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SPECIAL PROTECTION SCHEME FOR OPERATION OF CENTRAL ZAGREB TRANSMISSION SYSTEM

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Abstract: *The paper presents a Special Protection Scheme solution for the central Zagreb transmission system. The Central Zagreb transmission system is characterized by a highly meshed network with combined overhead and cable sections and a special operation of the 110 kV cable link between two power plants important for the city's heat and electricity supply. The Special Protection Scheme is developed using static and dynamic analyses of different network scenarios. Island operation is simulated for a consumption and generation surplus, and an underfrequency load shedding scheme is determined. The Special Protection Scheme architecture is presented with a brief description of the telecommunication infrastructure.*

Keywords: – special protection scheme
– automated system control
– transmission system
– wide-area measurement system
– island operation

1. INTRODUCTION

Residential areas, especially centers of the large cities, are characterized by highly meshed networks, both transmission and distribution. Government buildings and offices, business blocks, shopping malls, etc. lead to a dense concentration of people and, consequently, high electricity consumption. Additionally, both transmission and distribution networks are combined, consisting of overhead lines and underground cables, which leads to more complicated operating schemes in order to provide a stable and secure electrical energy supply. Power plants that are located in residential areas often provide heating energy besides electricity, which gives even more importance to its stable operation.

In the central Zagreb area operating schemes are even more complicated by the fact that an important underground transmission cable loop, connecting the most important 110 kV substations and two power plants located in the city center, has to be split because of two reasons: the first is an inability to control power flows through the residential transmission network, and the other is the influence of the closed loop on the short circuit current level in that part of the network. The consequence is a radial operation of the major supplying 110 kV substation at one end of the opened loop, and a radial operation of the 100 MW power plant with supplying 110 kV substation at the other end.

The two mentioned power plants have a total rated electrical power of 550 MW and total rated heating power of 1000 MWh. Because of their location, both power plants are ideal for black start and island operation ancillary services provision. That way, in case of severe system disturbances important customers would be supplied with electrical energy, and system restoration would be improved.

The main goal of the Special Protection Scheme (SPS), proposed in the paper, is to improve the reliability of the electrical energy supply in the central Zagreb area. This can be achieved by solving two main issues:

1) Closing of the 110 kV transmission loop to improve service reliability in the city central area by monitoring and mitigating potential overloading issues,
2) Configuring and maintaining service for the central Zagreb grid during major outside system disturbances by the following automatic procedure:
   a. Detecting critical disturbances with security against misoperation,
   b. Forming an operating island,
   c. Balancing island load and local generation.

The objective is to construct a SPS based on anticipated functional requirements developed through system studies and through industry experience with SPSs. The multifunctional system requires a flexible and general architecture based on centralized control and data communications. The SPS must have the flexibility to be programmed with a range of specific algorithms that might be created as study and development continues. Power system operating specifics impact specific SPS calculations and algorithms, but the overall SPS is to have a common and consistent design that can be modified and expanded as needed.

2. SYSTEM OPERATION OVERVIEW

2.1. Transmission system overview

The central Zagreb 110 kV transmission network is presented in Fig. 1. The area of interest for the implementation of SPS is bordered with a blue line. The area comprises two power plants, named ELTO and TETO, and five 110 kV substations. There are two connections that are out of operation in the usual operating regimes, marked in the scheme with dashed lines and red crosses. The described operation is a countermeasure against a high short circuit current level that exceeds the circuit breaker rated current in several 110 kV substations. The direct consequence of such an operation is an opened cable loop between the ELTO and TETO power plants and an opened connection between the eastern and western part of the Zagreb transmission network, due to the split busbars in the TETO power plant.
The network complexity is additionally burdened with different ownership of the facilities. Power plants, together with associated 110 kV substations, are under the ownership of the power production company (PPC). The two 110 kV substations and corresponding transmission lines belong to the distribution system operator (DSO), while three 110 kV substations and corresponding transmission lines belong to the system operator (TSO). The ownership is indicated in Figure 1. Additionally, lower voltage sides of all seven 110 kV substations belong to the DSO. These facts are also important in the creation of the SPS because of the responsibility and controlling ability of the different actors over different parts of the network and facilities. Power system defense strategy, including load shedding and island operation schemes, is a task of the TSO, but implementation and execution is also a task of the DSO and the PPC.

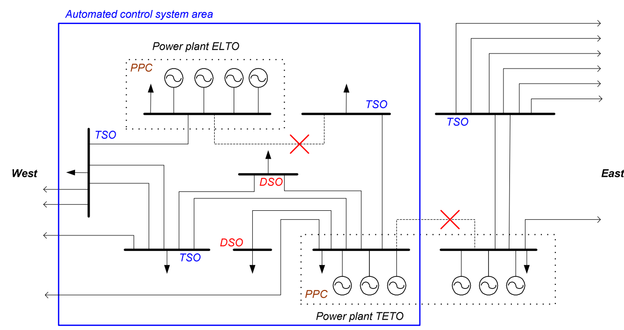

Figure 1. Central Zagreb 110 kV transmission system

The combined heat and power (CHP) power plant TETO is comprised of 6 generating units, three with gas turbines and three with a classic steam turbine. The total electrical power is rated at 450 MW. Distribution load from the plant substation is up to 65 MW. The CHP power plant ELTO consists of two steam units, 32 MW and 12 MW (G1 and G2), and two gas units, 25 MW each (G3 and G4). The distribution load from the plant substation is up to 63 MW. The maximum load of the central Zagreb area is roughly 500 MW.

2.2. Split busbar and opened cable loop operating conditions

The split busbars at TETO normally operate with the tie breaker open to split the station. The system operator assigns specific TETO generating units to the east or west part of the busbars, according to the situation in the network, to avoid fault current duties beyond the ratings of circuit breakers and to control the power flows. The 110 kV cable from ELTO to TETO is normally kept open as shown in Figure 1. Opening the loop avoids unpredictable power flows caused by the relatively low cable impedances compared to the surrounding overhead network. The cable load rating for each of these loop cable paths is 140 MVA. The opened transmission path thus exposes critical central Zagreb loads to outages from a single transmission failure contingency. The first objective of the proposed SPS is to support the safe operation of the system with the transmission cable in service to close the loop and increase reliability. The SPS manages loading issues that can arise due

to certain configurations of TETO generation combined with other transmission outages.
Studies described in Sections 3 show that, for most operating circumstances that are consistent with islanding preparedness, the cable paths should not be overloaded. Furthermore, opening the overloaded cable only (which an overload relay on the cable would do) may protect the cable but is not the optimum action for overall system operating integrity. Therefore, managing the cable loading by other actions such as generator dispatch before protective relays trip the cable on overload is a task for the SPS.

2.3. Islanding operation

In the case of a major outage of the Croatian national grid or beyond, the restoration strategy is to keep the central Zagreb network operating with local generation at TETO and ELTO. The task of an islanding implementation in the proposed SPS is to accomplish the following:

a) Detecting the external emergency for which islanding is required. Measurements can include:
   - Load flow patterns.
   - Frequency or change of frequency at specific locations.
   - Bus voltage magnitude relationships (require information gathered from phasor measurement units (PMU)).
   - Bus voltage angular relationships across the area.
   - Trigger from a specific contingency identified in planning studies, such as loss of a critical 400 kV line external to the central loop area.

The detection algorithm may include multiple-factor authentication of the emergency for high security – it is critical to avoid islanding and associated load shedding for transient recoverable system disturbances. Once a system emergency is detected, the task of the SPS is to form an island with the best achievable balance of load and generation—with small excess load, some of which is then shed to achieve a load-generation balance; or with some excess generation which is reduced by governors.

b) Forming an island

The island comprises the system section presented on Figure 2. If the network topology is standard, then opening of 4 ties secures the island. If the busbars at TETO power plant are not split, opening of three lines tied to the east bus secures the island. There are several islanding possibilities, depending on the network state. As the SPS secures the island, the strategy is to close the bus tie between the split TETO buses and obtain all TETO generation for the island, while immediately disconnecting ties to the east. Formation of islands requires generation and load tracking, balancing calculations, transmission loading calculations, load shedding, and restoration support. While the island operation lasts, the task of the SPS is to constantly balance the island by managing the load, together with generating units' governors action.

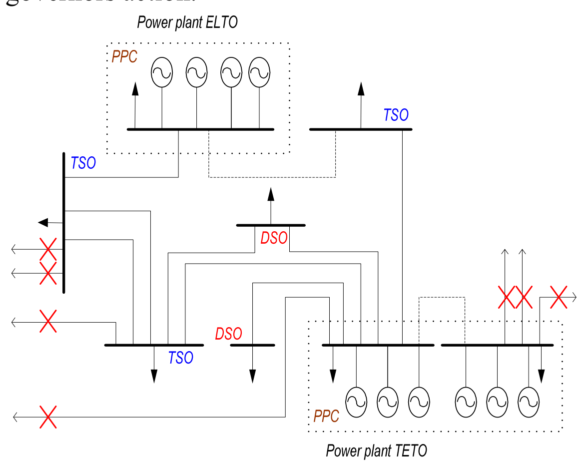

Figure 2. Central Zagreb islanding area

3. SYSTEM ANALYSES

3.1. Static analysis

The power flow and short circuit calculations were carried out in order to determine the SPS concept solution. The power flow calculations of the normal integrated city network operation, with the 110 kV cable TETO-Trpimirova both in operation and outaged, then various TETO and ELTO generation outputs, as well as examples of the lines congestions (criterion N-1 and N-2) were carried out. Different cases of the generation arrangement for two island operation configurations were analyzed (the radial configuration connected with the north cables and the proposed loop configuration, which includes the south overhead lines and substations). The gained results are important for understanding the impact of the issued congestions.
The power flow calculations include examples with the N-1 criterion which could affect the generators arrangement in ELTO, as well as connection of the generators in TETO on the east or west busbar. In some of the analyzed cases, configuration of the

generators in combination with the cables outages (criterion N-1 or N-2) leads to the predicted overloads. The control of these overloads could be based on an on-line security analysis and the appropriate configuration, set by operators. The SPS will be programmed to control the overloads and shedding and/or to rearrange the generators in the case when the cable outage could cause an overload with the sufficient generation during the disturbance conditions. Figure 3. gives the power flow calculation results for the possible closed loop scenario. It was assumed that the parallel lines that connect Jarun and Botinec were outaged due to an overload. As a result, the cable 110 kV TETO-Trpimirova gets overloaded.

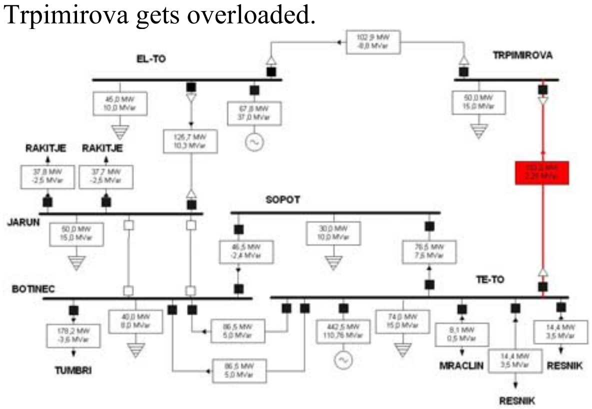

Figure 3. Power flow calculation results for the possible closed loop scenario

3.2. Stability analysis

Stability analyses were carried out in order to determine the behaviour of the generation units during major system faults, including the island operation of an ELTO power plant on local residential consumption. The following network scenarios were simulated and analysed:

a. Determination of ELTO generating units critical fault duration for a nearby three-phase fault,
b. Island operation of ELTO generating units G3 and G4, with consumption surplus,
c. Island operation of ELTO generating units G3 and G4, with generation surplus.

A detailed model of a local network was established for stability analysis purposes, Figure 4.

ELTO generating units critical fault duration time was determined on the basis of a three-phase short-circuit on 110 kV busbars in substation Jarun. The calculated critical fault duration time for all four units is presented in Table 1

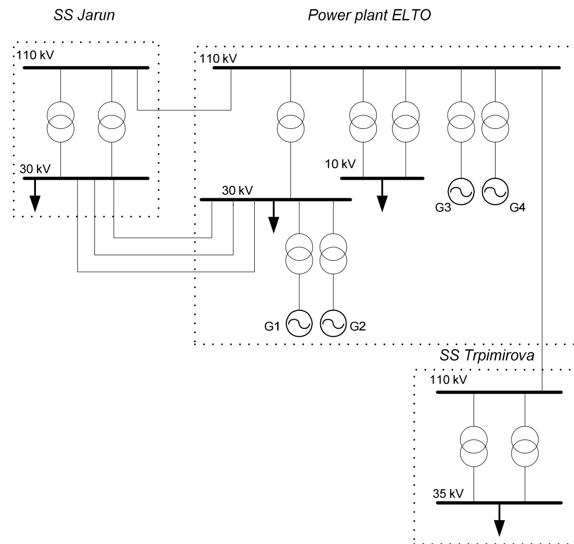

Figure 4. A detailed model of local network

Table 1. ELTO units critical fault duration time

ELTO generating units	Critical fault duration time (ms)
G1, G2	295
G3, G4	254

An angle response of units G1 and G3 due to a three-phase short-circuit fault on 110 kV busbars in substation Jarun, with a duration of Tcr = 160 ms (60ms is the time of circuit breaker activation) is presented in Figure 5.

Island operation of ELTO generating units G3 and G4 with consumption surplus was simulated in the following way: after a three-phase short-circuit on the 110 kV line Jarun – ELTO, with the duration of 160 ms, the fault was cleared by tripping the line. The 30 kV cables between Jarun and ELTO were out of operation for analysis purposes.

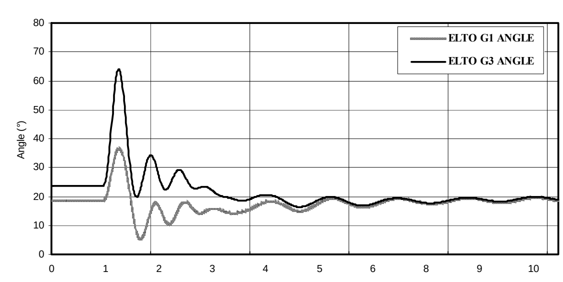

Figure 5. Angle response of units G1 and G3, three-phase short-circuit fault on 110 kV busbars in SS Jarun, Tcr = 160 ms

After line tripping, an island was established, with 46 MW of generation (units G3 and G4) and 74

MW of consumption, including the load in SS Trpimirova that has been connected to the ELTO and disconnected from TETO in this scenario. The generating unit G1, with pre-fault production of 18 MW, was automatically disconnected from the network after islanding due to the inability to work in island operation. After a sudden drop in frequency, the underfrequency load-shedding relays were activated. The load was shedded in three steps. The underfrequency load shedding scheme, designed to support SPS implementation, is given in Table 2.

Table 2. Underfrequency load shedding scheme

Underfrequency real step	I step f=49,2 Hz (MW)	II step f=48,8 Hz (MW)	III step f=48,4 Hz (MW)	IV step f=48,0 Hz (MW)
Percentage of the total load	10	15	15	15

After load-shedding, a balance was reached, with a slight generation surplus. The electrical power production response of units G3 and G4 is shown in Figure 6, while the system and sub-system frequency response is given in Figure 7.

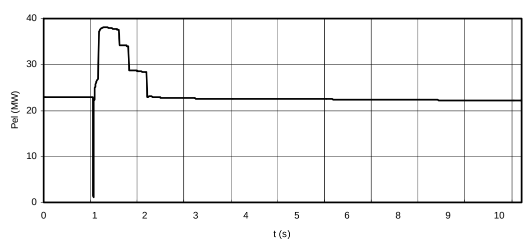

Figure 6. Electrical power production response of units G3 and G4, an islanding scenario with consumption surplus

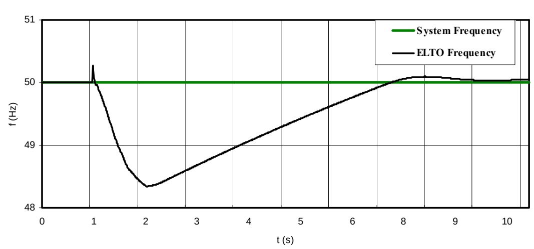

Figure 7. System and sub-system frequency response, an islanding scenario with consumption surplus

Island operation of ELTO generating units G3 and G4 with generation surplus was simulated in the same way as in the previously described scenario. After line tripping of the 110 kV line Jarun – ELTO, an island was established with 46 MW of generation (units G3 and G4) and 32 MW of consumption. The generating unit G1 was automatically disconnected from the network after islanding. After a sudden increase of frequency, gas unit turbine governors reduced the output power in order to decrease the frequency. The electrical power production response of units G3 and G4 is shown on Figure 8, while the system and sub-system frequency response is given in Figure 9.

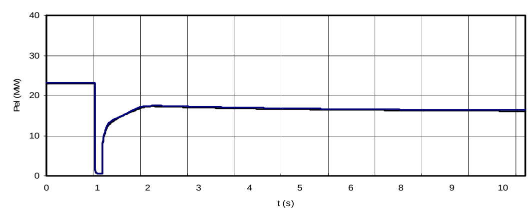

Figure 8. Electrical power production response of units G3 and G4, an islanding scenario with generation surplus

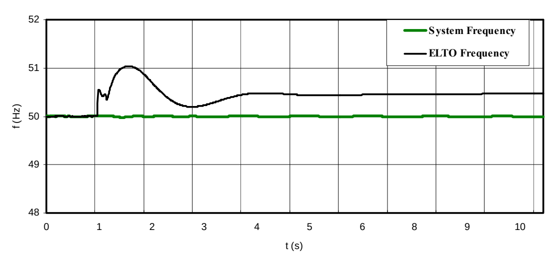

Figure 9. System and sub-system frequency response, an islanding scenario with generation surplus

4. SPS ARHITECTURE

Since the SPS is expected to perform mission critical functions in spite of equipment maintenance or failures, it has to be realized in a dual redundant configuration. The objective of dual redundancy is for the SPS to continue to perform its required functions, with no significant degradation of performance and no loss of data, following the failure of any single SPS component (central controller, relay, or communication circuit). For some components, such as controllers or communications networking connections within a facility, additional redundancy may be designed into each of the two SPS systems. For example, the central controllers in each of the separate systems are sometimes configured as dual redundant or triple redundant to achieve availability and security approaching that of the protective relays in the substations.
The dual redundant system should include the following major components, Figure 10:

- Dual redundant monitoring relays, System A and System B, at each substation in the SPS plan. These relays supply real-time information about transmission system flows, breaker states and operations, and contingencies (fault protection relay operations). Where a large number of values are to be gathered, multiple relays may be required for each of System A and System B.
- Dual redundant programmable central controllers that process information received from the SPS line monitoring relays to determine if any mitigating control actions are needed—System A and System B. Each central controller will be designed to handle the SPS analytics, data historian, external system interfaces, and input conditioning completely independent of the other controller.
- Dual-redundant mitigation relays—System A relays and System B relays, that execute the control actions requested by the SPS central controllers at substations in the SPS plan. These can be the same relays that perform the monitoring.
- Redundant communication links that carry the measurements, status indications, and control commands between the SPS substations and the SPS central controllers.

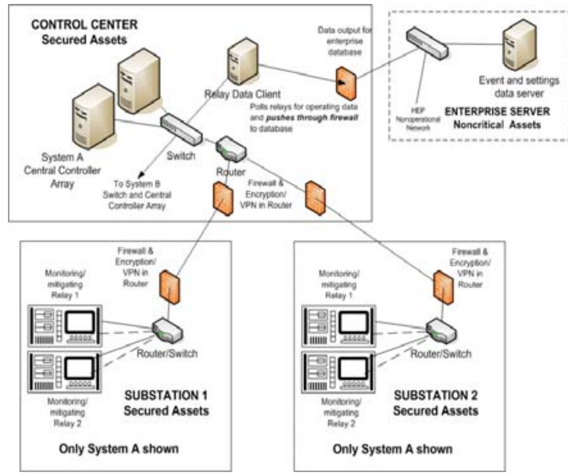

Figure 10. Secure communications architecture

The SPS communication network has to support a wide ETHERNET area (WAN) that will transmit Layer 2 multicast IEC61850 GOOSE messages for high speed measurement and control, and a third level IP-based network with data for system monitoring and control.
The network will be completely redundant and diversified, with two separate paths from each substation to the TSO control centre, without a single point of failure that could negatively influence the multiple redundant components or paths. The realization of all SPS components has to be constantly monitored and failure has to be alarmed. The system has to be immune to “broadcast storms” and malfunctions that are not alarmed, like controller blockade in code loop. All equipment has to support NERC CIP cyber security standards.

4. CONCLUSION

A solution for the Special Protection Scheme of the Transmission System of central Zagreb is presented in the paper. The solution provides more flexible operation of a transmission network, and automatic electrical island forming in the case of severe system disturbance. SPS architecture is described, together with communication network specification. Further system studies have to be focused on network-wide planning scenarios, to identify any specific vulnerability outside the central loop that should be detected or mitigated by the SPS.

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