System Integrity Protection Schemes in the 400 kV Transmission Network of Turkey

Francesco Iliceto
University of Rome

Özkan Akansel, Mevlüt Akdeniz, and Süleyman Erikci
TEİAŞ

Yusuf Zafer Korkmaz and Krishnanjan Gubba Ravikumar
Schweitzer Engineering Laboratories, Inc.

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Francesco Iliceto, *University of Rome*
Özkan Akansel, Mevlüt Akdeniz, and Süleyman Erikci, *TEİAŞ*
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Abstract—**Owing to delays in the construction of long 400 kV lines for power transportation from new power plants, the Turkish power system is suffering from regional transmission bottlenecks. The main remedy has been the installation of the system integrity protection schemes (SIPSs) described in this paper. Simulation of the disturbances to be countered showed that preference had to be given to response-based SIPSs. An innovative contribution has been the identification for each SIPS of a specific indicator of the large family of disturbances that may occur anywhere in the national system. These indicators are identified by means of the fast elaboration of electrical measurements made at the location of the SIPS controller. A challenging requirement was the very short time available (≤ 300 milliseconds) for the successful action by two of the SIPSs. This paper reports the results of system analyses performed, the technical specifications of the SIPSs, the up-to-date hardware and software applied to comply with the stringent specified requirements, the applied complex logic and reliability criteria, the settings of the SIPS controllers, and operational experience.**

I. Introduction

The electric power system (EPS) of Turkey serves a population of 75 million in a national territory of 780,000 km^2. The largest part of the load is located in the western regions, while an important part of the generation (in particular, state-owned hydroelectric power plants [HPPs] and thermoelectric power plants [TPPs] fired with local lignite) is located in the eastern regions. This situation requires a large east-to-west power transmission system that is built at 400 kV ac (50 Hz) over distances up to 1,300 km.

As of 2015, the Turkish transmission system had the following assets:

- 18,400 km of 400 kV transmission lines (TLs) (98 percent are single-circuit).
- 37,800 km of 154 kV TLs (many are double-circuit).
- 140 x 400 kV substations, most of which are equipped with 400/154 kV autotransformers and several with 400/34.5 kV step-down transformers.
- 870 x 154 kV medium-voltage step-down transformer substations (most medium-voltage distribution is made at 34.5 kV).
- 17 x 400 kV series capacitor banks in the long east-to-west TLs.
- 53 x 420 kV shunt reactors.

The total installed generation capacity is 72,400 MW (36 percent HPPs, 21 percent lignite- and other coal-fired TPPs, 35 percent natural gas and liquefied petroleum gas [LPG] combined-cycle TPPs, and 8 percent other renewables). In 2015, the summer peak power demand was 43,300 MW and total energy demand was 264 TWh.

Since 2010, the Turkish EPS has been synchronously operated with the European Network of Transmission System Operators for Electricity/Continental Europe Synchronous Area (ENTSO-E/CESA) system. There are three 400 kV interconnection TLs, two with Bulgaria (to Maritza East) and one with Greece (to Nea Santa).

Several new TPPs and HPPs have been built by independent power producers (IPPs) in locations far from the load areas, with construction times much shorter than in the past. However, in some regions the Turkish Electricity Transmission Company (TEİAŞ) has not succeeded in building, in a coordinated time, the necessary new 400 kV TLs. Delays have had various causes (environmental impacts; TL routes in impervious mountains; financing, bidding, and construction with the complex procurement regulations of state and financing agencies; and so on). This has created transmission bottlenecks, with risks of regional blackouts and/or automatic separation of the Turkish EPS from the ENTSO-E system.

An effective remedial action has been the installation of system integrity protection schemes (SIPSs). The subject of this paper is two regional SIPSs implemented with the most up-to-date technology, which have been in service since the fall of 2014. Their goal is to avoid regional blackouts in Turkey and the propagation of disturbances to neighboring countries. In the next section, information is also presented about a SIPS that has been in service since 2010.

II. Function and Experience of the SIPSs in Operation in Turkey

A. *SIPS in the Interface Between the Turkish and European Power Systems*

The SIPS between the Turkish and European power systems is response-based. It has been in service since 2010 when the synchronous interconnection with the ENTSO-E system was commissioned. The purpose of this SIPS is to avoid a loss of synchronism, separation from the ENTSO-E system, and the cascade tripping of generators and TLs; to monitor interarea oscillations with Western Europe; and to minimize the effects in neighboring countries of disturbances that occur in Turkey.

The Turkish EPS is connected to the Western European system through the long longitudinal transmission system of the Balkan countries, where the generation in service is small relative to that of Turkey. The synchronous area in Southern Europe spans over 4,700 km from Portugal to Eastern Turkey. About 80–85 percent of the ENTSO-E/CESA power generation (at peak load, the demand is about 500,000 MW) is located in Western-Central Europe. Because of this system configuration, any sudden large loss of generation or of load occurring in Turkey is made up, in the amount of 80–85 percent, by the kinetic energy of the rotating masses and by the primary frequency control of the Western-Central Europe system. If not adequately mitigated, sudden, large load-generation imbalances in Turkey cause a large power flow to or from Turkey through the Balkan countries, with possible TL tripping on overload, voltage collapse, or a loss of synchronism. The balancing action in Turkey of the secondary power frequency control starts after 20–30 seconds and is not effective during the initial electromechanical transient.

Analyses have shown that the high transfer impedance between the Western-Central European system and Turkey yields a dominant interarea oscillation mode of low frequency (0.12–0.13 Hz; oscillation cycle of 7.5–8 seconds) [1]. This frequency decreases to ~0.10 Hz if only the Turkey-to-Greece interconnection TL is in operation. Consequently, in case of a sudden, large loss of generation or load in Turkey, the makeup power from (or to) Western Europe to (or from) Turkey builds up in ~1.8–2 seconds (i.e., about one-quarter of an oscillation cycle) as needed for the change of the transmission electrical angle. This leaves a time of 2–2.3 seconds for the SIPS to compensate most of the imbalance in Turkey with load shedding (LS) or generation dropping (GD).

Simulations of a variety of disturbances that may occur in the EPS of Turkey have shown that the events that might cause the separation of Turkey from the ENTSO-E system upon overload, angular instability, or voltage collapse are the sudden, large losses of generation or load. The SIPS has, therefore, been specified to counter these events.

The SIPS has a master controller and a slave controller in the two 400 kV substations interfacing with Bulgaria and Greece. It detects any sudden load or generation imbalance in Turkey by monitoring the following:

- The sum and signs of the active power flows in the three 400 kV interconnection TLs, $\Sigma P(t)$, computed as the average of 25 values in the last 5 seconds.
- Every 100 milliseconds, the rate of change (first derivative) of $\Sigma P(t)$ averaged during the last 1.5 seconds, i.e., [d$\Sigma P(t)$/dt] 1.5”.

If the absolute values of $\Sigma P(t)$ in megawatts and [d$\Sigma P(t)$/dt] 1.5” in megawatts per second are higher than the preset values, the SIPS performs LS or GD according to the sign (+ or –) of the two values.

Twenty-four pairs of $\Sigma P(t)$ and [d$\Sigma P(t)$/dt] 1.5” thresholds initiate, via remote control on optical ground wires (OPGWs), LS in eleven 154/34.5 kV substations or GD in three HPPs and three TPPs. The LS or GD is fast and simultaneous in one, two, or three ~500 MW blocks of load or generation, selected by the SIPS according to the type and severity of the detected disturbance (i.e., the size of the sudden load or generation imbalance) and the system operation condition (i.e., a high or low system load and the number of 400 kV interconnection TLs in service). The megawatt output of the generating units subject to GD is continuously monitored by the SIPS, and hydroelectric units are prioritized for GD if they are in service.

B. *SIPS of the Eastern Black Sea Region*

The Eastern Black Sea region has a geographical extension of 500 km along the Black Sea coast. As shown in Fig. 1, the region is connected to the western and central portions of the national grid through a 460 km coastal single-circuit 400 kV TL from the Deriner HPP substation to the OMW TPP substation and a 540 km inland single-circuit 400 kV TL from the Deriner HPP substation to the Keban substation, respectively.

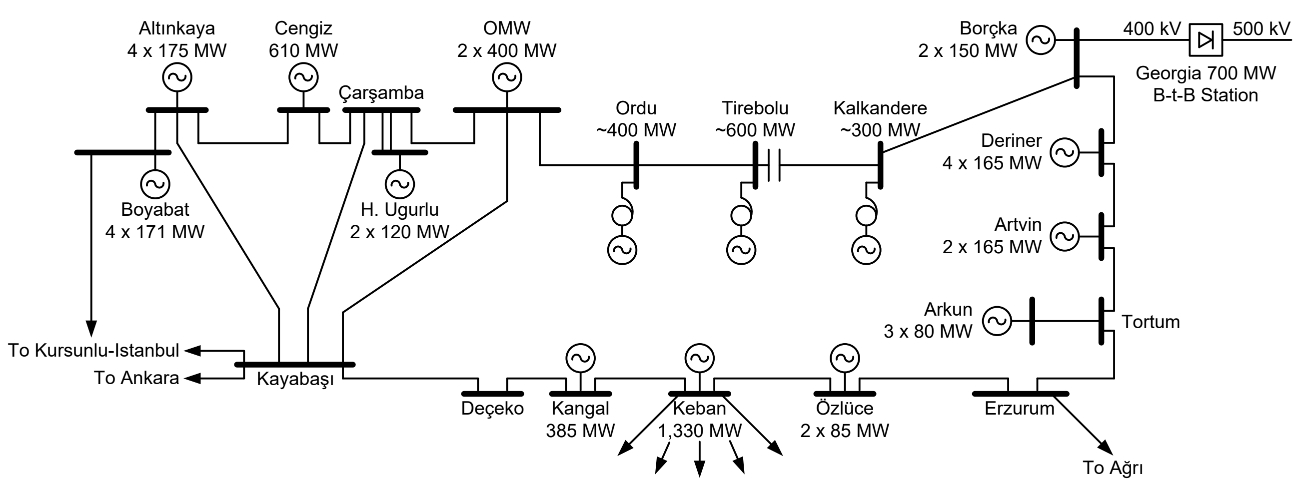

Fig. 1. Single-line diagram of the 400 kV Eastern Black Sea subsystem of Turkey

These TLs are all equipped with triple-bundle conductors and are interconnected with 400/154 kV autotransformers to an underlying 154 kV network, to which many HPPs of medium and small rated power are connected.

Many new HPPs and two gas-fired TPPs were commissioned between 2013 and 2015, tripling the installed generation capacity of the region from the initial ~2,000 MW to ~6,000 MW. In addition, a high-voltage dc (HVdc) link with the EPS of Georgia was commissioned in 2014 for power export to Turkey. It consists of a back-to-back line-commutated converter station rated at 700 MW located in Georgia and a 400 kV ac TL terminated at the 400 kV busbars of the Borçka HPP substation in Turkey (see Fig. 1). The back-to-back link has increased the power to be wheeled to central Turkey by the two 400 kV Eastern Black Sea TLs. The load in the region varies from 400 to 900 MW.

The construction by TEİAŞ of a third long 400 kV TL from the Borçka HPP substation to the Keban substation (560 km) and of a transversal 400 kV tie TL to the coastal and inland TLs has been delayed for the reasons mentioned in Section I. This has caused a very large power flow on the two existing TLs during the high water inflow months when limiting generation by water spilling in the HPPs is highly undesirable. If countermeasures are not applied, the tripping on a fault in any section of one of these 400 kV TLs causes an exceedingly large power flow in the other TL and in the 154 kV TLs that underlie the tripped 400 kV TL, along with cascade tripping on overload, a loss of synchronism, or large power oscillations (small signal instability). These phenomena could cause a regional blackout and a sudden generation deficit of up to 3,000 MW in the national system, activating the SIPS described in Section II, Subsection A. The new Eastern Black Sea region SIPS is designed to avoid these regional blackouts by means of very fast GD supplemented by the reduction of the power import from Georgia through the back-to-back HVdc link.

The technical specification of the SIPS was based on load flow, angular stability, and protective relay behavior analyses. Various combinations of generation dispatching in the Eastern Black Sea region and power import from Georgia through the back-to-back HVdc link were simulated. The disturbances of major concern are 400 kV TL trips caused by faults. Three-phase short circuits cleared in 120 milliseconds by permanent TL opening and single-phase-to-ground short circuits followed by successful and unsuccessful single-pole reclosing were also simulated. Short circuits were simulated at the sending end of all sections of the coastal and inland 400 kV TLs and in the 400 kV TLs that connect to the interconnected grid of the OMW TPP, Cengiz TPP, Altınkaya HPP, and H. Ugurlu HPP substations (see Fig. 1).

For the disturbances that can cause a regional blackout, fast GD combined with a power import reduction from Georgia via the back-to-back HVdc link was simulated by amounts tailored to the severity of the disturbance. The target was to stabilize the system with minimal GD and power import reduction.

A challenging design problem for this SIPS is that the electromechanical oscillation cycle in the Eastern Black Sea subsystem is only 1.2–1.5 seconds. Analyses have shown that, to be effective, the GD and power import reduction must therefore be performed very rapidly, generally within 300 milliseconds of the disturbance inception. This is opposed to the SIPS described in Section II, Subsection A for which the available time is 2–2.3 seconds. The 300 milliseconds must include the TL open status detection, signal transmission time, processing by the SIPS logic controllers, and putting into effect of the GD and/or power import reduction. On-off signal transfer time via OPGWs, including coding and decoding time, is ≤25 milliseconds from any outstation to the SIPS master controller in the Borçka HPP substation.

The initiating event for the possible intervention of the SIPS is the outage of any section of the two long 400 kV TLs of the Eastern Black Sea region for any reason. The open status of a TL is detected in the substations by any one of the following events, whichever occurs first:

- A trip signal by the local line distance protection relays (this is the fastest detection).
- The opening of a line circuit breaker (CB) detected by the change of position of the CB auxiliary contacts (pallets).
- The sudden collapse to less than 5 MW of the TL active power flow supervised by a current flow of ≤150 A (the detection of a TL opening only at the remote end, remaining energized at no load).

The generating units subject to GD are the following:

- For the SIPS installed in the Borçka HPP substation: 1 or 2 units in the Borçka 2 x 150 MW HPP, 1 or 2 units in the Deriner 4 x 165 MW HPP, 1 unit in the Artvin 2 x 165 MW HPP, and a group of small HPPs in Kalkandere. These HPPs are located near the border with Georgia (see Fig. 1).
- For local special relays: 1 to 4 units in the Altınkaya 4 x 175 MW HPP, 2 or 4 units in the H. Ugurlu 4 x 120 MW HPP, and 1 unit in the OMW 2 x 400 MW combined-cycle TPP. These power plants are close to the receiving end of the Borçka-OMW coastal 400 kV TL (see Fig. 1).

The hydroelectric units, if detected in operation as synchronous condensers spinning in the air, are not disconnected by the SIPS in order to preserve their stabilizing inertia. In addition to the GD described previously, the power import from Georgia through the back-to-back HVdc link, rated at 2 x 350 MW, is specified to be suddenly reduced by a signal from the SIPS down to the minimum allowed operation power of 2 x 35 MW for a time of 300 milliseconds to preserve system transient stability. Thereafter, the power import can be restored to part of the power flow prior to disturbance.

When an open status signal is received for the 400 kV transmission loop, the SIPS controller calculates the minimum number of in-service generating units to be dropped and the reduction of power import that is necessary for system stabilization. Three or four levels of generation and import relief are specified (from 300 MW to 1,000 MW) according to the detected location of the open TL and the measured active power flow prior to the disturbance in the 400 kV TLs terminated at the Borçka and Deriner substations. These power flows are good indicators of the westbound transmission stress. They are specified to be continuously calculated as the average of 25 equidistant measurements in the last 5 seconds to avoid using the last instant measurement, which in transient conditions may be meaningless.

The SIPS logic is event-based. With the exception of the TLs terminated at the Borçka and Deriner HPP substations, where the master and slave controllers are installed, the open status detection of the other 400 kV TLs of the Eastern Black Sea region loop depends on OPGW telecommunications from outstations and is therefore exposed to the risk of misoperation. As a result, response-based SIPS logic has been applied in parallel with the event-based SIPS logic to perform the system stabilization actions and intervene very dependably and rapidly.

The response-based SIPS logic was conceived based on the physical dynamic behavior of the Eastern Black Sea subsystem. When the coastal or the inland long TL is open in one section (see Fig. 1), the power flow westbound from the regional HPPs and the power import from Georgia is partly or totally transferred to the other TL. This transfer becomes effective when the electrical angle between the sending and receiving end 400 kV busbars has increased as required by the almost doubled transfer impedance. Initially, the power transmitted is not changed, and it thereafter gradually increases. The nontransmitted power causes a temporary acceleration of the generators located in the east and a frequency increase thereafter. Simulations have shown an almost linear increase of frequency for 100–120 milliseconds, with a rate of increase (df/dt) of 1.25–2.5 Hz per second depending on the generation level prior to the disturbance and the open TL location. An example is shown in Fig. 2.

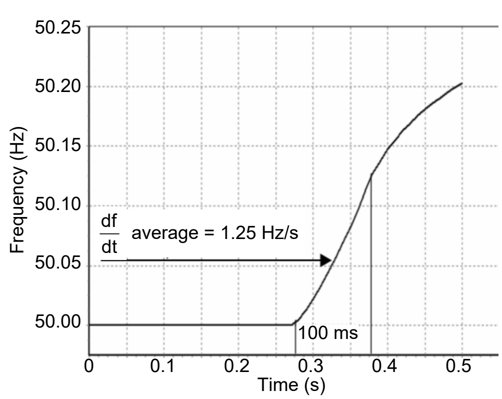

Fig. 2. Example of computed transient frequency versus time in the Borçka 400 kV busbars following tripping on a three-phase short circuit of the Erzurum-Özlüce 400 kV TL.

For the response-based action of the SIPS, the df/dt measurement is performed during the initial 100–120 milliseconds, with a pickup threshold of 0.75 Hz per second. Three levels of GD and import reduction can be implemented, depending on the power flow measured prior to the disturbance in the TLs terminated at the Borçka and Deriner HPP substations.

The transmission relief action is performed by the response-based or event-based logic, whichever intervenes first in each specific case. The total GD varies from ~300 MW to ~1,000 MW.

The OMW-Kayabaşı and Altınkaya-Boyabat-Kursunlu 400 kV TLs have only recently been commissioned. Previously, an outage during high-load operation of one of the Altınkaya-Kayabaşı or Çarşamba-Kayabaşı 400 kV TLs (see Fig. 1), which are equipped with twin-bundle conductors (the summer capacity at thermal limit is 1,000 MVA), would cause intolerable overload of the other TL. Special relays have therefore been installed within the scope of the SIPS for GD in the Altınkaya or H. Ugurlu HPP substations. They have been set with three GD levels that depend on the measured power flow on the TL with the outage prior to the disturbance. The SIPS relays were also specified to activate time-delayed moderate GD when both TLs are in service if the power flow in one of them exceeds 900 MVA for a preset time. A special relay with similar functions has been installed in the OMW TPP substation for GD in case of an outage of the OMW-Çarşamba 400 kV TL.

C. SIPS of the Southern Marmara Sea Region

The Southern Marmara Sea region SIPS is response-based. The installation of this SIPS was necessary because of a delay in the commissioning of new TLs, as described previously for the Eastern Black Sea subsystem.

Two IPPs have rapidly increased the generation capacity in the region from an initial 1,300 MW to 3,100 MW by commissioning the Bekirli 2 x 660 MW coal-fired TPP and a new 600 MW unit in the existing Bandırma 900 MW combined-cycle generation complex (see Fig. 3).

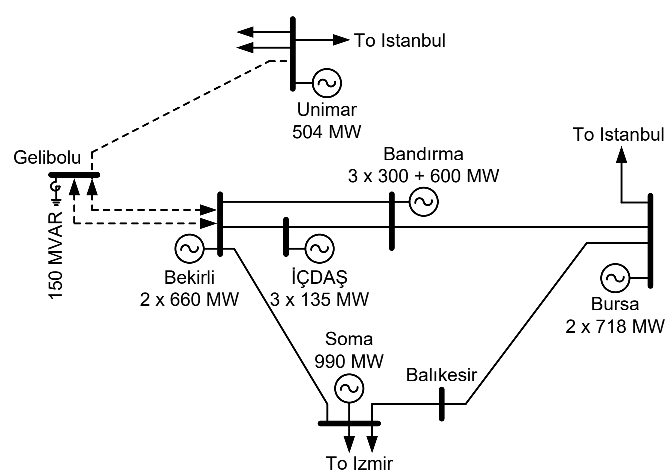

Fig. 3. Single-line diagram of the 400 kV Southern Marmara Sea subsystem of Turkey.

The load in the region supplied by the 400 kV grid is 300–400 MW. These TPPs are connected to the 400 kV national grid by two long single-circuit 400 kV TLs forming a loop, as shown in Fig. 3. To the east they are connected by the Bandırma-Bursa TL, and to the south they are connected by the Bekirli-Soma TL. A delay occurred in the construction of two new 400 kV TLs from the Bekirli TPP to the European part of Istanbul (see Fig. 3), which includes the 2 x 1,000 MW Dardanelles Strait submarine cable crossing.

In spite of the generation dispatch limitation by TEİAŞ in the TPPs of the region to no more than 2,500 MW, if the Bandırma-Bursa or Bekirli-Soma TLs trip, the regional subsystem (including the underlying 154 kV network) will collapse on an exceedingly large overload and/or on transient instability. The SIPS is designed to perform very fast GD in the Bandırma and İÇDAŞ TPPs when one of these 400 kV TLs trips for any reason.

The open status of the Bandırma-Bursa TL is detected as specified in Section II, Subsection B for the Eastern Black Sea region SIPS. The SIPS main controller is installed in the Bandırma TPP complex. Based on the results of load-flow analyses, angular stability, and protective relay behavior, the following logic has been specified:

- $P_{B\text{-}B,\ av,\ \Delta t}$ is the active power flow in the Bandırma-Bursa TL prior to the disturbance, calculated as specified in Section II, Subsection B for the Eastern Black Sea region SIPS (average of 25 measurements in the last 5 seconds).
- $P_{B\text{-}B}(t)$ is the actual value of the power flow in the Bandırma-Bursa TL, updated every 50 milliseconds or less.

For preserving transient stability, the intervention of the SIPS must be very fast, as for the Eastern Black Sea region SIPS, because the cycle of the electromechanical oscillations is low (1.3–1.6 seconds). The Bandırma SIPS logic is as follows.

If the Bandırma-Bursa TL is detected as open, the SIPS does the following:

- If $P_{B\text{-}B,\ av,\ \Delta t} \leq 650$ MW, no action is taken.
- If 650 MW < $P_{B\text{-}B,\ av,\ \Delta t} \leq 750$ MW, one 300 MW gas turbine is instantaneously tripped in the Bandırma TPP complex.
- If $P_{B\text{-}B,\ av,\ \Delta t} > 750$ MW, one gas turbine is tripped in Bandırma and the units in operation in the İÇDAŞ 3 x 135 MW TPP are tripped by transfer tripping.
- If the megawatt output of the new 600 MW Bandırma unit is ≥400 MW, it is tripped instead of a 300 MW gas turbine.

The tripping of the Bekirli-Soma TL cannot be telesignaled to the SIPS controller because no OPGW communication is available. On the other hand, when the Bekirli-Soma TL is tripped, the relevant power is transferred to the Bandırma-Bursa TL with a fast jump. An example is shown in Fig. 4.

Dynamic analysis has shown that the detection of the TL tripping (response-based) is made every 50 milliseconds if, in any moment during the last 1 second, the ratio (R) in (1) has exceeded preset values:

$$R_{1second} = \frac{P_{B-B}(t)}{P_{B-B,\ av,\Delta t}} \tag{1}$$

The Bekirli-Soma SIPS logic is as follows. If the Bekirli-Soma TL is detected as open, the SIPS does the following:

- If $P_{B\text{-}B,\ av,\ \Delta t} \geq 650$ MW and $R_{1second} \geq 1.5$ pu, one 300 MW gas turbine is instantaneously tripped in the Bandırma TPP complex.
- If $P_{B\text{-}B,\ av,\ \Delta t} \geq 850$ MW and $R_{1second} \geq 1.35$ pu, one gas turbine is tripped in Bandırma and the units in operation in the İÇDAŞ 3 x 135 MW TPP are tripped by transfer tripping.
- If the megawatt output of the new 600 MW Bandırma unit is ≥400 MW, this unit is tripped instead of a 300 MW gas turbine.

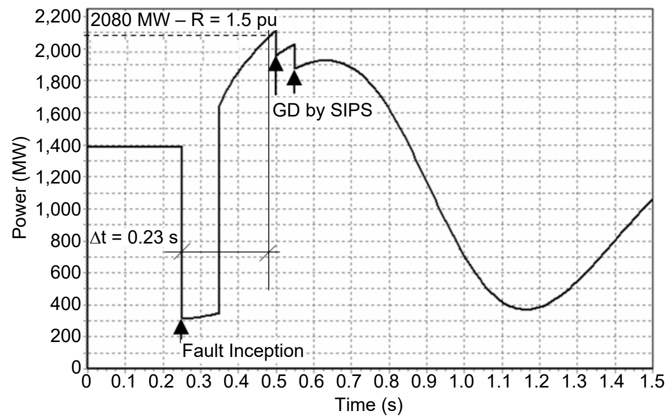

Fig. 4. Computed typical power flow versus time in the Bandırma-Bursa 400 kV TL following the tripping on a three-phase short circuit of the Bekirli-Soma 400 kV TL.

Following tripping of a gas turbine in the three-shaft 3 x 300 MW combined-cycle block in Bandırma, the associated steam turbine generator megawatt output is gradually reduced by half over 1–2 minutes.

When the two new TLs from the Bekirli TPP substation to the European side of Istanbul (dashed in Fig. 3) are in service, the sudden increase of ratio $R_{1second}$ to 1.5 pu or more will be applied to detect the tripping of the new TLs from the Bekirli TPP substation to Western Istanbul. The GD by the SIPS will be performed with the same response-based logic currently in force, described previously. However, the GD of a 1 x 300 MW gas turbine or of the 600 MW unit in the Bandırma generation complex and of the 135 MW unit(s) in the İÇDAŞ TPP will be staggered in three levels, depending on the actual power flow $P_{B\text{-}B,\ av,\ \Delta t}$ in the Bandırma-Bursa TL prior to the disturbance. The power flow ranges are ≥900 MW, 800–900 MW, and 650–800 MW. If $P_{B\text{-}B,\ av,\ \Delta t} < 650$ MW, no GD is performed.

III. SIPS Implementation

A. Eastern Black Sea Region SIPS Design

The Eastern Black Sea region SIPS uses a distributed design, consisting of independent controllers, remote input/output (I/O) modules, and communications equipment installed in substations on the 400 kV loop (see Fig. 1).

Automation controllers are used as remote binary I/O devices that quickly detect TL open conditions and send this information through OPGWs to the SIPS controllers. These devices have a processing interval of 2 milliseconds (i.e., they perform input scans and logic processing once every 2 milliseconds). To detect line open conditions, disconnect switch and CB status and trip signals from line protection devices are used as inputs. Each unit monitors two 400 kV TLs so that each TL is monitored from both ends, providing a backup mechanism.

The SIPS controllers are protective relay-based phasor measurement units that support freeform logic function implementation. The fast logic functions are executed deterministically 8 times each power cycle, whereas slower logic functions are executed every 100 milliseconds. SIPS controllers use busbar voltage transformer (VT) and bay current transformer (CT) signals, as well as disconnect switch and CB status and line protection trip signals, as inputs. Each SIPS controller has two sets of VT inputs and six sets of CT inputs and is capable of monitoring the power flow on up to six bays in a 400 kV substation.

The functions of SIPS controllers are as follows:

1. To monitor the active power flow and arming thresholds on 400 kV TLs. This includes instantaneous measurements and 5-second averages of 25 measurements (one sample every 200 milliseconds).
2. To monitor the active power output of generators based on 25-sample, 5-second averages.
3. To monitor disconnect switch and CB statuses.
4. To detect line open conditions via local inputs or via signals from remote I/O units.
5. To identify generator units that are in service and can be dropped.
6. To determine the number of generators to be tripped.
7. To trip the required number of generators or TLs.
8. To send line open conditions to other SIPS controllers, essentially acting as a remote I/O device.
9. To detect line open conditions via rate-of-change of frequency.
10. To detect TL overload.
11. To send remote trip signals to other SIPS controllers.
12. To send blocking signals to the HVdc back-to-back converter controller.

SIPS controllers have been installed in the Altınkaya HPP, Çarşamba TPP, OMW TPP, Borçka HPP, and Deriner HPP 400 kV substations. Functions 1–7 are implemented by all SIPS controllers. The Çarşamba TPP, OMW TPP, and Deriner HPP SIPS controllers implement Function 8. Only the Borçka HPP SIPS controller implements Function 9. The Altınkaya HPP and Çarşamba TPP SIPS controllers implement Function 10. Functions 11 and 12 are implemented by the Borçka HPP and Deriner HPP SIPS controllers.

Because of the importance of correct operation, a redundant system was designed. The failure of equipment should not be the cause of a misoperation of a critical SIPS in the power system. Redundancy allows part of the system to be left in service while redundant components are replaced during future upgrades. This is important for future planning considerations and should not constrain the SIPS.

The SIPS controllers installed in the Borçka HPP and Deriner HPP 400 kV substations are dual-redundant in a failover scheme. One of the controllers is the primary and the other is the backup. In case the primary controller fails or detects an input signal failure, the backup controller takes over until the primary controller returns to a normal state.

In addition to the self-supervision of the SIPS controllers for hardware and software failures, two supervision functions for input signals have been programmed. The first supervision function checks the bay current signal against the bay disconnect and breaker status. If the bay status is calculated as not connected to a busbar while there is load current present on that bay and the condition persists for a set time, a switch status alarm is generated. The second supervision function checks the bay active power against the bay current signal. If the bay active power is lower than a set value while the bay current magnitude is higher than a set value for a set amount of time, a loss-of-potential alarm is generated. The SIPS controller logic also continuously monitors communication with the SIPS communications controller. Any of these alarms causes a failover to the backup controller.

In the SIPS controller logic, provisions have been made for operators to manually enable and disable the controllers or enable and disable output contacts using the front-panel pushbuttons to allow for testing and maintenance.

Remote I/O units have been installed in the Tirebolu, Kalkandere, Erzurum, Özlüce, and Keban 400 kV substations. Each of the remote I/O units has self-supervision for hardware and software problems. Communications with the Borçka substation are continuously monitored. Failures exceeding a set time or hardware or software supervision alarms operate an output contact to drive both the substation audible alarm and an indication on the substation alarm annunciation board.

At each substation (except for the Altınkaya HPP 400 kV substation) where OPGW and synchronous digital hierarchy (SDH) infrastructure is not available, communications interface converter equipment has been used, converting the EIA-232 serial interfaces of the SIPS controllers and remote I/O units to the G.703 64 kbps codirectional interface of the existing TEİAŞ SDH/PDH (plesiochronous digital hierarchy) equipment. The interface converter equipment supports a maximum baud rate of 19,200 bps. The communications links are terminated in the Borçka HPP 400 kV substation, where a real-time automation controller is installed as a SIPS communications controller in order to multiplex all point-to-point communications links and route remote signals to their respective destinations.

Given the available bandwidth through the 64 kbps communications channels, the reliability and security requirements, and the constraints on the response time of the system, a proprietary, high-speed communications protocol was selected for communications between SIPS devices. This protocol is a serial peer-to-peer protocol that uses a small data frame to exchange 8 bits of binary data between the two ends.

Because the data frame size is small, the bandwidth delay is minimal. Data integrity is always monitored, and the frames are transmitted continuously, which provides high security and reliability. The typical round-trip times recorded during a commissioning test run at the Borçka HPP substation varied from 16–28 milliseconds, including a 2-millisecond processing delay at the remote end. Thus, the one-way transmission delay is measured to be 7–13 milliseconds. A typical value for bandwidth delay at 19,200 bps is 6.3 milliseconds. The communications controller processing interval, as well as the distance to the remote end location and the number of hops traversed on the SDH/PDH network, are sources of variance in the total transmission delay.

B. Southern Marmara Sea Region SIPS Design

It is important to balance equipment capabilities and contingency actions. Changes in power system topology or overloads in critical system components need to be clearly identified. Because the devices and assets of the Southern Marmara Sea region and the Eastern Black Sea region differ, the systems need to be designed differently. However, they need to have similar functions based on the contingencies and actions identified for the respective regions.

The Southern Marmara Sea region SIPS is installed in the Bandırma TPP 400 kV substation only (see Fig. 3) and consists of primary and standby protective relay-based SIPS controllers. Because of the unavailability of reliable communications channels, no communications equipment or remote I/O modules are used.

The Bandırma TPP SIPS controller implements the previously discussed Functions 1–7 (see Section III, Subsection A) with minor variations and additional functions. Different from the Eastern Black Sea region SIPS controllers, the selection of generator units is performed via a selector switch with three positions indicating the preference for Unit 1, Unit 2, or automatic selection. As discussed in Section II, Subsection C, the unique function of this controller is the rate-of-change of real power detection. This function calculates the ratio of instantaneous real power on the Bandırma-Bursa 400 kV TL to the 25-sample, 5-second average real power on the same line from 1 second prior. If the load flow on the line is above arming levels and this ratio exceeds the set value, the controller takes action.

IV. Closed-Loop Testing Using Real-Time Simulator

A real-time transient simulator model was developed to validate SIPS functionality. The model was based on the electrical configuration of the TEİAŞ power system. The model had the SIPS control systems connected to it to achieve a closed-loop validation of the SIPS systems.

A. Simulation Data

The data required for modeling different power system components (generators, transformers, TLs, distribution lines and cables, loads, and so on) were extracted from a PSS®E model used by TEİAŞ. Where these data were insufficient, the authors made appropriate assumptions based on previous modeling experience. To facilitate network simplification to meet simulator limitations, certain components of the system were combined during model development. The 154 kV underlying network in the TEİAŞ power system was not modeled due to simulator node limitations and was represented as either aggregated load or aggregated generation. The network equivalent was modeled as a synchronous machine at the Kayabaşı and Keban and (Eastern Black Sea region) and Bursa and Soma (Southern Marmara Sea region) substations. Loads were aggregated at the Altınkaya, Çarşamba, Kalkandere, Borçka, Erzurum, Keban, and Karabiga substations.

B. Simulation Results

Factory acceptance testing was conducted to verify the functionality of the SIPSs for various contingencies. Various initiating events were simulated to verify SIPS performance. Examples include contingency line local breaker opening, contingency line remote breaker opening, and contingency line protection tripping under fault conditions. Other response-based triggers, such as df/dt and low-power/low-current conditions, were also simulated and tested.

All of the tests were successfully passed, and they provided valuable insights into system behavior. For each test, the controller actions were verified against the expected GD results. Also, the time-stamped sequential event records for each test provided the total round-trip time from the start of the event to the generator breaker opening. This timing was compared for various initiating events along with the response-based triggers.

V. Testing Analysis and Conclusions

Where response-based SIPSs can be applied, they are preferable to event-based SIPSs because they require little or no telecommunications from outstations to the SIPS controller. In addition, response-based SIPSs do not require major modifications when new assets are added to the system, are simpler, and are conceptually more dependable. For the SIPS in service in the interface with the European system (see Section II, Subsection A), it would be practically infeasible to cover all of the events that may occur in the Turkish system with an event-based SIPS.

Planning of each response-based SIPS requires the identification of the ad hoc detector(s) of the disturbances to be countered, which in Turkey must be quickly detected by the controller. The selected detector(s) are as follows:

- Turkey-ENTSO-E interface SIPS: the 1.5-second averaged derivative of the sum and the sum of three TL power flows.
- Eastern Black Sea region SIPS: the derivative of the transient local frequency increase during 100–120 milliseconds.
- Southern Marmara Sea region SIPS: the ratio between the instantaneous power flow in a TL and the predisturbance power in the same TL.

Lastly, closed-loop testing provides a controlled platform to test various system events and validate all SIPS logic.

VI. Operational Experience

During five years of operation, the SIPS in the interface with the European system (Section II, Subsection A) has acted 26 times, in most cases following a large, sudden generation loss in Turkey (1,000–2,700 MW). These losses were caused by regional operation disturbances where, for the reasons explained in Section I, the N-1 transmission security criterion is not yet complied with. This SIPS has prevented system instability and separation from the ENTSO-E system and has eliminated or drastically reduced the propagation of disturbances to the Balkan countries.

The SIPSs of the Eastern Black Sea and Southern Marmara Sea regions have been in operation since 2014 and have correctly acted many times with successful effects. The GD and power import reduction were tailored to the severity of the disturbances, up to a maximum of 1,000 MW. The control actions occur very quickly (i.e., ≤150 milliseconds including the high-voltage and extra-high-voltage CB trip times, lower than the allowed time of 300 milliseconds). The two regional SIPSs in operation since 2014 have prevented blackouts in their supervised regions and have consequently strongly reduced the sudden loss of generation in the national power system, thus drastically reducing the number of the interventions of the SIPS installed in the interface with the European system.

VII. Conclusion

One of the keys to any SIPS implementation is to be deterministic on the speed of reaction to a system disturbance. Typically, most systems have a maximum allowed time from when the disturbance is detected to the time that the corrective action needs to be put into effect (300 milliseconds for the Eastern Black Sea region and Southern Marmara Sea region SIPSs). To accomplish this, reliable equipment must be used to perform all of the required calculations, make the proper decisions, and take the proper actions within a given amount of time. It is also desirable to have a communications protocol that is reliable and deterministic in the amount of time it takes to bounce a signal from the remote device to the SIPS controller and back [2]. Given the large number of devices and time accuracy required for SIPS operations, a sequential events recorder is vital to understanding and monitoring changing system dynamics and operating conditions.

The power system upgrades and additional generation assets, including the power import associated with the SIPS initiative in Turkey, have increased the power flows on some existing TLs and components. It is important to review the protective relay settings for the TLs in a timely manner, where applicable, to avoid unnecessarily tripping components.

VIII. References

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IX. Biographies

Francesco Iliceto (SM '71; F '85) was born in Padua, Italy, in 1932. He received his doctoral degree, with honors, in electrical engineering in 1956 from Padua University. After nine years of work with two power utilities, in 1965 he joined the faculty of engineering of the University of Rome, where he was responsible for research on applied electrical engineering. After his retirement at the age of 75, he was appointed an emeritus professor. He was a Life Fellow of the IEEE and an Eminent Member of CIGRE. He served as a technical consultant in over 30 countries. From 1968–2016, he was a consultant to the Turkish Electricity Authority. From 1977–2016 he was a consultant to the national Electricity Corporation of Ghana.

His main fields of interest were high-voltage and extra-high-voltage transmission; the analysis, planning, and design of power systems; and rural electrification in developing countries. He developed innovative solutions in the fields of electricity transmission and distribution. He was author or coauthor of many technical papers and the author of five tutorial books.

Özkan Akansel received his B.Sc. degree in electrical and electronics engineering from Fırat University, Elazığ, Turkey, in 1994. He is the manager of the protection systems division at the Turkish Electricity Transmission Company (TEİAŞ). He has worked on the control of expansion projects and high-voltage secondary projects, relay commissioning and testing, and the commissioning of substations for 13 years.

Mevlüt Akdeniz is a network planning engineer at the Turkish Electricity Transmission Company (TEİAŞ). Mevlüt completed a B.S. in electrical engineering at the Middle East Technical University, Ankara, Turkey. He has worked for two years as a junior researcher in the Scientific and Technological Research Council of Turkey (TÜBİTAK).

Süleyman Erikci received his B.Sc. degree in electrical and electronics engineering from Selçuk University, Konya, Turkey, in 2002. He is deputy manager of the protection systems division at the Turkish Electricity Transmission Company (TEİAŞ). He has worked on the installation of substations; control and approval of primary and secondary projects; control of expansion projects and high-voltage secondary projects; commissioning, testing, and maintenance of secondary systems; and commissioning of substations for 11 years.

Yusuf Zafer Korkmaz received his B.Sc. in electrical and electronics engineering from the Middle East Technical University, Ankara, Turkey, in 1995. He worked on protection and control schemes, substation automation and telemetry systems, and generator autosynchronization systems before he joined Schweitzer Engineering Laboratories, Inc. in 2013.

Krishnanjan Gubba Ravikumar received his M.S.E.E. degree from Mississippi State University and his B.S.E.E. from Anna University, India. He is presently working as a supervising engineer in the Schweitzer Engineering Laboratories, Inc. engineering services division, focusing on model power system development and testing for special protection systems. His areas of expertise include real-time modeling and simulation, synchrophasor applications, remedial action schemes, and power electronic applications. He has extensive knowledge of power system controls and renewable distributed generation. He is a member of the IEEE and the Eta Kappa Nu Honor Society.

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