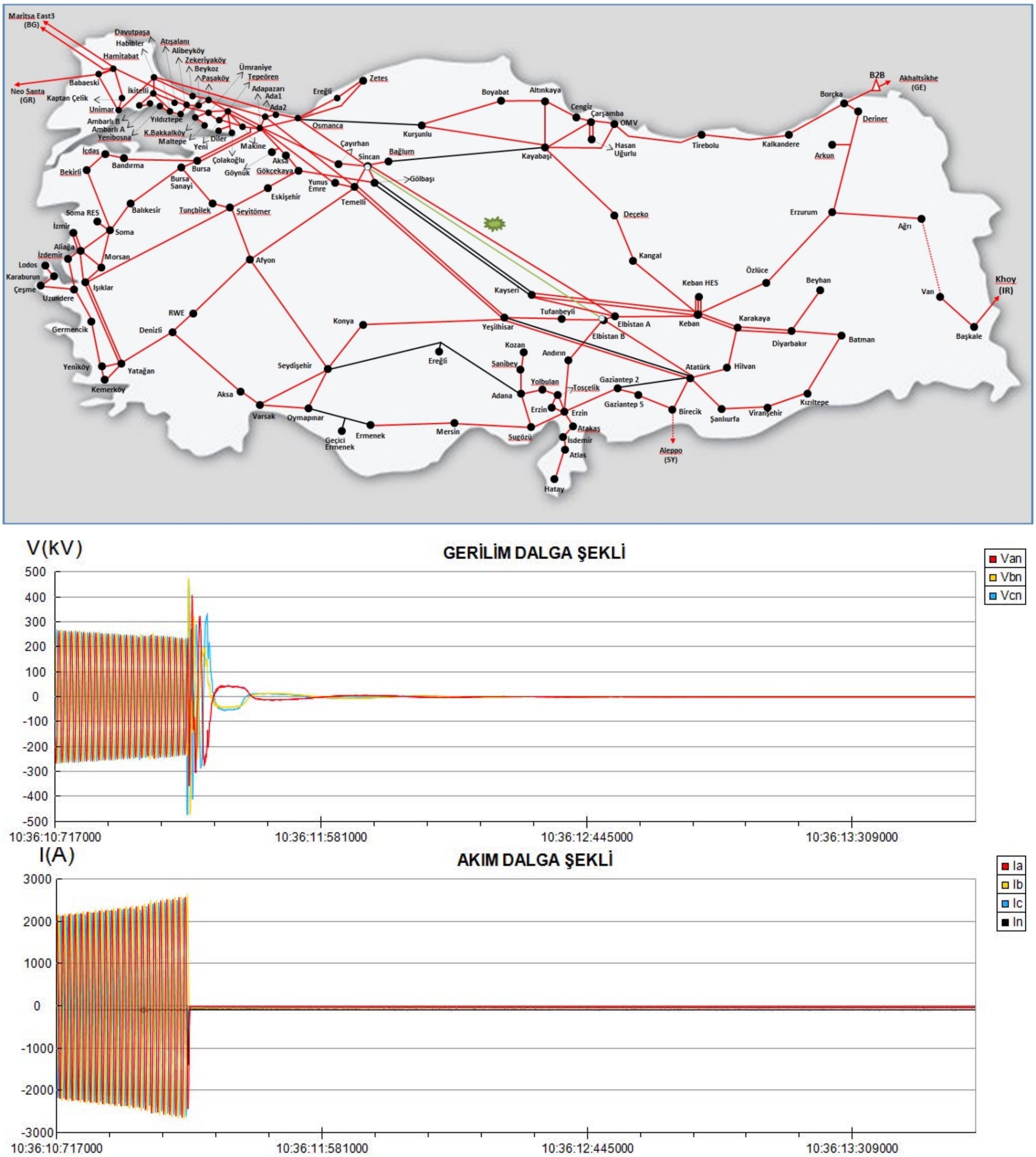
Appendix- 2: Opening of Kursunlu-Osmanca 400 kV TL



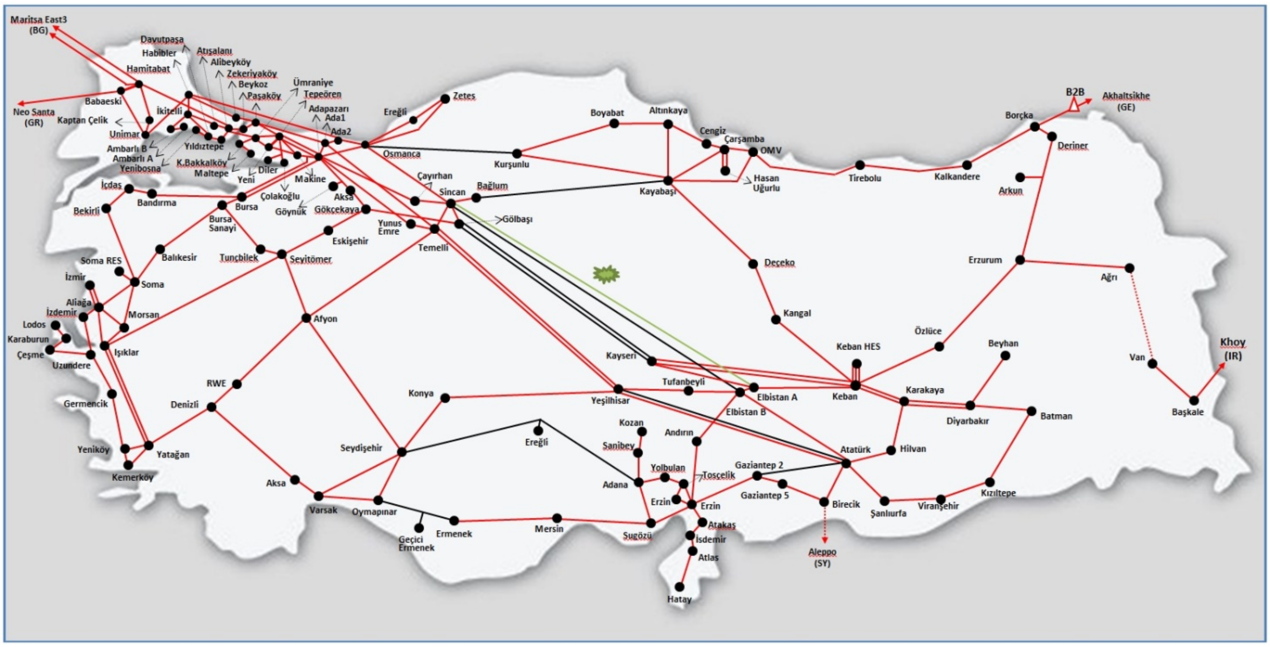
Appendix- 3: Opening of Ataturk-Yesilhisar Kuzey (North) 400 kV TL

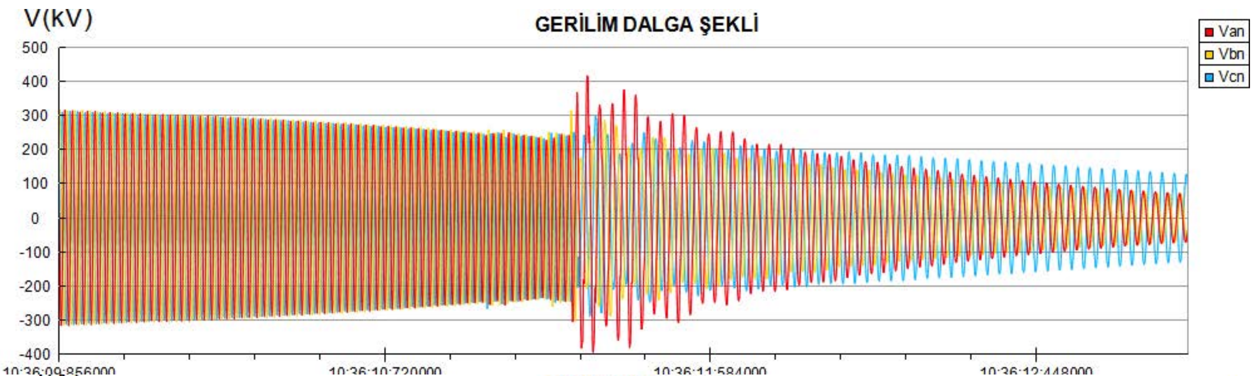


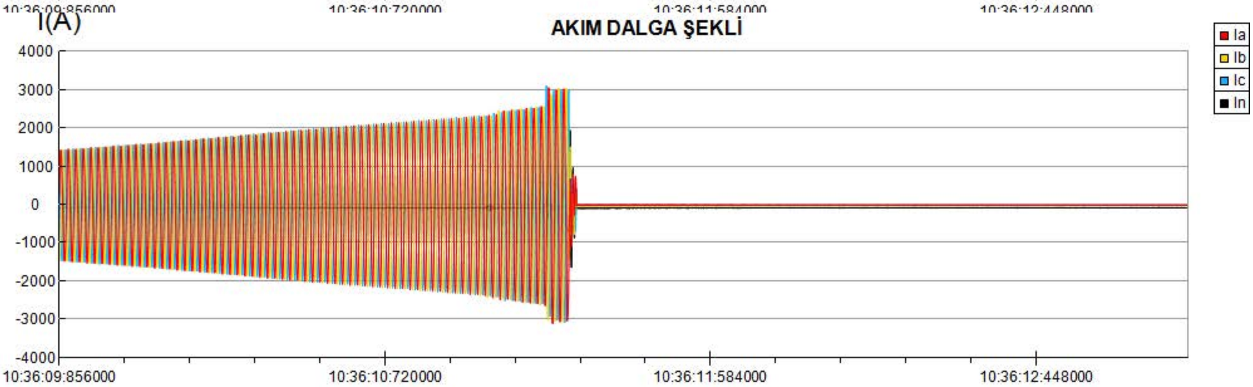
Appendix- 4: Opening of Seydisehir-Adana 400 kV TL



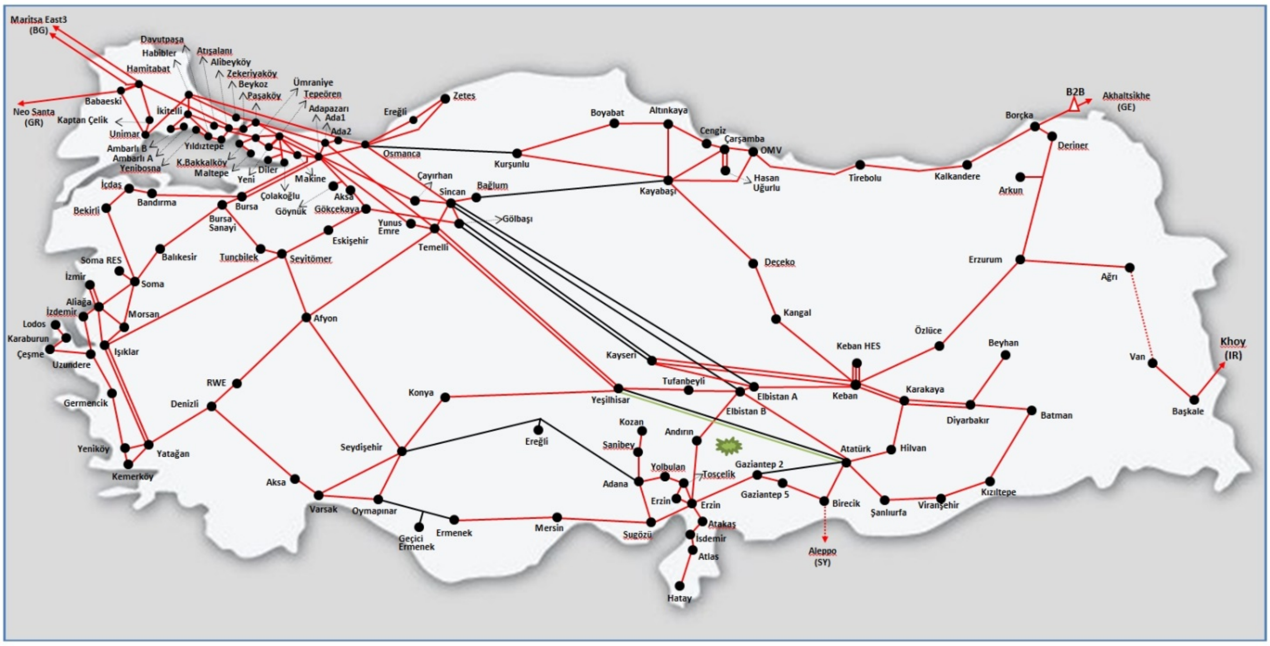
Appendix- 5: Opening of Sincan-Elbistan B 400 kV TL

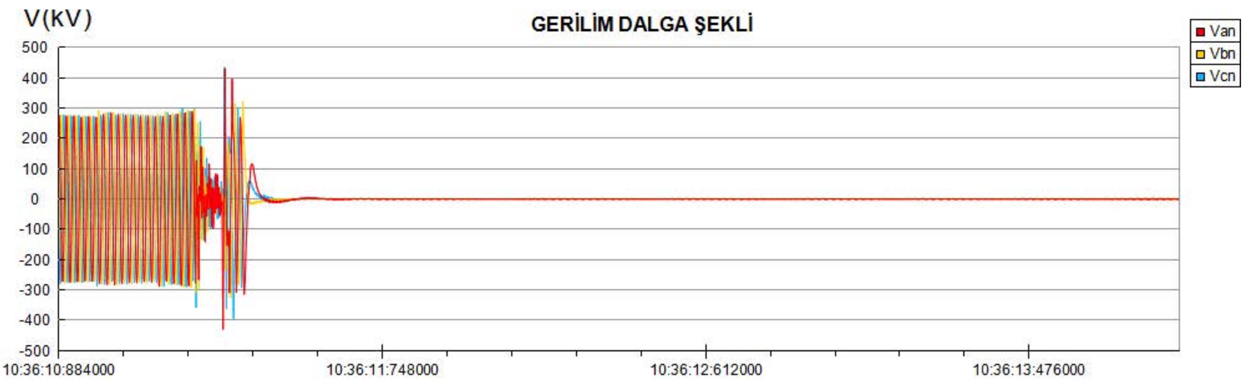


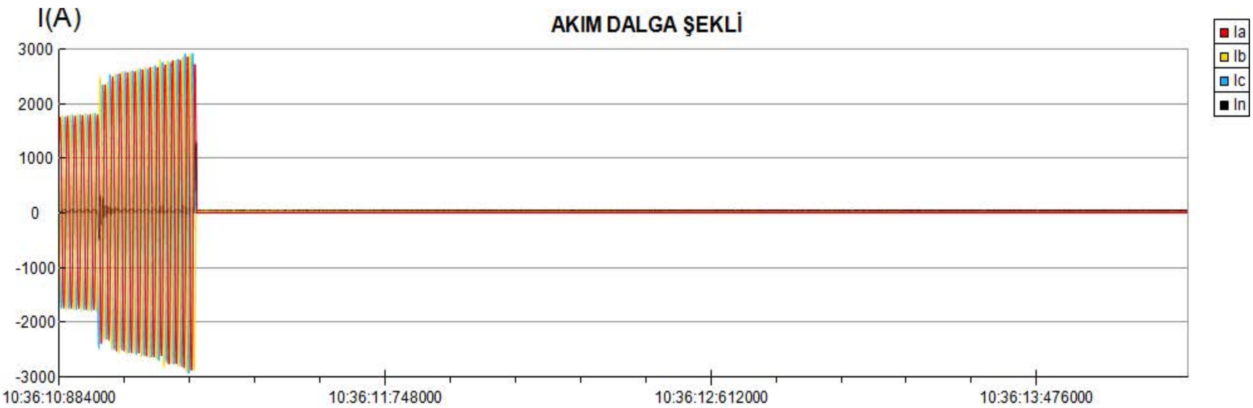




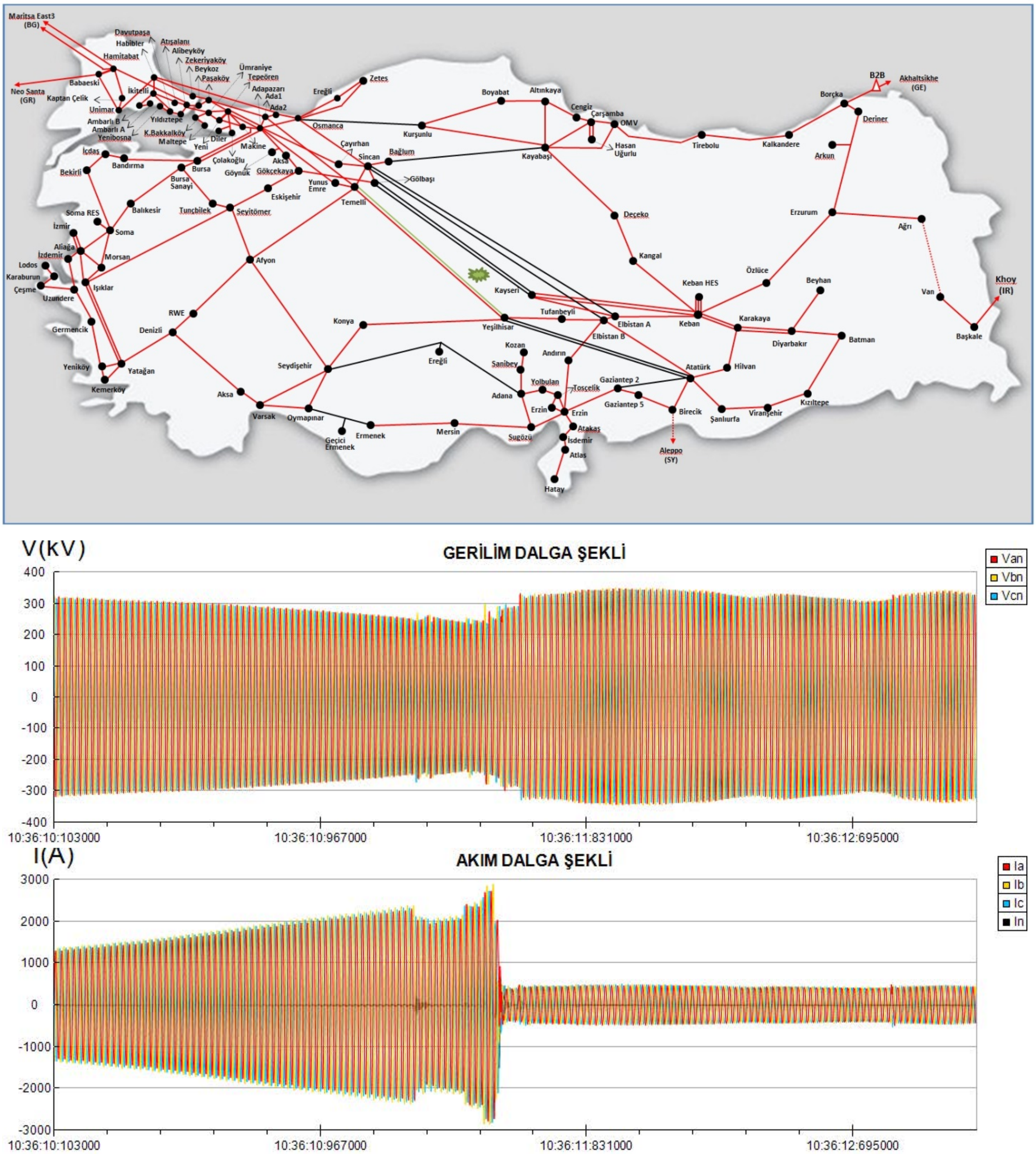
Appendix- 6: Opening of Sincan-Elbistan A 400 kV TL



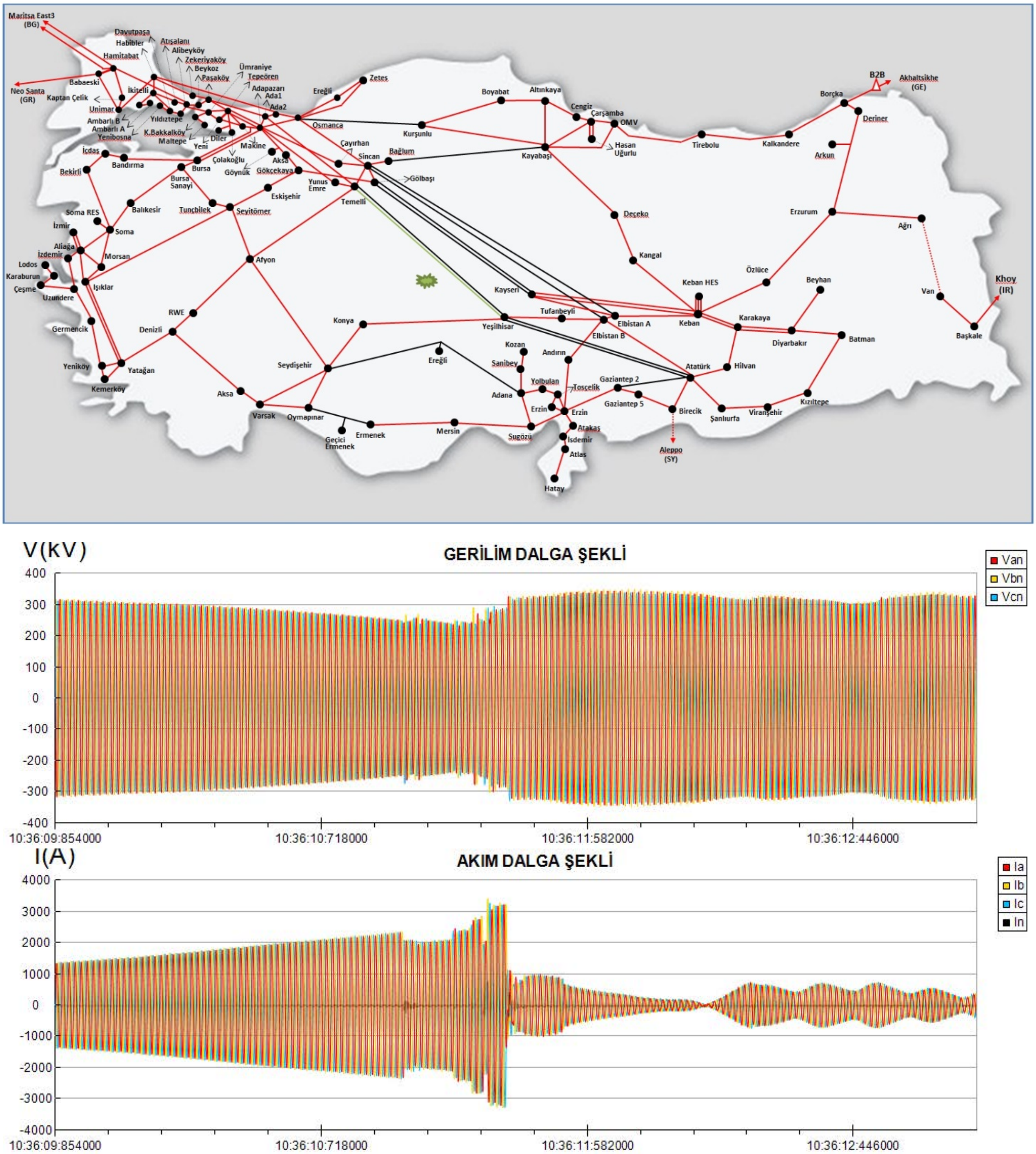




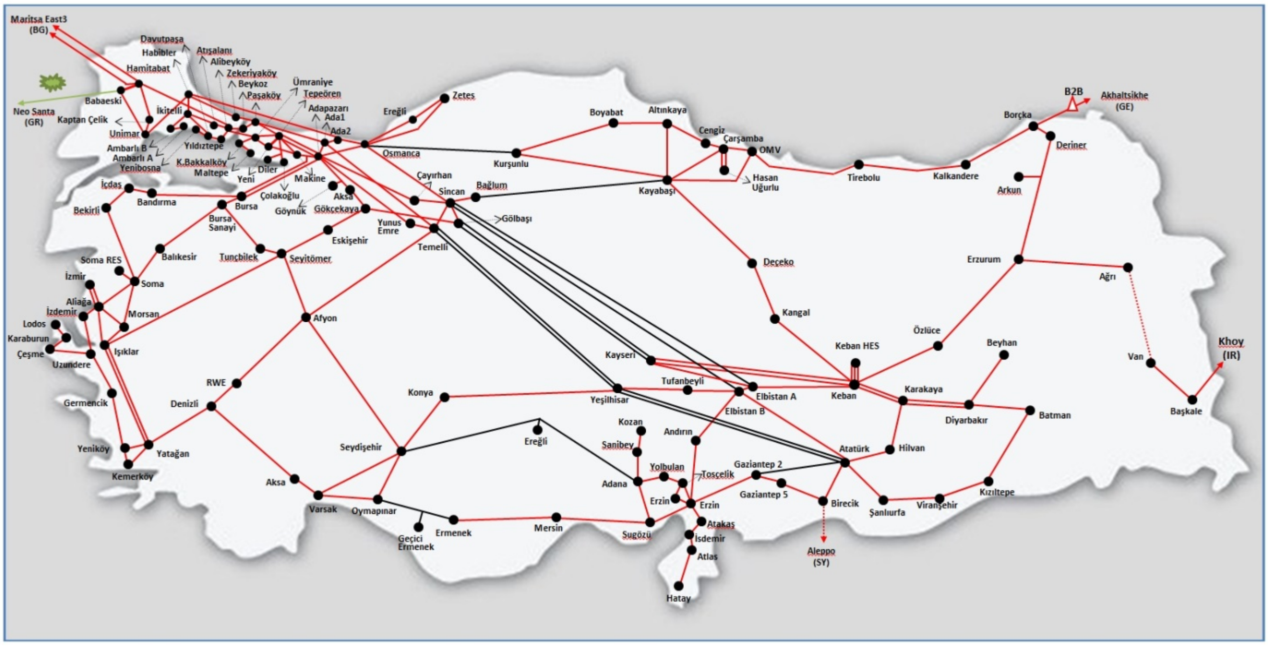
Appendix- 7: Opening of Ataturk-Yesilhisar Guney (South) 400 kV TL

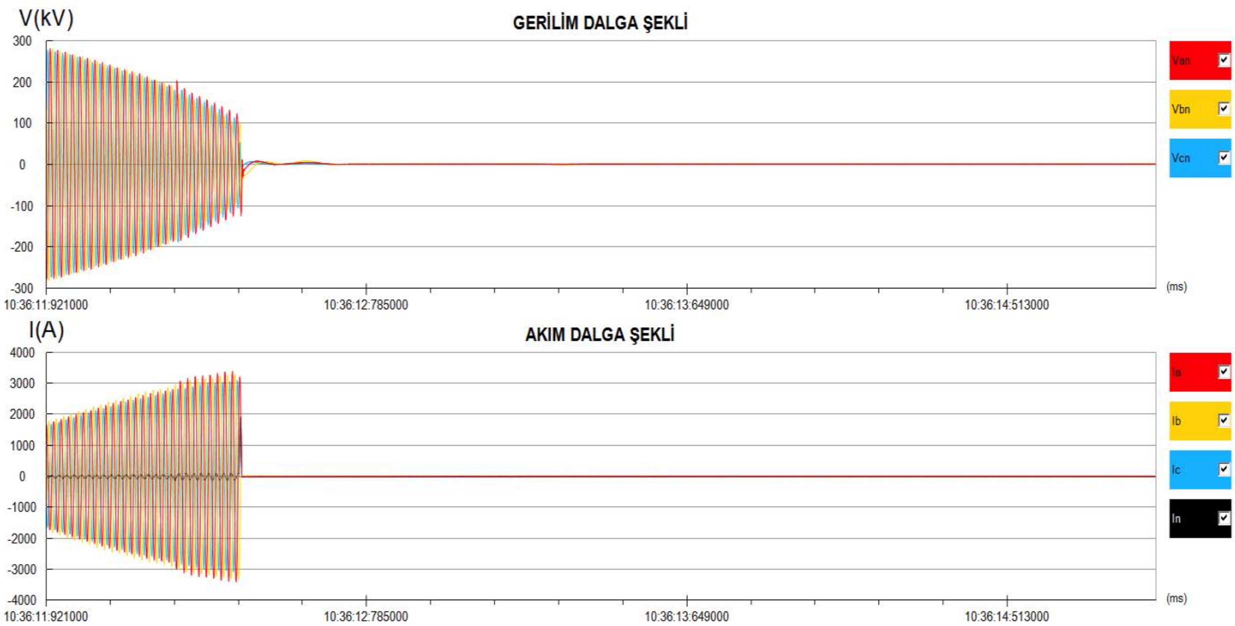


Appendix- 8: Opening of Temelli-Yesilhisar Kuzey (North) 400 kV TL

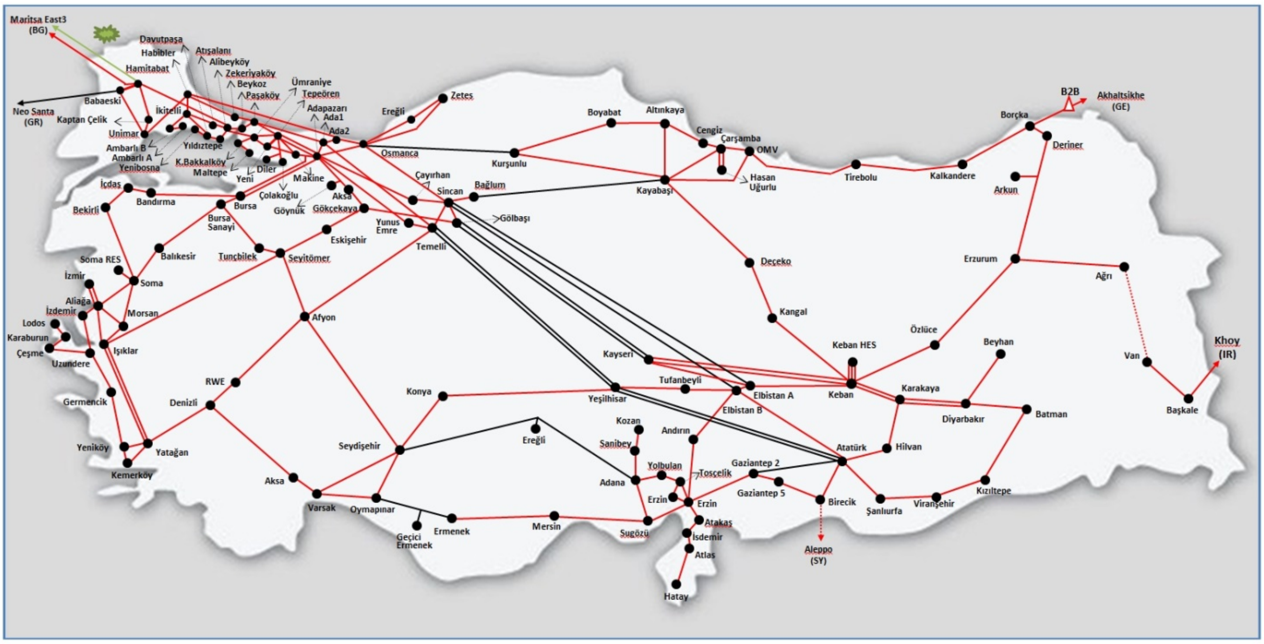


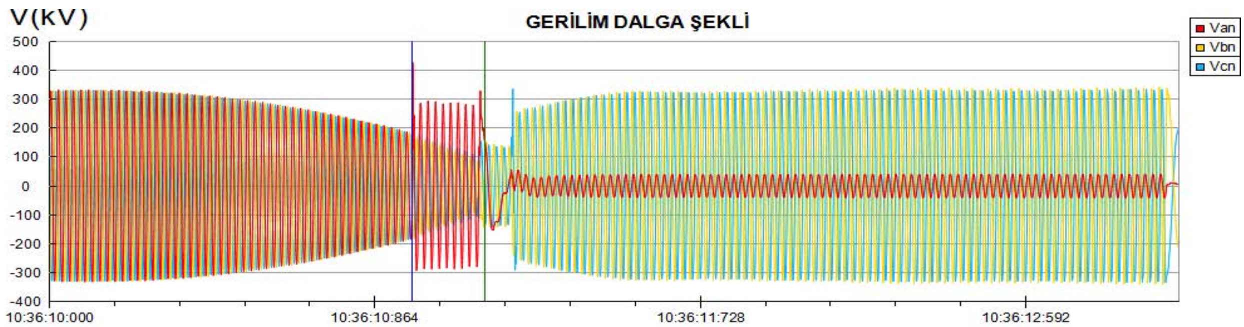
Appendix- 9: Opening of Temelli-Yesilhisar Guney (South) 400 kV TL

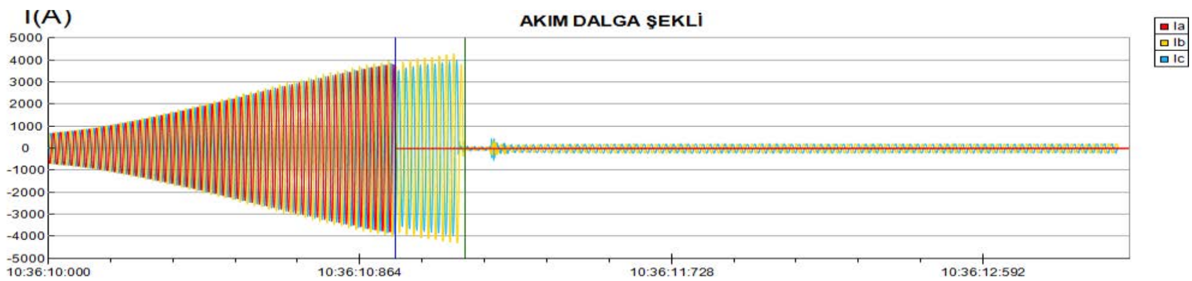




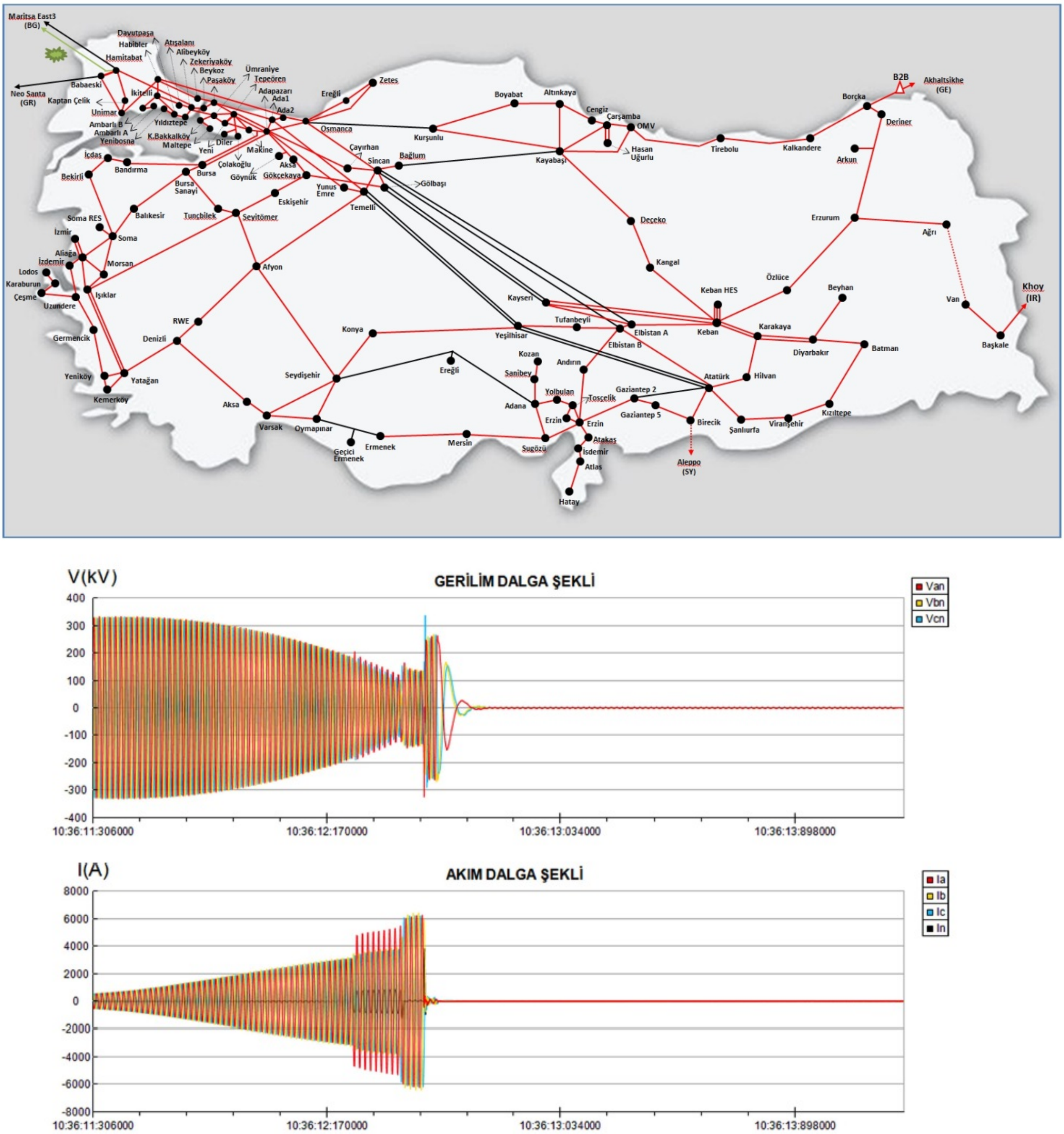
Appendix- 10: Opening of Babaeski (TR) – Nea Santa (GR) 400 kV TL



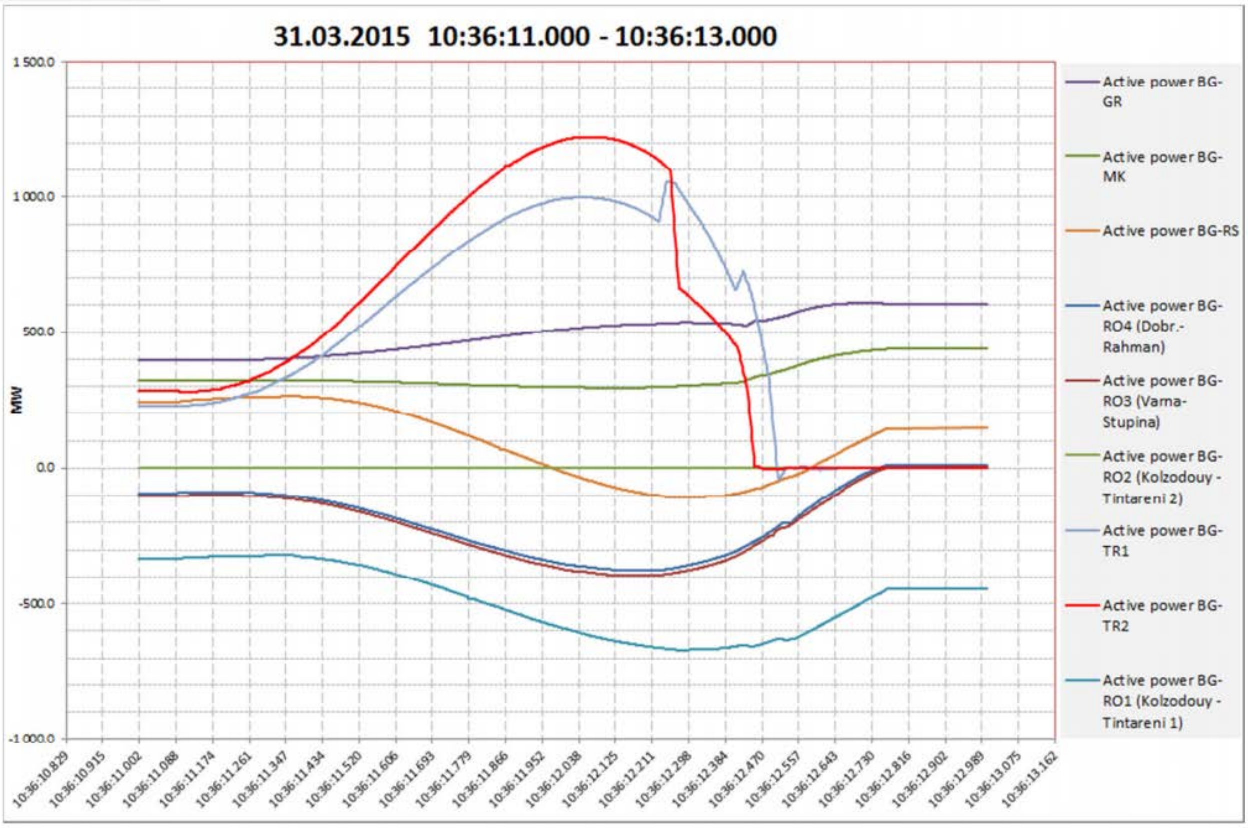




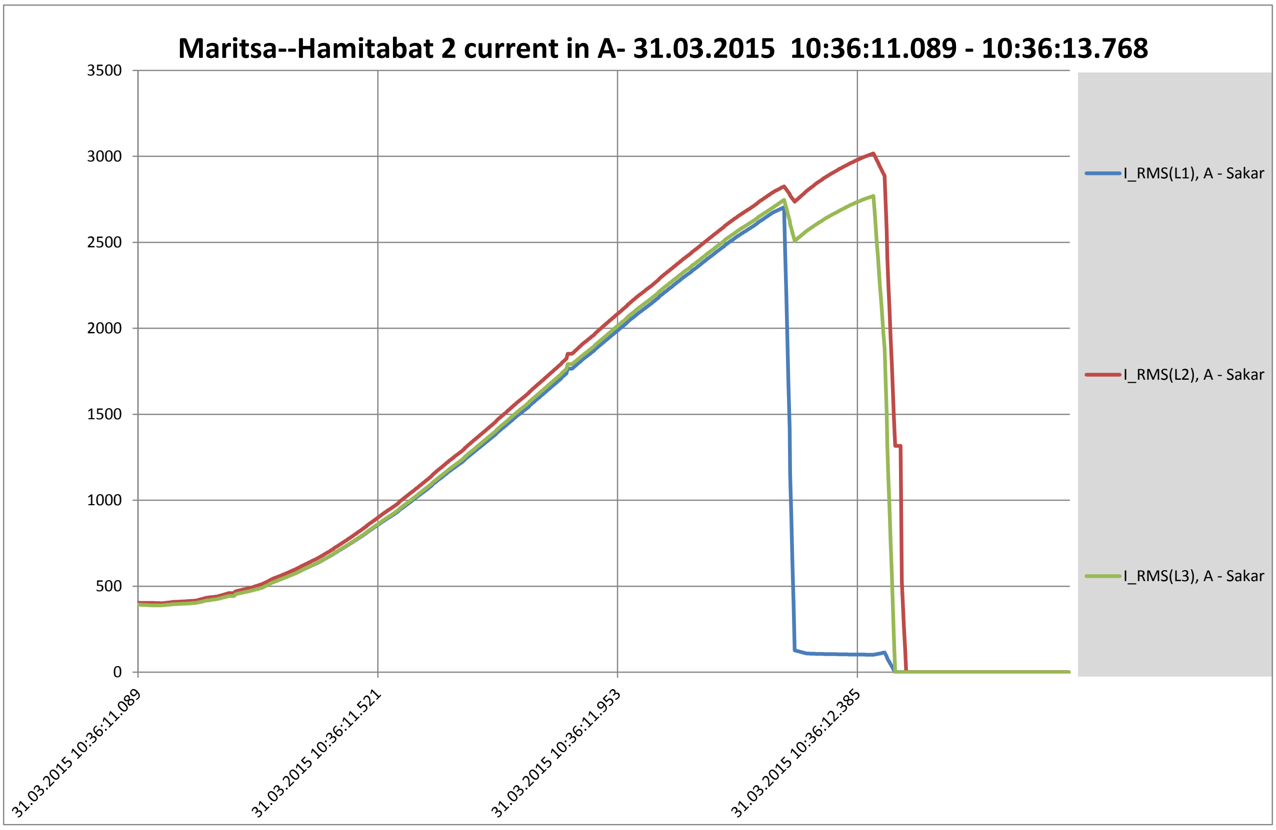
Appendix- 11: Opening of Hamitabat (TR) – Maritsa East 3 (BG) line 2 400 kV TL

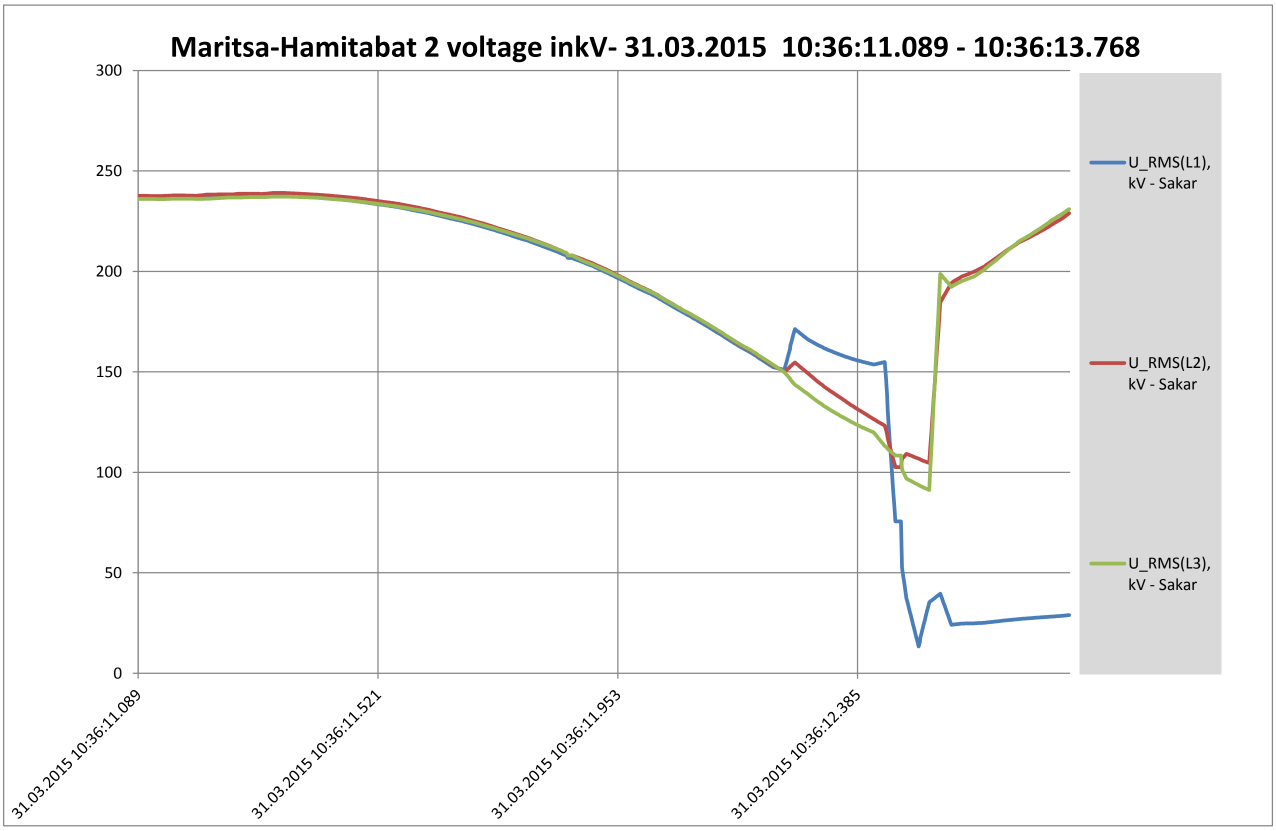


Appendix- 12: Opening of Hamitabat (TR) – Maritsa East 3 (BG) line 1 400 kV TL

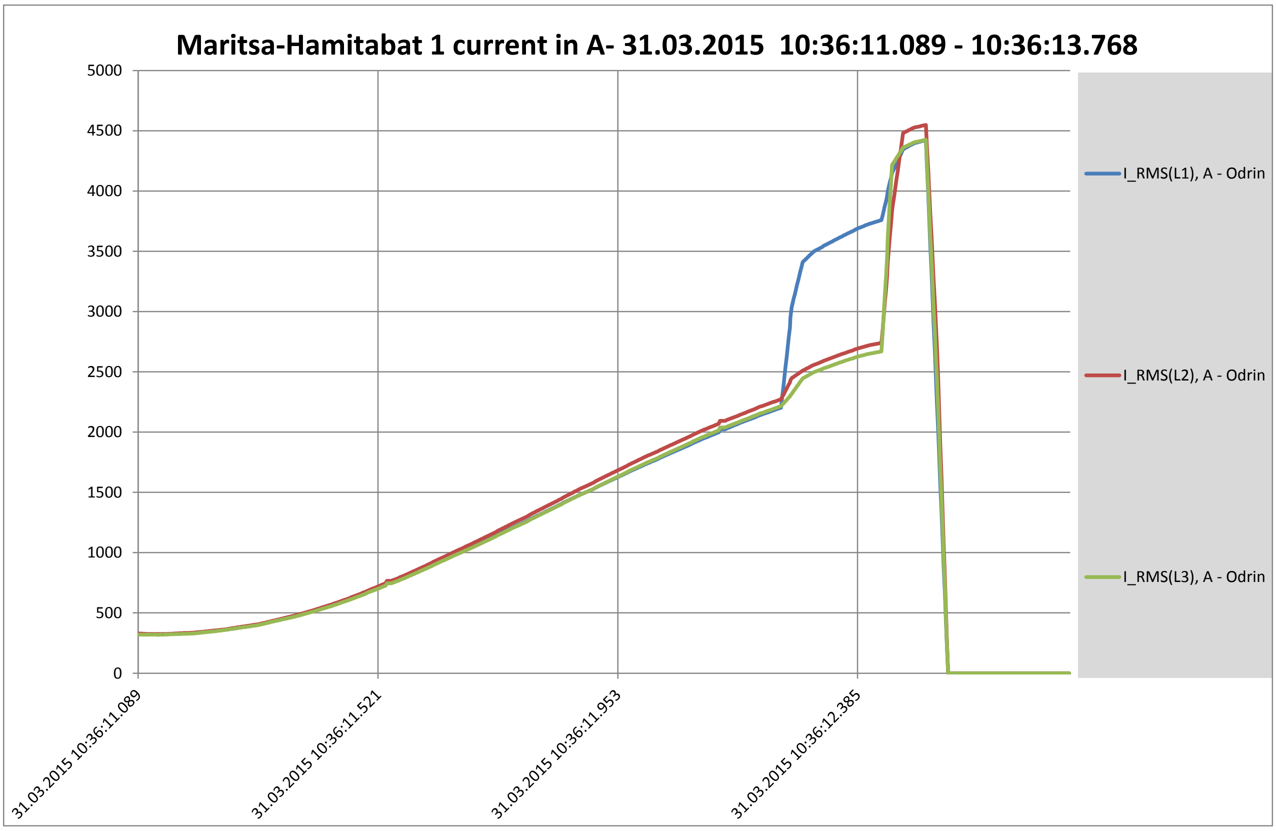


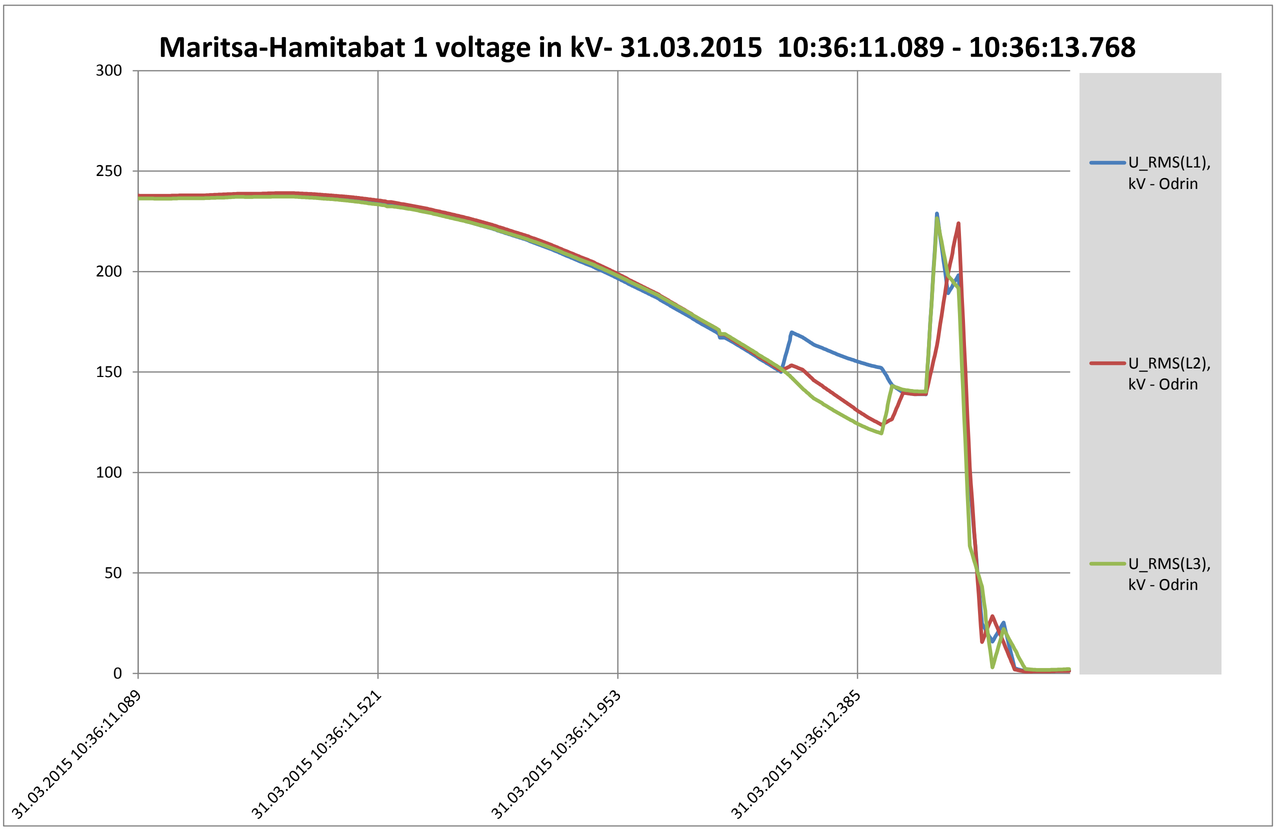
Appendix- 13: Power flow recordings on TR-BG interconnections, EET time stamp



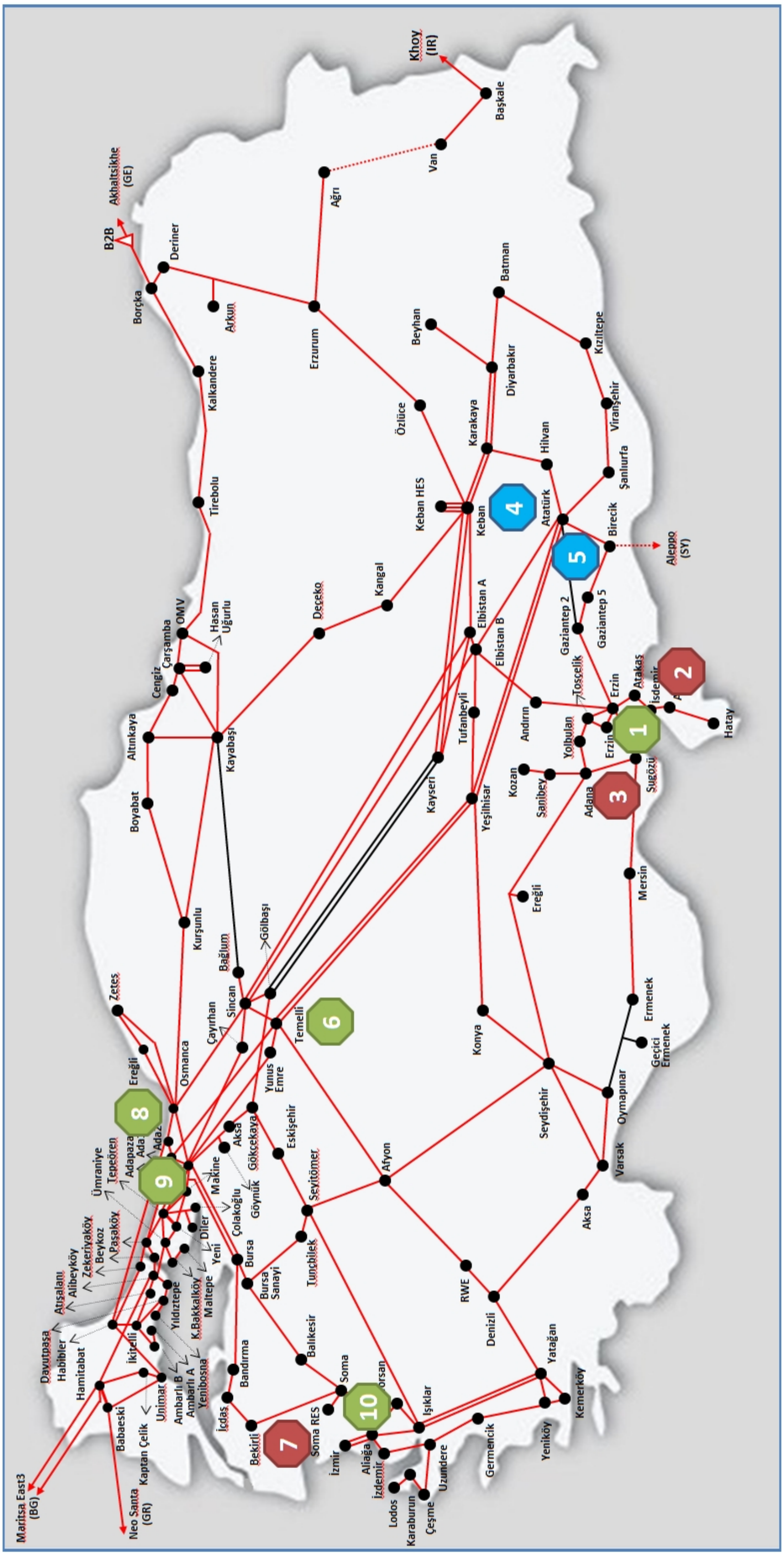


Appendix- 14: Currents and voltages of Maritsa-Hamitabat 2 line, EET time stamp

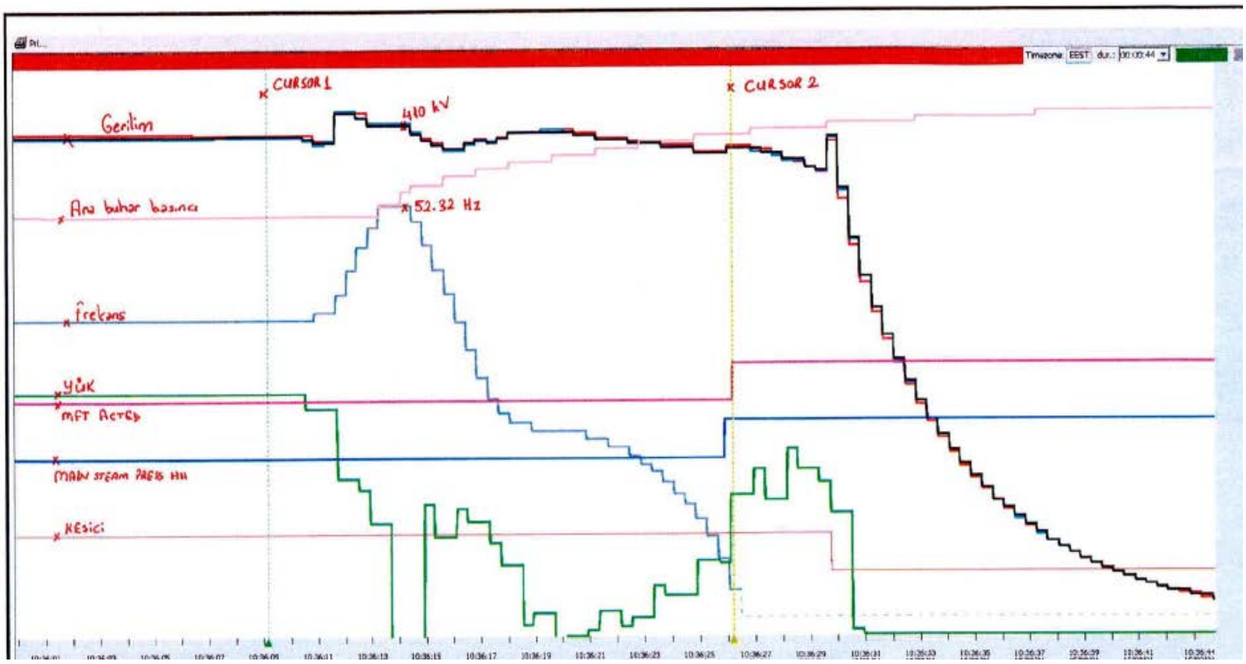




Appendix- 15: Currents and voltages of Maritsa-Hamitabat 1 line, EET time stamp



Appendix- 16: Location of the power plants



In the graph above:

Black colour (Gerilim) represents the network voltage where PP is connected

Pink colour (Ana buhar basıncı) represents the main steam pressure

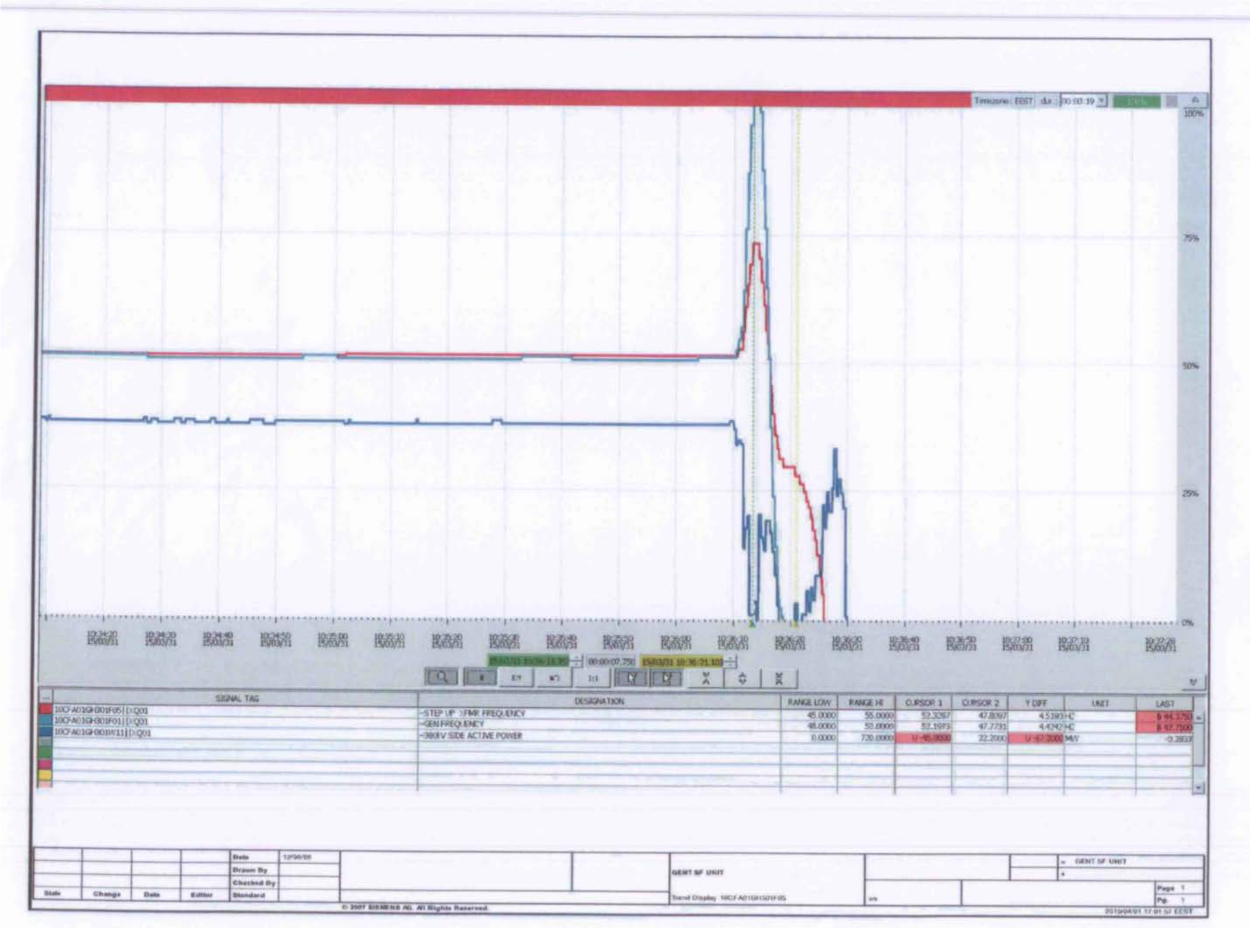
Light blue colour (Frekans) represents the network frequency

Green colour (Yuk) represents PP MW output

Pink colour (KESİCİ) represents the position of main switch

Each cell represents 1 seconds, (in total 44 seconds starting from 10:36:00 EET)

Appendix- 17: Power plant SCADA output of Erzin NGCCPP during the blackout



In the graph above:

Red colour represents the network frequency

Blue colour represents PP MW output

Green colour represents the generator frequency

Each cell represents 10 seconds, (in total 200 seconds)

Appendix- 18: Power plant SCADA output of Atlas TPP during the blackout

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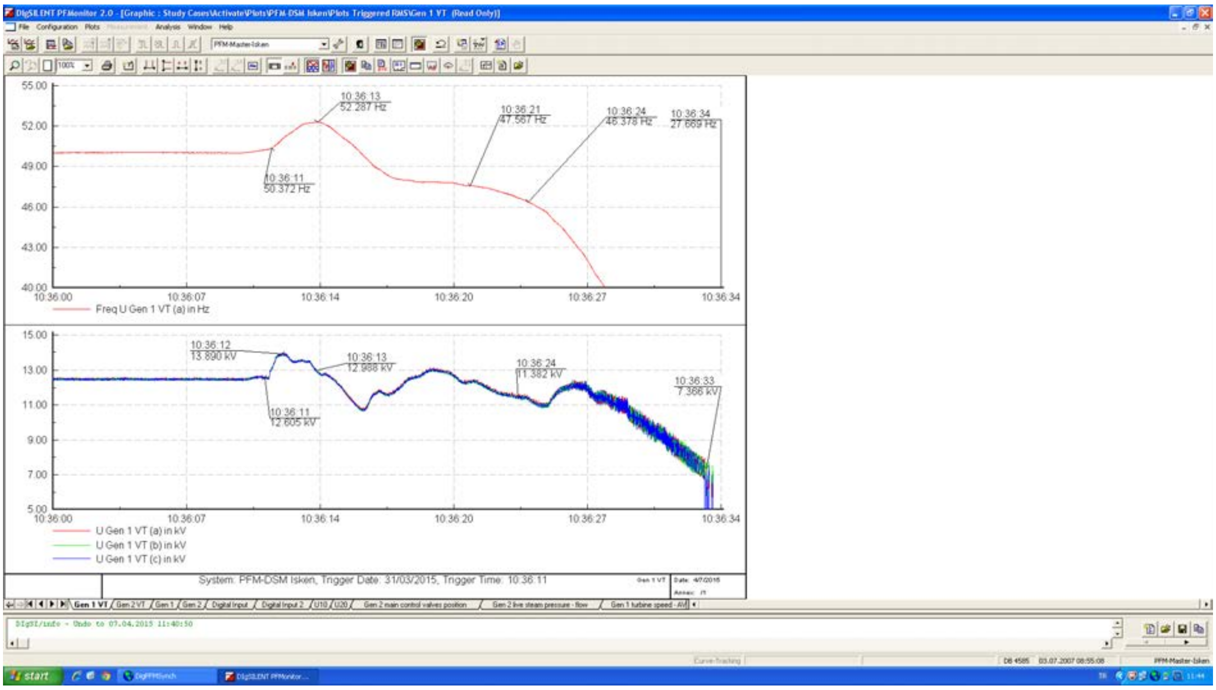
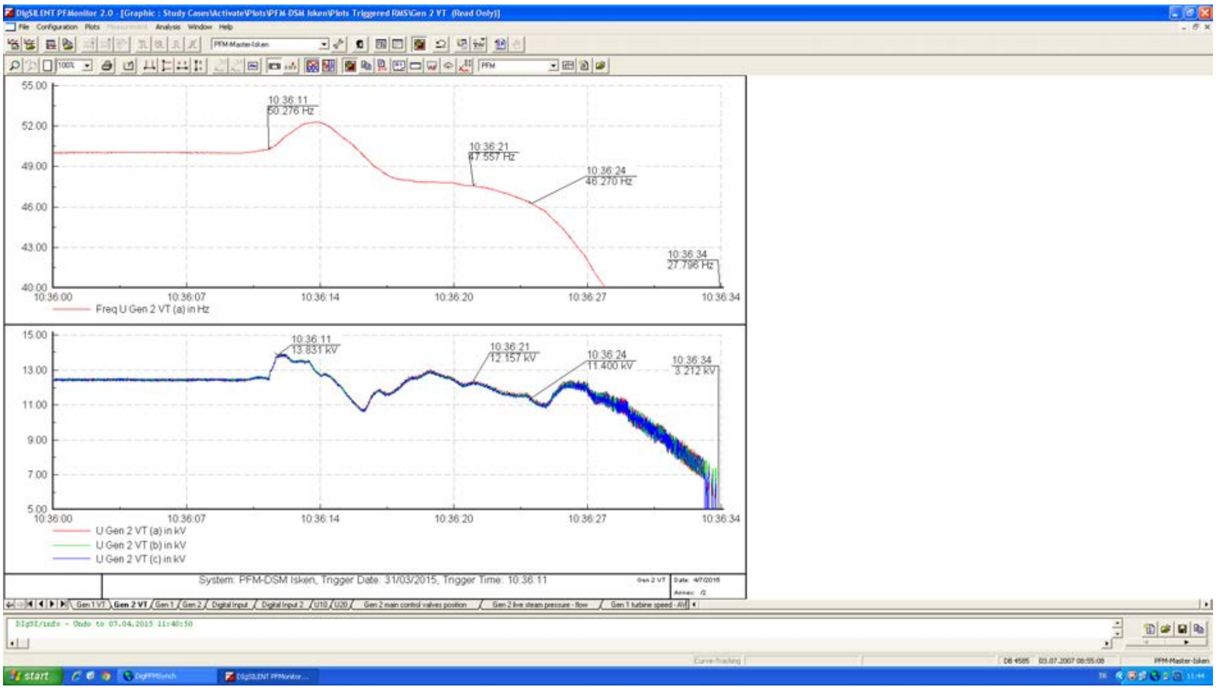




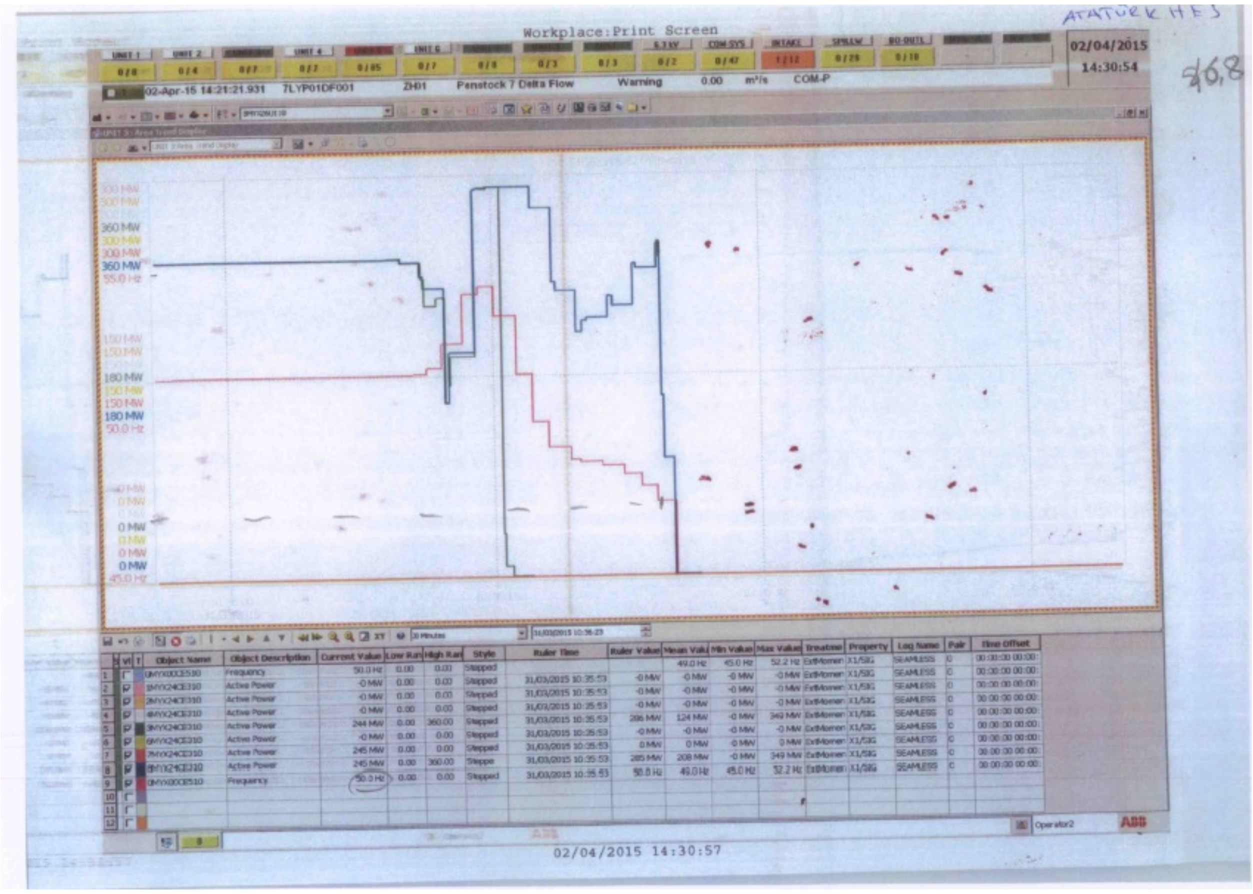
In the graphs above:

Red colour represents the network frequency

Blue colour represents unit terminal voltage (L-N) in kV

Each cell represents 7 seconds, (in total 34 seconds)

Appendix- 19: Power plant SCADA output of Unit 10 and Unit 20 of Sugozu TPP during the blackout



In the graph above:

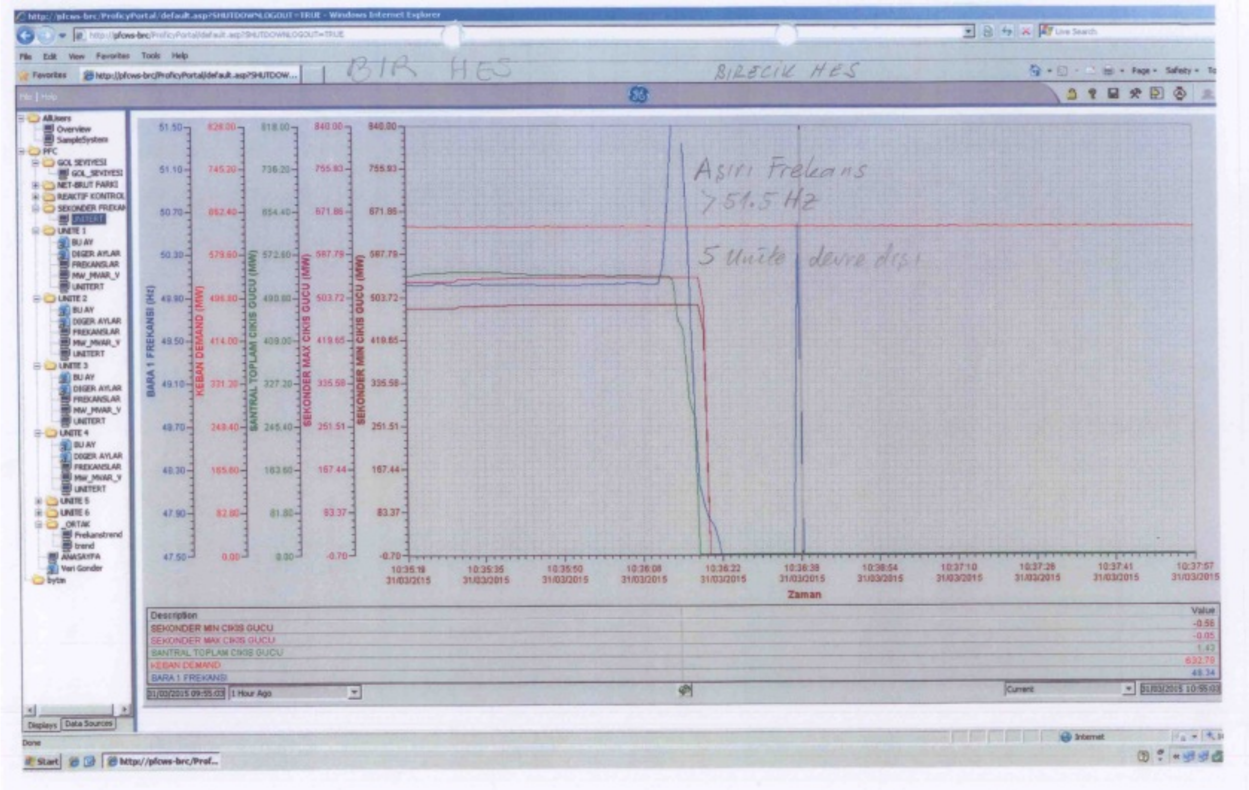
Red colour represents the network frequency

Dark blue colour represents PP MW output of one unit.

Dark green colour represents PP MW output of other unit.

Each cell represents 20 seconds, (in total 60 seconds)

Appendix- 20 :Power plant SCADA output of Ataturk HPP during the blackout



In the graph above:

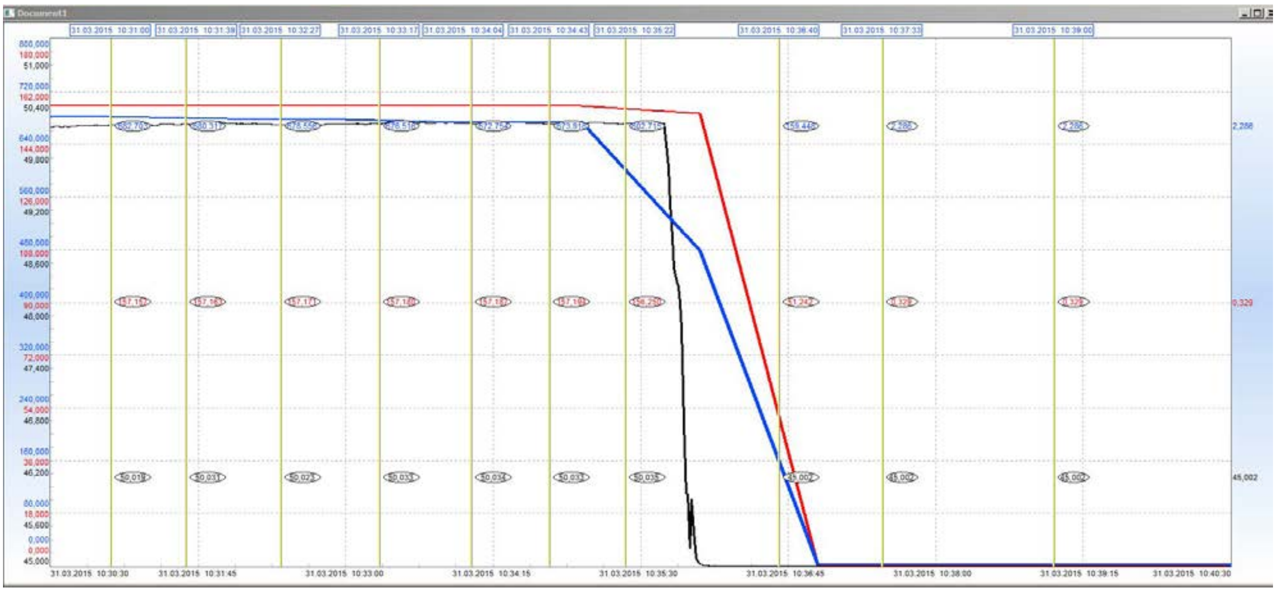
Blue colour (Frekans) represents the network frequency

Green colour represents PP MW output

Red and brown colour represents the maximum and minimum active power limits of the plant respectively.

Each cell represents 1 second, (in total 160 seconds)

Appendix- 21: Power plant SCADA output of Birecik HPP during the blackout



In the graph above:

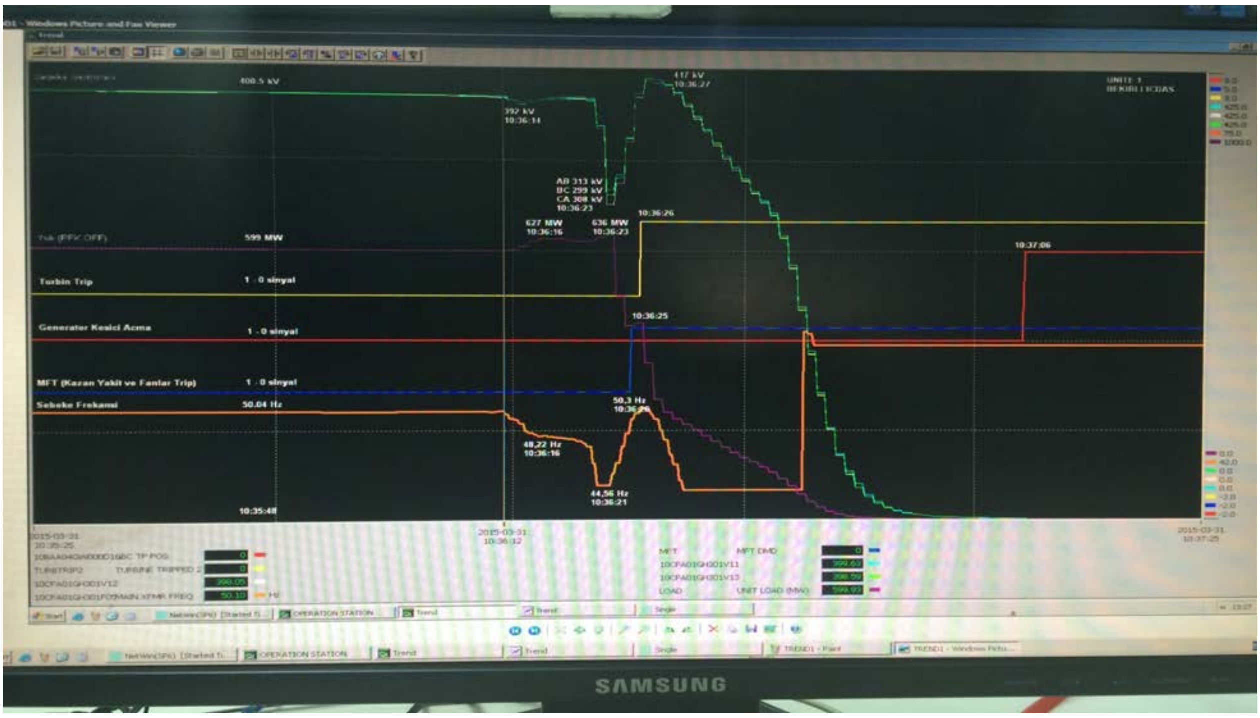
Black colour represents the network frequency

Red colour represents the bus voltage

Blue colour represents the block output power

Each cell (dashed vertical lines) represents 75 seconds, (in total 10 minutes)

Appendix- 22: Power plant SCADA output of Temelli NGCCPP during the blackout



In the graph above:

Green colour (Şebeke Gerilimi) represents the network voltage where PP is connected

Yellow colour (Turbin Trip) represents the turbine tripping digital signal

Orange colour (Sebeke Frekansi) represents the network frequency

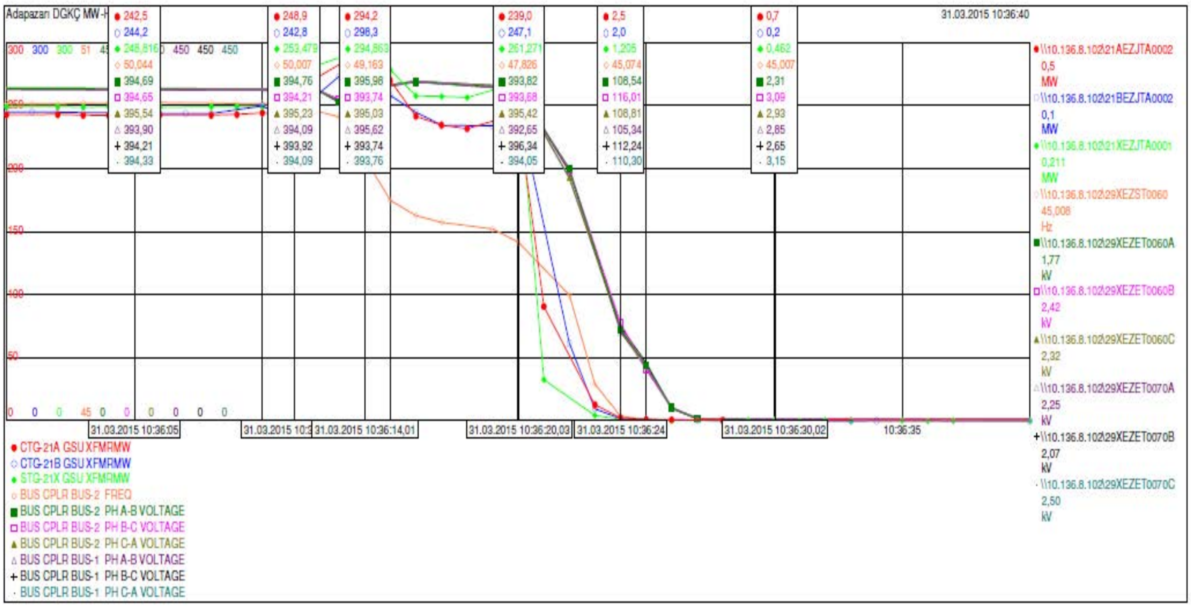
Purple colour (Yuk) represents PP MW output

Blue colour (Kazan Yakıt ve Fanlar Trip) represents Boiler fuel and fans tripping digital signal

Red colour (Generator Kesici Acma) represents the generator circuit breaker opening digital signal

Each cell represents 24 seconds, (in total 96 seconds)

Appendix- 23: Power plant SCADA output of Bekirli TPP during the blackout



In the graph above:

Orange colour represents the network frequency

Blue colour represents PP MW output of first gas turbine

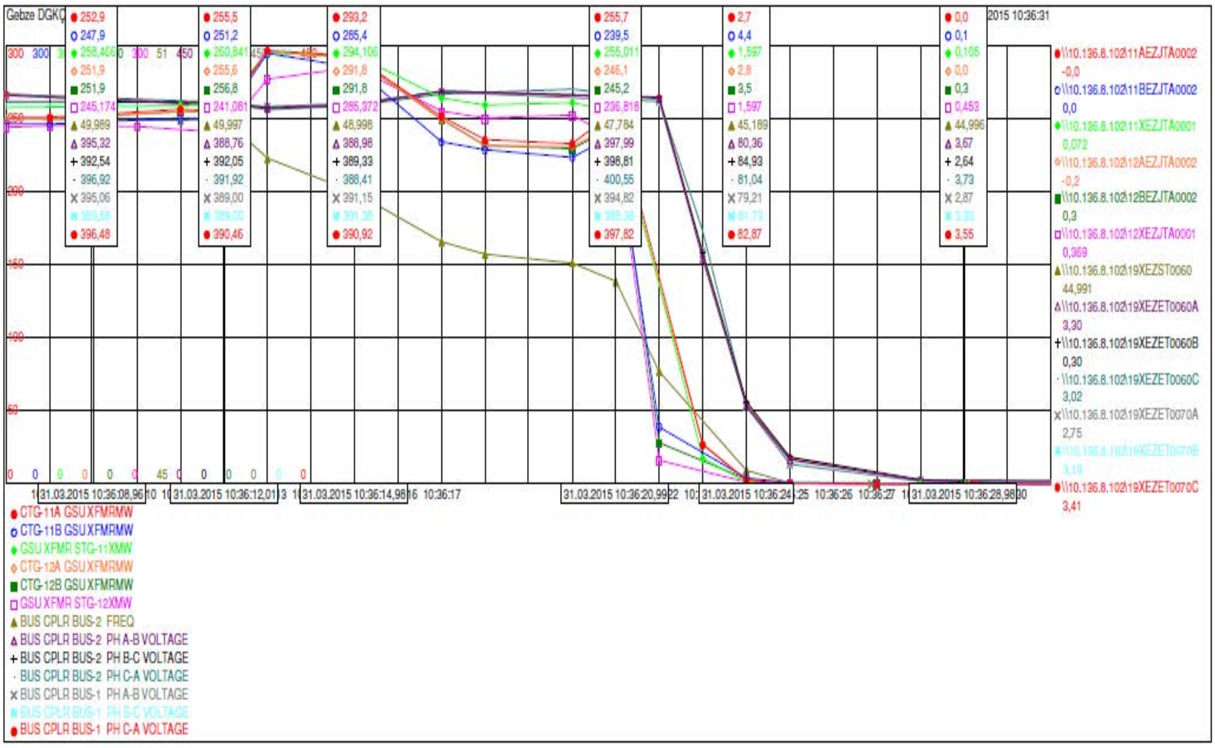
Red colour represents PP MW output of second gas turbine

Light green colour represents PP MW output of steam turbine

Other colours represent busbar voltages where PP is connected

Each cell represents 5 seconds, (in total 40 seconds)

Appendix- 24: Power plant SCADA output of Adapazari NGCCPP during the blackout



In the graph above:

Navy green colour represents the network frequency

Red colour represents PP MW output of first block first gas turbine

Blue colour represents PP MW output of first block second gas turbine

Light green colour represents PP MW output of first block steam turbine

Orange colour represents PP MW output of second block first gas turbine

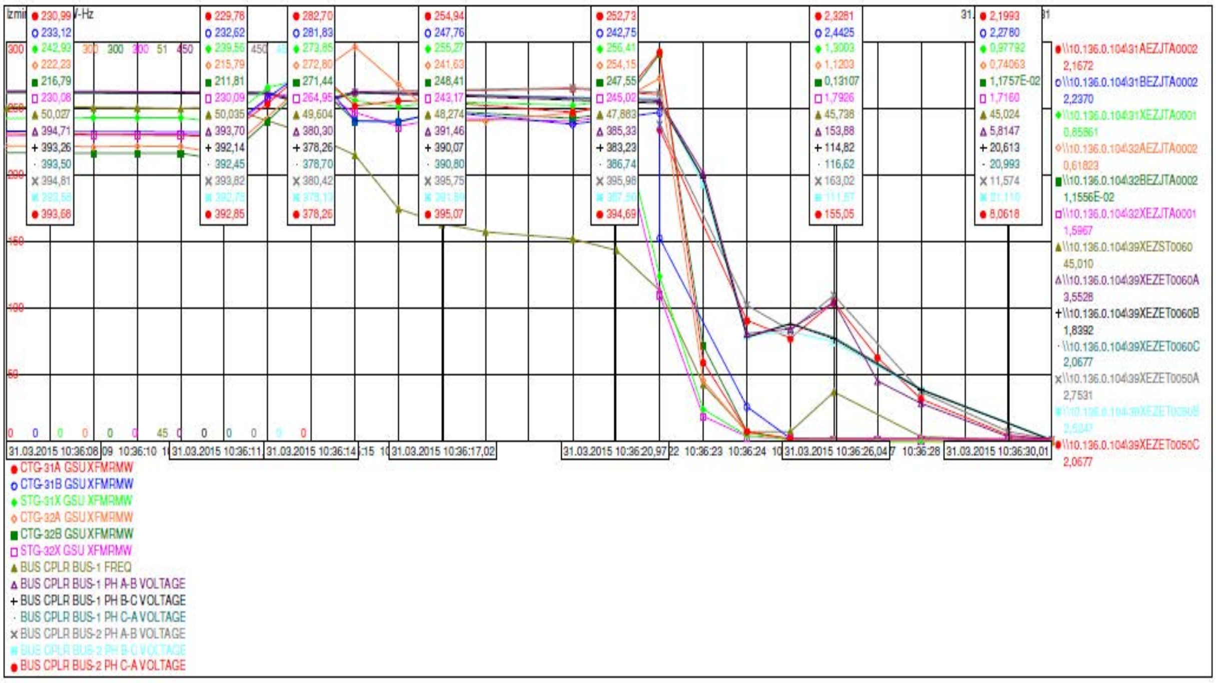
Dark green colour represents PP MW output of second block second gas turbine

Pink colour represents PP MW output of second block steam turbine

Other colours represent busbar voltages where PP is connected

Each cell represents 1 second, (in total 24 seconds)

Appendix- 25: Power plant SCADA output of Gebze NGCCPP during the blackout



In the graph above:

Navy green colour represents the network frequency

Red colour represents PP MW output of first block first gas turbine

Blue colour represents PP MW output of first block second gas turbine

Light green colour represents PP MW output of first block steam turbine

Orange colour represents PP MW output of second block first gas turbine

Dark green colour represents PP MW output of second block second gas turbine

Pink colour represents PP MW output of second block steam turbine

Other colours represent busbar voltages where PP is connected

Each cell represents 1 second, (in total 24 seconds)

Appendix- 26: Power plant SCADA output of Izmir NGCCPP during the blackout

Setting of the Hamitabat SPS is given below:

1. Load Shedding and Generation Dropping:

With 3 Interconnection lines in operation:

i) *High load system operation, with 3 tie-lines in service:*

Load Shedding (LS)

- 1200-1500 MW LS: $|d\sum P/dt|_{1.5"}$ = -900 MW/s; $\sum P$ = -1300 MW
- 800-1000 MW LS: $|d\sum P/dt|_{1.5"}$ = -700 MW/s; $\sum P$ = -1000 MW
- 400-500 MW LS: $|d\sum P/dt|_{1.5"}$ = -500 MW/s; $\sum P$ = -800 MW

Generation Dropping (GD)

- 1200-1400 MW GD: $|d\sum P/dt|_{1.5"}$= +750 MW/s; $\sum P$ = +1200 MW
- 800-1000 MW GD : $|d\sum P/dt|_{1.5"}$= +600 MW/s; $\sum P$ = +800 MW
- 400-600 MW GD : $|d\sum P/dt|_{1.5"}$= +450 MW/s; $\sum P$ = +500 MW

ii) *Low load system operation, with 3 tie-lines in service:*

Load Shedding (LS)

- 600-900 MW LS: $|d\sum P/dt|_{1.5"}$= -750 MW/s; $\sum P$ = -1300 MW
- 400-600 MW LS: $|d\sum P/dt|_{1.5"}$= -600 MW/s; $\sum P$ = -1000 MW
- 200-300 MW LS: $|d\sum P/dt|_{1.5"}$= -450 MW/s; $\sum P$ = -800 MW

Generation Dropping (GD)

- 1200-1400 MW GD: $|d\sum P/dt|_{1.5"}$=+700 MW/s; $\sum P$ = +1200 MW
- 800-1000 MW GD : $|d\sum P/dt|_{1.5"}$=+600 MW/s; $\sum P$ = +900 MW
- 400-600 MW GD : $|d\sum P/dt|_{1.5"}$=+500 MW/s; $\sum P$ = +600 MW

With 2 Interconnection lines in operation:

i) *High load system operation, with 2 tie-lines in service:*

Load Shedding (LS)

- 1200-1500 MW LS: $|d\sum P/dt|_{1.5"}$ = -800 MW/s; $\sum P$ = -1200 MW
- 800-1000 MW LS: $|d\sum P/dt|_{1.5"}$ = -600 MW/s; $\sum P$ = -900 MW
- 400-500 MW LS: $|d\sum P/dt|_{1.5"}$ = -400 MW/s; $\sum P$ = -800 MW

Generation Dropping (GD)

- 1200-1400 MW GD: $|d\sum P/dt|_{1.5"}$= +700 MW/s; $\sum P$ = +1100 MW
- 800-1000 MW GD : $|d\sum P/dt|_{1.5"}$= +550 MW/s; $\sum P$ = +800 MW
- 400-600 MW GD : $|d\sum P/dt|_{1.5"}$= +400 MW/s; $\sum P$ = +500 MW

ii) *Low load system operation, with 2 tie-lines in service:*

Load Shedding (LS)

- 600-900 MW LS: $|d\sum P/dt|_{1.5"}$= -700 MW/s; $\sum P$ = -1200 MW
- 400-600 MW LS: $|d\sum P/dt|_{1.5"}$= -550 MW/s; $\sum P$ = -900 MW
- 200-300 MW LS: $|d\sum P/dt|_{1.5"}$= -400 MW/s; $\sum P$ = -800 MW

Appendix- 27: Settings of the Hamitabat SPS

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Generation Dropping (GD)

- 1200-1400 MW GD: $|d\sum P/dt|_{1.5"}$=+700 MW/s; $\sum P$ = +1100 MW
- 800-1000 MW GD : $|d\sum P/dt|_{1.5"}$=+550 MW/s; $\sum P$ = +800 MW
- 400-600 MW GD : $|d\sum P/dt|_{1.5"}$=+450 MW/s; $\sum P$ = +550 MW

Notes

- ΣP : algebraic sum of the active power of the 3 interconnection lines, positive for export from Turkey, negative for import into Turkey, up-dated every 100 ms
- $|d\sum P/dt|_{1.5"}$: average value of the 1st derivative of ΣP in a time span of 1.5", up-dated every 100 ms; positive for increase of export from Turkey or reduction of import into Turkey
- High system load: ≥ 27000 MW

2. Inter-area oscillation detector

The inter-area oscillation detector is set as follows when 2 or 3 interconnection 400 kV TLs are in service:

- Pick-up frequency range: 0.12-0.15 Hz
- Alarm: amplitude of oscillations: 30 mHz; delay 10 secs
- Tripping of all the interconnections TLs: amplitude of 60 mHz; delay 50 secs

If only the Babaeski (TR) – Nea Santa (GR) 400 kV interconnection TL is in service:

- Pick-up frequency range is automatically reduced to 0.08-0.12 Hz.
- Setting for the alarm and tripping is same as above.

3. Overload (back-up) protection of the Hamitabat (TR) – Maritza (BG) 400 kV interconnection lines

- In case that the sum of the power import into Turkey via the two parallel Maritza – Hamitabat 400 kV lines is detected to be ≥ 1380 MW during 3.5 sec, the 3rd block of load shedding (LS) is activated by the SPS, via transfer tripping to substations on OPGWs.
- One N60 GE relay measures the active power of the two lines from the line VTs and CTs, makes the summation and initiates the LS within ~ 50 ms if the power and time thresholds are exceeded. In case of failure of the N60, the same function is performed with automatic change-over by the pre-existing apparatuses of the SPS; however, in this case initiation of LS will take ~ 300 ms.
- If, in spite of the 3rd block of LS of 1st bullet, the power import from Bulgaria via the two parallel lines remains still ≥ 1380 MW, 6 sec after the start of overload the 2nd block of LS is initiated by the SPS, with the logics as specified in previous bullet.
- During operation with only one 400 kV line in service between Maritza and Hamitabat, the power import threshold of the overload (back-up) protection is automatically reduced to 1100 MW.

4. LS in case of loss of generation from the ZETES thermal power plant (TPP)

In case of receipt in Hamitabat of a signal from the ZETES TPP the 1st block of LS is immediately performed by the SPS. The signal will be sent to Hamitabat via a Telecom fibre optic link in case of outage of the ZETES TPP – Osmanca 400 kV line when it is heavily loaded, and in case of large loss of

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generation in the ZETES TPP (installed capacity is 2x660 MW + 1x160 MW). This function is currently disabled because the 2nd 400 kV power evacuation line from Zetes TPP is in operation.

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The evaluation by NCC operators of the (N-1) dynamic security of critical transmission/generation operation conditions requires the acquisition by the NCC of a reliable system dynamic model and of analysis expertise.

For the near future, an estimate of the too risky contingency operational conditions (probable non-compliance with the (N-1) dynamic security) can be done by some indicators resulting from the load flow contingency analysis. Such indicators are commented below for the operational status prior to the blackout on 31st March 2015.

Let us call:

ϑ_X : the electrical angle of the voltage vector of the 400 kV X busbar referred to the swing busbar (Ataturk generator busbar); positive = advance; negative = retard

$\Delta\vartheta_{X-Y} = \vartheta_X - \vartheta_Y$: the electrical angle between the voltage vectors of busbars X and Y

P_{X-Y}: the active power flow from the busbars X and Y (positive for power flow from X to Y).

The longest power transfer distance through several series connected TLs is from the Deriner HPP (close to the border with Georgia) (in short "Der") to the Ikitelli substation (Istanbul European side) (in short "Iki"). "Kur" and "Osm" stand below for the Kursunlu and Osmanca substations.

Some significant results of the analyses for the system status of 31.03.2015 are as follows:

i. **Case 1** – Load flow prior to blackout as per the last available system snapshot (with all the SCs by-passed):

$\vartheta_{Der} = 27{,}4°$; $\vartheta_{Kur} = -0{,}7°$; $\vartheta_{Osm} = -25{,}2°$; $\vartheta_{Iki} = -43{,}7°$

$\Delta\vartheta_{Kur-Osm} = 24{,}5°$; $\Delta\vartheta_{Der\text{-}Iki} = 71{,}1°$

ii. **Case 2** – Load flow after tripping of Kursunlu – Osmanca TL (with all the SCs by-passed)

$\vartheta_{Der} = +32{,}9°$; $\vartheta_{Kur} = +24{,}9°$; $\vartheta_{Osm} = -55{,}5°$; $\vartheta_{Iki} = -71{,}4°$

$\Delta\vartheta_{Kur-Osm} = 80{,}4°$; $\Delta\vartheta_{Der\text{-}Iki} = 104{,}3°$

Comparison with Case 1 shows that $\Delta\vartheta_{Kur-Osm}$ is increased, after tripping of the Kursunlu – Osmanca TLs, from 24,5° to 80,4°. The total transmission angle from the Deriner HPP to Istanbul is increased from 71,1° to 104,5°. The angle of 80° between the Kursunlu and Osmanca 400 kV busbars blocks the possibility of reclosing the line, for the integrity preservation of the turbine-generators.

In the Central part of the East to West transmission system, where the power flow is ~ 4,700 MW, there are also very large electrical angles across the long transmission lines, particularly in Northern Anatolia, with a small stabilization by the power plants in intermediate points where only few units (or none) were in service. This is an indicator that the transient created by the tripping of the most heavily loaded TL, Kursunlu – Osmanca, very probably causes angular instability and loss of synchronism.

iii. **Case 3** – Load flow after tripping of Kursunlu – Osmanca TL with all the SCs in service.

In this case, $\Delta\vartheta_{Kur-Osm} = 58{,}3°$ and $\Delta\vartheta_{Der\text{-}Iki} = 83°$. Both these $\Delta\vartheta$ are reduced by ~ 20° in comparison with the load flow of Case 2, which resulted in a vast loss of synchronism. With the SCs in service the system dynamic response would have been much better.

In this case, if all the SCs are assumed in service except the SC in the Kayabasi – Kursunlu TL, the current in the Kursunlu – Osmanca TL is reduced to ~ 1600 A, and tripping protection does not occur.

Appendix- 28: Contingency analyses recommendation

iv. **Case 4 –** The Kayabasi – Baglum TL, which was one of the 4 TLs out of service, is assumed to be in service. All the SCs are assumed to be bypassed, as on March 31st 2015.
In this case, $P_{Kur-Osm}$ = 877 MW and the risk of disconnection of the Kursunlu – Osmanca TL by the protection is eliminated. On the other hand, if the Kursunlu – Osmanca TL is tripped, the load flow yields: $\Delta\vartheta_{Der\text{-}Iki}$ = 74.7° with a moderate electrical angle in the East to West central transmission section. This is an indicator of stable operation.

v. Load flows calculations by separately considering in service also 1 of the 4 TLs which were out of service prior to the blackout, (i.e. considering out-of-service any 3 of these 4 TLs) all yield currents in the Kursunlu – Osmanca TL which are lower, with a good margin, than the 1820 A which caused the line trip, and also yield lower transmission angles across the grid.

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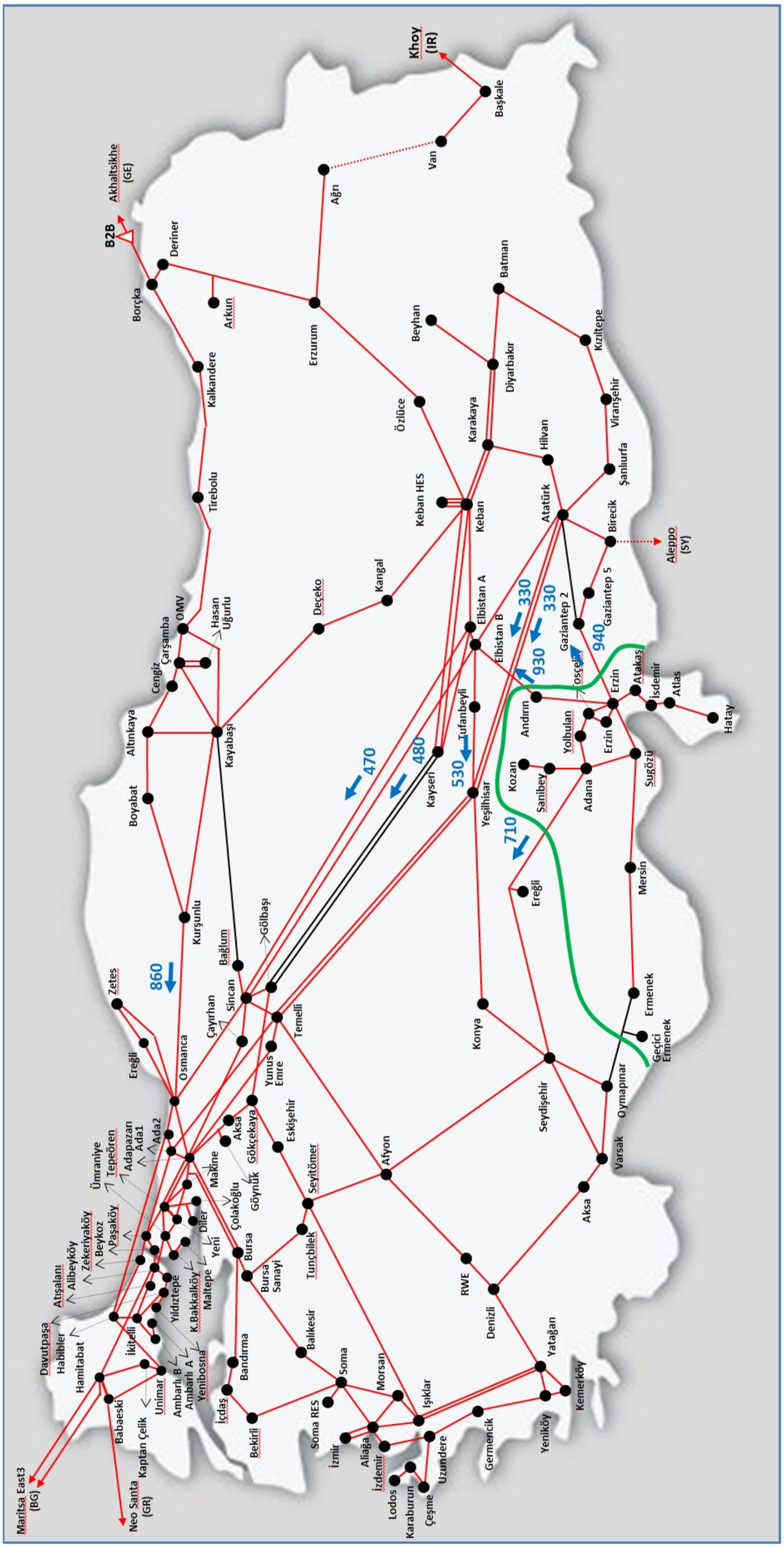
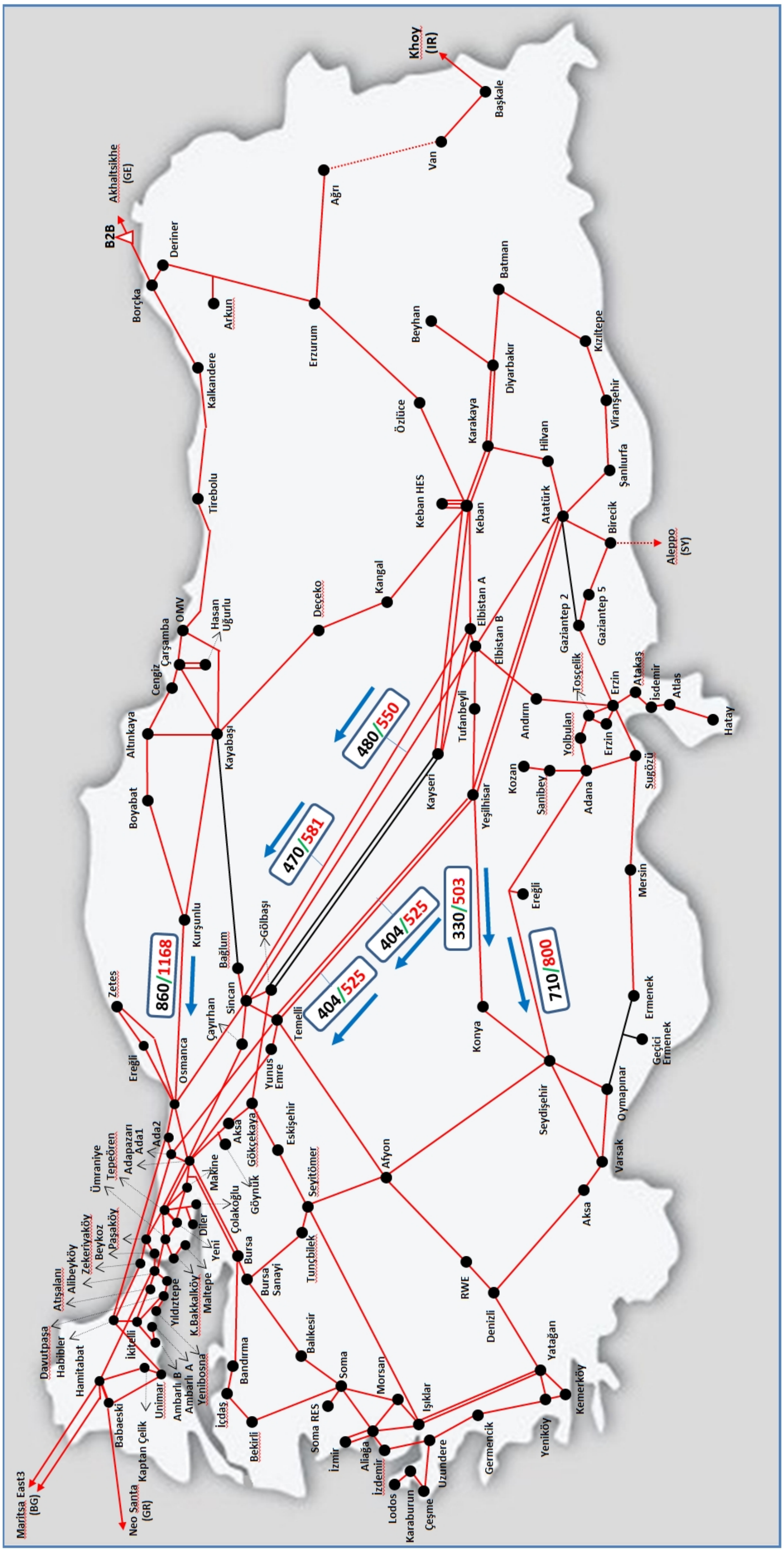


Appendix- 29: Power flows before the incident on 30th March



Appendix- 30: Comparison of power flows on 30th (black) and 31st March (red) 2015

11. References

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