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Implementation of a Special Protection System (SPS) in the Interconnection between the Turkish and ENTSO-E Power Systems to Counteract Propagation of Major Disturbances

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1 INTRODUCTION

At the request of the ENTSO-E (European Network of Transmission System Operators - the Association of the TSOs of N°34 European countries) extensive system studies, field tests and adjustments of the control systems of various Turkish power plants had been performed as a preparatory work for the synchronous connection of the Turkish power system to the Continental Europe system, that is in trial operation since September, 2010.

ENTSO-E has requested that the Defense Plan against propagation of major disturbances across borders shall include an Emergency Control System, with a Special Protection System (SPS) as 1st line of defense, to be installed in Turkey in the interface with the 400kV transmission grids of the neighbouring countries, Bulgaria and Greece. The main scope of the SPS is to minimize the consequences of major disturbances liable to occur in Turkey, in particular:

- Avoid as far as possible the loss of synchronism of the Turkish system towards the rest of ENTSO-E Continental system, or loss of synchronism of generating units in Turkey and in the Balkan countries, thereby minimizing in extreme contingencies the loss of load and generation, and risk of regional or national blackouts.
- Limit the consequences of disturbances to other ENTSO-E member countries within tolerable levels. In particular limit transmission temporary overloads and excessive voltage deviations in the Balkan countries and in Turkey
- Avoid voltage collapse
- Avoid putting equipment at risk of damage
- Monitor the inter-area electromechanical oscillations

In very recent years, a considerable literature has become available on the SPS [3], [4], [5], [6], [7]. However each SPS has to be tailored to the specific requirements of the power system to which it is applied, in particular in the case dealt with in this report.

2 INFORMATION ON TURKISH SYSTEM INTEGRATED IN ENTSO-E SYSTEM

The total installed generation capacity at the end of 2010 is ~49,500MW, out of which ~1/3 is hydroelectric, ~1/3 is thermoelectric lignite-coal fired, ~1/3 is thermoelectric natural gas fired (mostly high efficiency combined cycle); ~2% is geothermal and wind. In N°8 hydroelectric power plants (HPPs) part of the units, with a total rated power of 2700MVA, can operate as synchronous condensers spinning in the air.

In the year 2010, the national peak demand has been ~34,000MW and energy generation 209.3 TWh. Fig. 1 is a single-line diagram of the 400kV Turkish and of the Bulgarian and Greek 400kV interconnection in service in 2010. The interconnection of Turkey with ENTSO-E grid is made by

three 400kV transmission lines: two single-circuit 153km long lines between the Hamitabat (Turkey) and Maritza 3 (Bulgaria) 400kV substations; one single-circuit 130km long line between the Babaeski (Turkey) and Nea Santa (Greece) substations.

With the addition of Turkey located in the South-Eastern part, the European system will have a longitudinal configuration (point-to-point distances are 2700km from Eastern Turkey to the border Italy/Slovenia and 4500km from Eastern/Turkey to Portugal). The load of Turkey almost equals the total load of the Balkan countries. About 80-85% of total ENTSO-E Continental synchronous system load is located in Central-Western Europe, outside the Balkan countries and Turkey. Consequently, a sudden load/generation imbalance occurring in Turkey due to the outage of a large power plant or loss of a regional load, is made up by 80-85% from the kinetic energy of rotating masses and by the primary frequency control of Western-Central Europe systems, causing a large power flow to or from Turkey via the transmission networks of the Balkan Countries.

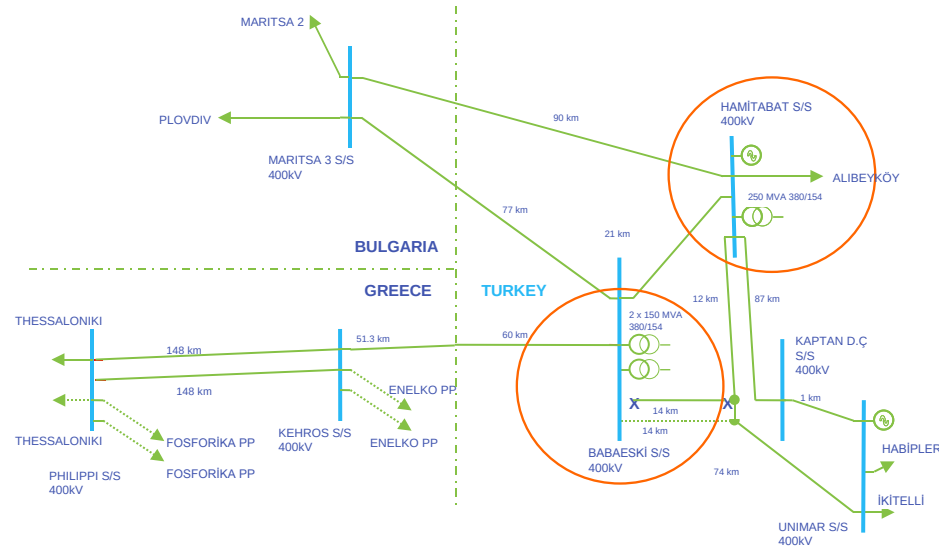


Fig. 1: Interconnection lines with the 400kV grids of Bulgaria and Greece

3 STRATEGY OF THE DEFENSE PLAN TO COUNTERACT SYSTEM DISTURBANCES

In the isolated operation, the Turkish system is provided with a defense plan using under frequency load shedding (LS) relays and over frequency generation dropping (GD) relays, that has proved to be efficacious for riding through also the major disturbances. The SPS is aimed at extending the defense plan for minimizing the consequences of possible major contingencies in the synchronous operation with the large ENTSO-E system, where frequency variations are very small [1].

Fast build-up disturbances liable to occur in Turkey can be divided in three classes of increasing severity, as follows:

- A.** Disturbances that will not cause operation problems in the systems of neighbouring countries, that will not cause loss of synchronism of the Turkish system with the ENTSO-E system and that can be overcome by the conventional protection and control systems in existence, thus not requiring the intervention of the SPS. The performed dynamic analyses [1] [2] have shown that line short circuits and sudden loss of generation or load of up to 1200MW fall in this class.
- B.** Disturbances that will need the intervention of the SPS in order to avoid the events i), ii), iii) and iv) listed in par. 5. On the basis of the performed dynamic analyses [1] [2], the class of major contingencies to be countered by the SPS includes the following:
 - Sudden loss of up to 2600MW of generation in Turkey (full output of one of the largest power plants or generation complex) due to very severe evolving electrical faults or due to exceptional atmospheric conditions. These events are more severe if Turkey is importing power (assumed up to 1200MW) prior to disturbances.
 - Sudden loss of up to 2500-3000MW of load in Turkey due to evolving faults causing separation of a regional subsystem importing power from the National system. These events are more severe if Turkey is exporting power (assumed up to 1200MW) prior to disturbance.

- Build-up of large persistent or amplified power/frequency inter-area oscillations between the Turkish system and the rest of ENTSO-E system.
- C. The 3rd class of incidents is very rare extreme contingencies due to complex combinations of adverse factors, causing a sudden load/generation imbalance in Turkey exceeding 3000MW, with prior to disturbance possible export/import from/to Turkey aggravating the event. Although the SPS will correctly intervene, it may not be sufficient in these extreme contingencies for preserving the synchronous operation of Turkey with the ENTSO-E system. In case of occurrence of this 3rd Class of events, it is accepted that the out-of-step tripping (OST) relays will intervene to fastly open the three 400kV interconnection lines.

The Emergency Control System against propagation of disturbances across borders consists of the SPS that has been installed in Hamitabat (Turkey), conceived as the basic 1st line of defense, backed by an overload protection monitoring the power flow and Electrical angle between the voltage vectors at the two line ends, approximately computed from the electrical quantities measured at one line end only (2nd line of defense), in turn backed by the out-of-step protection of the tie lines (last line of defense) that will separate the Turkish from ENTSO-E system in case of loss of synchronism. These two back-up protections have been installed in Maritza (Bulgaria) and Nea Santa (Greece).

4 SYSTEM MODELLING AND ANALYSIS OF MAJOR DISTURBANCES

The dynamic modeling of the ENTSO-E Continental system including the Turkish system, and the performed simulation of major disturbances required for the specification of the SPS, have been reported in [1] and [2].

5 FUNCTIONAL TECHNICAL SPECIFICATION OF THE SPS AND OF ACTIVATION OF LS AND GD BY THE SPS

The performed analyses have provided the following results and address for the specification of SPS (see ref. [1] and [2]):

- i. The disturbances liable to occur in Turkey and to cause loss of synchronism, or in-acceptable transmission overloads/voltage deviations in the Balkan countries are the large sudden load/generation imbalances.
- ii. Owing to the location of Turkey in the tail of a long longitudinal system, the load/generation imbalances to be counteracted by the SPS invariably initiate fast changes and oscillations of power flow across the three 400kV tie lines with Bulgaria and Greece. Analyses show that the very long inter-area oscillation period (6 to 7.5 s) allows a time of about 2.5 s for detection of the disturbances in the Hamitabat interfacing substation in Turkey (see Fig.1) and for implementation of LS or GD by remote control, when necessary.
- iii. Since the credible major contingencies that can occur are a large number, it is strait-forward and effective in the specific case to detect and counteract at the Hamitabat interfacing substation the consequences of the contingencies occurring in Turkey liable to propagate in the neighbouring countries (response based SPS), rather than trying to individually detect and counter the variety of actual contingencies throughout Turkey (event based SPS).
- iv. The following electric variables have been found the best indicators of type and size of the severe disturbances to be counteracted by the SPS. The variables are to be computed at short time intervals, by the master PLC of the SPS to be located in Hamitabat 400kV substation, by elaborating the currents and voltages from the secondary windings of the current transformers (CTs) and potential transformers (PTs):
 - Sum of actual active power flows in the tie lines in operation between Turkey and Bulgaria/Greece, up-dated at intervals $\leq 100\text{ms}$: $\sum P$ (MW). The active power of the tie line with Greece will be measured by a slave PLC located in the Babaeski 400kV substation and will be transmitted to Hamitabat via OPGW.
 - Change of sum of active power flows on said tie-lines, as intervened in the last 1.5sec, up-dated at intervals as short as feasible: $|\sum \Delta P| 1.5''$ (MW)
 - Average value of the derivative of sum of power flows on the three tie-lines (1st bullet) calculated during the last 1.5'', up-dated at time intervals as short as feasible: $|d\sum P/dt| 1.5''$

- Voltage imbalance factor, $k_i = V_1 / V_2$ (V_1 and V_2 positive and negative sequence voltages), up-dated at time intervals $\leq 50\text{ms}$.
- Tie-line(s) between Turkey and Bulgaria/Greece out of service, if any.

Signs of ΣP , of $|\Sigma \Delta P| 1.5''$ and of $|d\Sigma P/dt| 1.5''$ will be as follows:

- ΣP : positive for export from Turkey; negative for import in Turkey.
- $|\Sigma \Delta P| 1.5''$ and $|d\Sigma P/dt| 1.5''$: positive in case of increase of export or of reduction of import; negative in case of increase of import or reduction of export

Voltage imbalance (4th bullet) is considered, for distinguishing the changes of electrical quantities caused by unsymmetrical short circuits on tie lines and adjacent lines.

Two status of operation, low and high system load (above and below a preset total system MW) will be entered in the PLC of SPS for computation of the minimum required LS or GD activation in case of very severe contingencies.

The LS, up to a total max. of 1400MW, will be performed by tripping the loads of HV/MV step-down transformers of a number (up to 15) of substations located in Istanbul region (Asiatic and European sides). Loads liable to be shed have been defined by TEIAS.

The SPS may issue shedding orders to the amount of load computed by the PLC on the basis of the calculated values and signs of ΣP and of $|d\Sigma P/dt| 1.5''$, of number of interconnection lines in service, of system operation conditions (high or low load).

The GD, up to a max. of about 1300-1400MW, will be performed: by disconnecting with priority via transfer tripping on OPGWs hydroelectric generators in Eastern Turkey during operation at peak load when several hydroelectric units are in service; by disconnecting via transfer tripping on OPGWs a few gas turbines in Central-Western Turkey during operation at minimum load. Combination of hydroelectric GD and gas turbine GD can also be performed, according to a priority list. The SPS includes equipment for telemeasurement to the PLC in Hamitabat of the total actual MW output and of number of generating units in service in each of the three hydroelectric power plants (HPPs) and three thermoelectric power plants (TPPs) subject to GD. Telemeasurement is up-dated at intervals (less than 1 minute).

Flexibility for re-setting and, in case, for improvement of functions, is therefore a leading requirement for the SPS.

6 PROJECT DEVELOPMENT AND IMPLEMENTATION

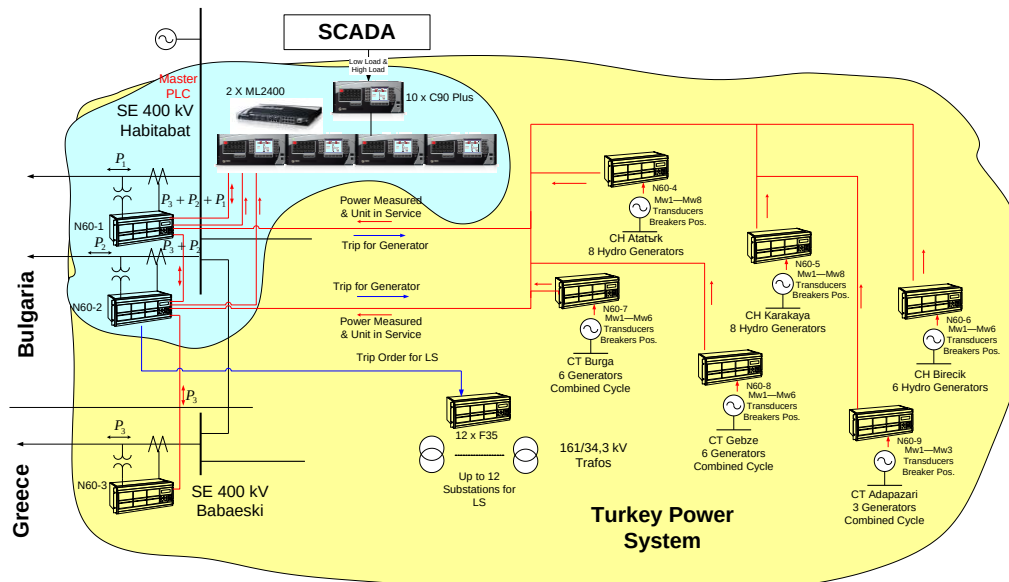


Fig. 2: Distribution of SPS relays

The implementation of the load shedding (LS) and generation dropping (GD) logics is based on the signed ΣP and $d\Sigma P/dt$ values, interconnection lines in service (two or three tie lines in service are considered), the voltage imbalance factor (V_2/V_1) and the High/Low System Load condition received

from the National Control Center of Turkey via the SCADA system. In both cases there are three levels of power (in steps of ~ 400 MW) of LS or GD, that operate depending on preconfigured couples of ΣP and $d\Sigma P/dt$ thresholds. The GD system considers the working generators and prioritizes the tripping of hydraulic generators rather than thermal generators. Fig. 2 shows the distribution of the SPS relays.

6.1 Load Shedding

The LS logic consists of three pre-defined groups of load shedding based on a matrix of loads Vs group. The selection of the group to be shed (automatically done by the SPS) is based on three couples of ΣP and $d\Sigma P/dt$ and on the group(s) associated to each couple. For each of the following conditions: 3 lines/2 lines in service, High Load / Low Load, there are three couples (for a total of 12 couples). Each of these couples is set independently. Fig. 3 shows the LS process.

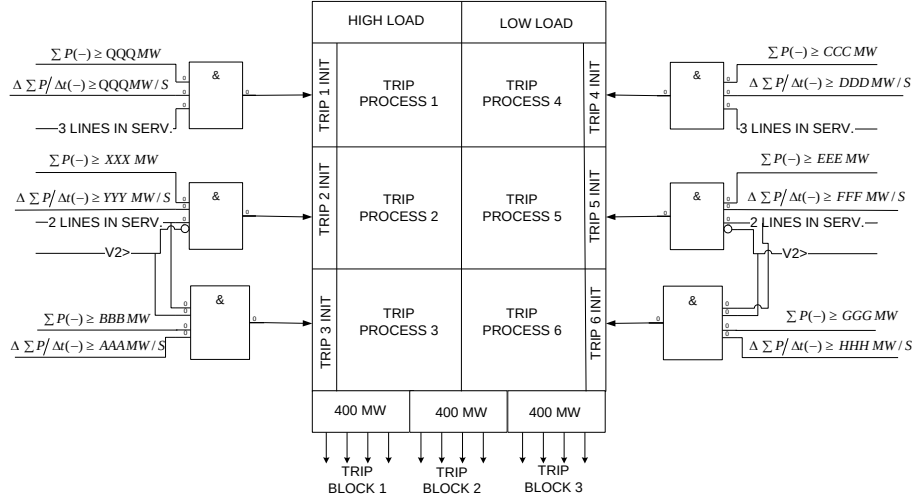


Fig. 3: Load Shedding process

6.2 Generation dropping

The supplier of the SPS has succeeded to implement sophisticated logic functions for disconnection of the generating units in the three selected HPPs and three selected TPPs. Three preset couples of ΣP and $d\Sigma P/dt$ will define three levels of desired GD, to be performed according to the following priorities:

- A.** Hydroelectric units in service will be dropped as 1st priority
- B.** Generating units loaded below manually entered pre-defined levels will be considered out of service (circuit breaker open)
- C.** The logic controller in Hamitabat will at 1st check if the MW output of Ataturk HPP exceeds the MW to be shed (1st predefined block, or 1st+2nd predefined blocks, or 1st+2nd+3rd predefined blocks, as determined by the controller). If answer is “yes”, GD will be performed entirely in Ataturk HPP (with a minimum of two generators). If answer is “no”, all of Ataturk available generators are tripped. The balance GD will be performed in the Karakaya HPP or, in case it were insufficient, in Birecik HPP. It will be accepted that some overdropping of generation will occur.
- D.** If GD performed in the HPPs turns out to be less than required (sometimes overnight, all the three HPPs may be even entirely out of service), the logic controller will perform the balance of the total GD in the TPPs, according to the following priorities:
 - 1st and 2nd priority: one gas turbine (GT) in Bursa TPP and, if insufficient, one GT in Gebze TPP is also dropped, according to pre-defined values that will be set by TEIAS
 - 3rd and 4th priority: if GD performed in the three HPPs and in the thermal units of 1st bullet is insufficient, one GT in Temelli TPP will be disconnected and, if still insufficient, an additional GT will be disconnected in the Bursa TPP according to pre-defined values that will be set by TEIAS.
 - 5th priority: if GD performed as per 2nd bullet is still insufficient, an additional GT will be disconnected in the Gebze TPP according to pre-defined values that will be set by TEIAS.
- E.** It is assumed that the units in service in each HPP and TPP are equally loaded.

- F.** In case that in the Birecik HPP one or more units perform directed generation to Syria, i.e. not connected to the Turkish system, these units will be considered out of service (open CB) with a manual entry by the operators in the Birecik HPP.
- G.** It is possible, with a revision of logic, to manually set the desired GD for each of the three blocks, in the range of 250 to 500MW.

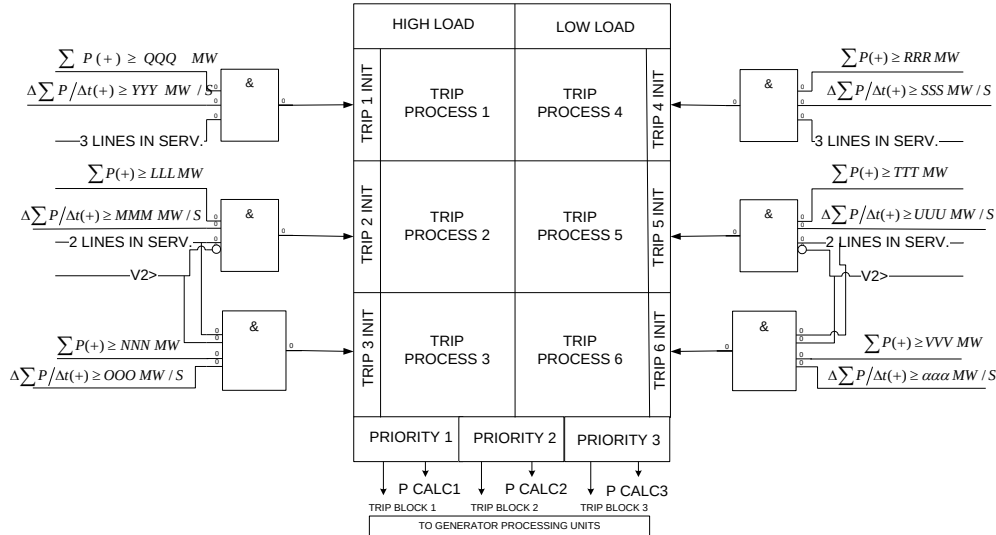


Fig. 4: Generation Dropping process

6.3 Capabilities of Devices Used

The capabilities of the relays are as follows: Protection: Out-of-step tripping, Power Swing Blocking, Under- & over-frequency, Rate of change of frequency, Sensitive Directional Power, dP/dt , dV/dt , Overcurrent, Under- & over-voltage. Control: Open pole detection, Synchrocheck, Programmable Logic Control, Add, Subtract, Compare, Select. Communication: Peer-to-peer via Ethernet, Peer-to-peer via SONET, G.704, RS422, C37.94, Fiber, Flexible communications. Architectures, Telemetry with 8-bit resolution, Respond to remote & local data.

7 FACTORY ACCEPTANCE TESTS (FATs)

As all SPS actions are to be taken on the Turkey installations (or interconnection lines), it has been accepted to perform the FATs with the Real Time Digital Simulator (RTDS) of the SPS's supplier, by reducing the interconnected power systems as described below.

7.1 ENTSOE – Continental System equivalent

Two equivalent generators to represent ENTSO-E system: 200,000 MW of installed power in Bulgaria and 100,000 MW in Greece. Each generator is equipped with its own generator/turbine, excitation system and PSS.

Additionally, two dynamic loads represent power consumption equivalents in Bulgaria and Greece.

7.2 Turkey equivalent

The Turkish equivalent has been modeled in a more precise manner due to the geographical separations between loads and generations that are susceptible to be acted on by the SPS.

- one main generator for the core generation of Turkey (40,000 MW),
- one additional generator for TPP and three groups of three generators for HPP, one group for each plant on which SPS can act and, in each plant, three generators to represent: two individual generators and one equivalent for the remaining generators of the plant.

Transmission lines are simulated from the entry node (Hamitabat/Babaeski) to Istanbul, from Istanbul to Adapazari where two TPPs are located, from Adapazari to South-Eastern Turkey where HPPs are located. An appropriate line is simulated to represent the South-Eastern transmission corridor.

Fig. 6 provides information on flow during the RTDS tests, an example of performed tests and the physical arrangement of the SPS in the RTDS.

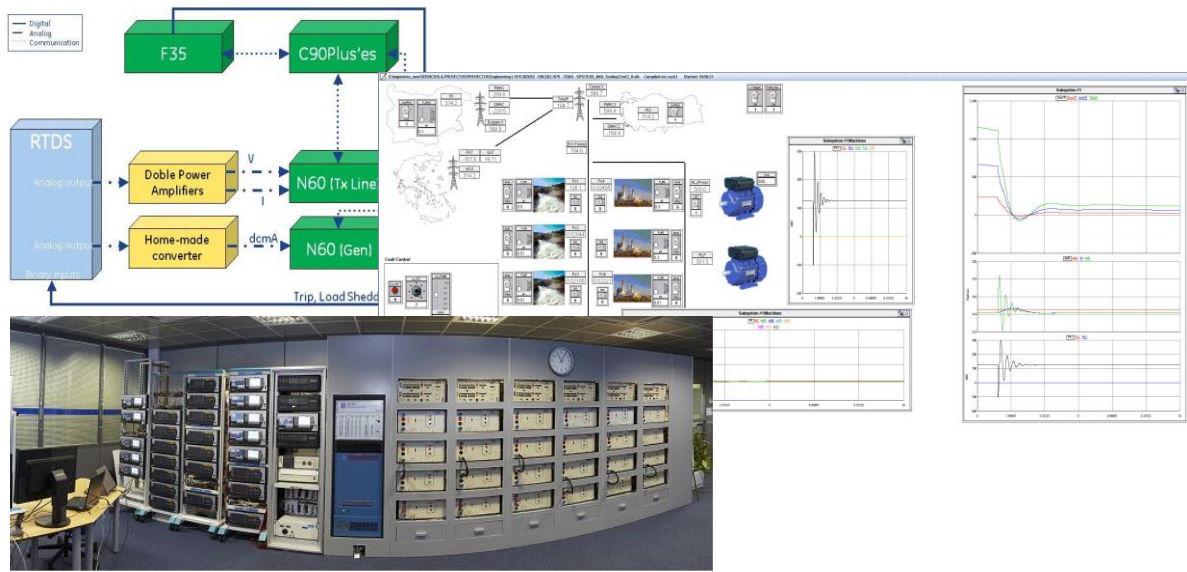


Fig. 6: Information flow, Example of test performed Physical arrangement of the SPS (left) in the RTDS tests

8 SITE ACCEPTANCE TESTS (SAT)

For the SATs, Power System topology was arranged for High and Light load conditions. Total Active Power flow was recorded (oscillography) from the RTDS during the FAT and the records were downloaded in one of the N60's in Hamitabat, using a portable test device.

The results were similar to the ones obtained during the FAT, but in this case the transmission and reception of the trip signals to the corresponding generators and loads have been checked.

The FATs and SATs have confirmed that the complete process of SPS, from the moment of occurrence of disturbance to completion of LS or GD in the outstations, is performed within 2.5s, with the specified processing time of the tie-lines power flows of 1.5'' ($|\Sigma P|_{1.5''}$ and $|d\Sigma P/dt|_{1.5''}$).



Table 1 Load Loss 1300 MW (action: drop 1200 MW)							
Plant power (Units in service)						Trip	
HPPI	HPP2	HPP3	TPP1	TPP2	TPP3	Units	Power
208 (1)	470 (1)	123 (1)	471 (2)	773 (3)	514 (2)	1-2-1	1294
0 (0)	0 (0)	0 (0)	398 (2)	878 (4)	440 (2)	0-0-0	858
1588 (6)	1323 (5)	460 (4)	219 (1)	439 (2)	219 (1)	1-2-1	1361
						6-0-0	
						0-0-0	

Fig. 9: Site acceptance test (SAT) in Hamitabat SS

9 PROTECTION IN CASE OF BUILD-UP OF INTERAREA OSCILLATIONS ON THE INTERCONNECTION LINES

The SPS is specified to monitor the inter-area power and frequency oscillations in the three 400kV tie-lines, to give an alarm if a threshold is exceeded and eventually, as a last line of defense, to trip with appropriate time delay the three tie-lines in case that a 2nd threshold were exceeded or oscillations would happen to be progressively amplified, with danger of disorderly disruption of power system and of equipment damage. The SPS will process the frequency at Hamitabat, by filtering to eliminate the DC-offset and frequency noise and to detect the oscillations components in the range of interest, i.e. 0.1 to 0.2Hz. [8].

10 INITIAL SETTINGS AND OPERATION RESULTS OF THE SPS

The SPS has been in service since the start of the synchronous operation of the Turkish system with the ENTSO-E Continental system.

During operation at high system load, three levels of LS are foreseen, of ~ 400MW, ~ 800MW and ~ 1200MW according to the severity of disturbance associated with the sudden large loss of generation. The corresponding thresholds for LS activation when all the 400kV interconnection lines are in service, are from – 700MW/s to – 1000 MW/s for the function $|\Delta\Sigma P/\Delta t|_{1,5}$ and from – 850MW to – 1600MW for the function $|\Sigma P|_{1,5}$, respectively. During system operation at low load, the three levels of LS are of 200-280MW, 400-550MW and 600-800MW according to severity of disturbance. The thresholds for activation are 7 to 20% lower than the ones at high load.

Three levels of GD are foreseen, of 400-600MW, 800-1000MW and 1200-1400MW, according to severity of disturbance associated with sudden large loss of load. The corresponding thresholds for GD activation with all the 400kV interconnection lines in service during operation at high system load, are from + 600 MW/s to + 800 MW/s for the function $|\Delta\Sigma P/\Delta t|_{1,5}$ and from + 750MW to + 1500MW for the function $|\Sigma P|_{1,5}$. Slightly higher threshold have been set for system operation at low system load.

The inter-area oscillation detector has been set as follows:

- Alarm: 30mHz with 10s delay
- Tripping of the three 400kV interconnection lines: 60mHz with time delay of 50s.

It is foreseen that the above initial settings will be reviewed on the ground of operation experience.

As of end of January 2011, the inter-area oscillation detector has intervened only once, issuing only the alarm. LS and GD has never been activated, because: the power exchange between Turkey and the rest of ENTSO-E system has so far been nil or small; the sudden generation loss in Turkey has never exceeded 930MW; the sudden loss of load in Turkey has never exceeded 600MW.

Operation results so far indicate that the applied SPS is secure (it did never intervene without need); on the other hand, dependability (i.e. reliable intervention in case of large disturbances) could not be validated by experience. Information for post-mortem analysis (oscillography, event recorder) is available in each device. From SCADA signals for High and Low load are used.

11 CONCLUSION

In the light of all the tests that have been performed, the SPS system proves to be operating as per specifications, in accordance with TEIAS requirements. The SPS is expected to avoid crossborder propagation of major disturbances, to preserve as far as possible the synchronous operation of the Turkish with the ENTSO-E system and to improve the overall reliability and effective operation of the system.

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