Static and Dynamic Analysis of Reconnection of Former Two UCTE Synchronous Zones

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Abstract: - Considering the European electric power systems there is a yearly increased consumption of electricity everywhere (from 1% to even 4% in some cases). The processes of developing and connecting existing electric power systems are very complex. Preconditions for connecting two UCTE synchronous zones (1st and 2nd Pan-European synchronous zones) in one European electric power system were created in 2000. The UCTE synchronous zones were formed when the outage of the 400 kV overhead line Ernestinovo – Mladost on September 26, 1991 caused the system to separate. The reconnection was carried out on October 10, 2004 following the important decision which was passed by the UCTE Steering Committee at its meeting in early 2002 in Brussels.

Static and dynamic analysis with respect to reconnection of electric power systems, such as transit analysis, analysis of capacity flows, short circuits, N-1, dynamic behavior, angle analysis, voltage stabilities, frequency oscillations, changes of capacity flows in a short time period, were outlined in the paper. Special attention is paid to the mathematical base significant for carrying out the analysis of conditions in certain electric power system.

Key-Words: - European transmission system, Reconnection, Static and dynamic analysis, Synchronous zone

1 Introduction

The basic aim for creating the common European transmission system was to increase security; i.e. in case of a disturbance the systems will provide mutual support in order to prevent damage which could lead to a system breakdown. It is a known fact that a break-up in electricity supply causes enormous economically negative consequences. According to some analyses, the price or damage caused by one non-delivered kWh reaches up to 50 times higher values. Expanding or increasing tendencies follow the establishment of such a system.

The Union for the Coordination of Production and Transmission of Electricity (UCPTE) was joined by former YU in 1974. This work manner continued until the war in former Yugoslavia, when the outage of the 400 kV overhead line Ernestinovo – Mladost on September 26, 1991 caused the system to separate following the line through Bosnia and Herzegovina therefore creating a second synchronous system to which Romania and Bulgaria were also connected.

The main reason for the (UCPTE) separation was the destruction of the TS Ernestinovo, the key 400/110 kV substation with accompanying lines, during the war aggression against the Republic of Croatia. The accompanying lines were: 400 kV TS Ernestinovo – TS Tumbri, TS Ernestinovo – TS Mladost and TS Ernestinovo – TS Ugljevik overhead lines. In 1992 during the war aggression against Bosnia and Herzegovina, 400/110 kV Mostar substation with accompanying lines was destroyed.

The Lisbon Memorandum of Understanding was signed in Portugal in 2001 [1] between the Union for the Coordination of Transmission of Electricity (UCTE), the national power company of Croatia "Hrvatska elektroprivreda" (HEP), the Joint Power Co-ordination Center (ZEKC) – BIH and Electric Power Industry of Serbia (EPS) – SRJ for the purpose of conducting necessary reconnection activities.

Financing for the construction of necessary infrastructure was provided during 2002. HEP secured a loan from Croatian Bank for

Reconstruction and Development for financing the construction of key transmission facilities: Ernestinovo and Žerjavinec substations with their accompanying lines. ZEKC with its electric power companies- founders (Bosnia and Herzegovina) and the Power III Program financing (World Bank, EBRD, EIB) completed the rehabilitation of Mostar substation and key transmission facilities in August 2004.

The Project Manager of the UCTE reconnection was the UCTE Executive Team. It was in charge of the coordination of all required reconnection activities. The main aim was to prepare the signing and implementation of resynchronization procedures as well as to draft all necessary documentation through the final Multilateral Re-synchronization Program and to conduct the reconnection. The UCTE Steering Committee approved the project realization from the National Dispatch Center on December 10, 2004 (after having agreed on all issues in a meeting held in Sarajevo in late August 2004).

2 Description of the situation prior to reconnection

Electrification of the continental Europe [2] started from smaller areas which were steadily expanding parallel with simultaneous rise and voltage levels. The long history of their interconnection started in 1920s (for exploiting the Alps hydro-energy). It was intensified in 1949, the process which has been undergoing until today. Mesh national networks have grown into cross-border ones in order to increase system security and achieve commercial exchange between (integrated) power utilities. This long process has been monitored by UCPTE from 1951 when it was founded by power utilities representatives from the before-mentioned eight countries. It has also been carried out in accordance with strict technical rules which have gradually been compiled not only for the operation of synchronously interconnected systems but also for the nearly standardized interconnection development process.

In the years to come the UCPTE membership was expanded by representatives from 4 more countries (ex Yugoslavia, Greece, Portugal and Spain) following the years of parallel operation between their systems and UCPTE, while the western part of the Danish system remained only the associate member and the Albanian in parallel operations. During the previous decade UCPTE on several occasions experienced even deeper changes.

During the 1991 aggression against Croatia (and against Bosnia and Herzegovina in 1992), destruction of key substations Ernestinovo (followed by Mostar 4) and parts of 400 kV overhead lines led to the separation of the UCPTE synchronous area into two parts, so-called zones. Soon after, during 1993, the parallel operation of the islanded system of Serbia, Montenegro, Macedonia, Greece and a part of BIH (called 2nd synchronous zone) was joined first by the Romanian and consequently by the Bulgarian systems. This operation was initially called the trial one only to become permanent after having obtained the UCPTE preliminary license in 1995. However, regular testing and trial operation didn't commence until 1997 after setting up the competent UCTE Technical Committee/Bulgaria – Romania and defining an appropriate group of concrete preconditions for accession into the full membership. This procedure is being successfully completed this year only with 2nd synchronous zone although it was originally planned to conduct testing including the entire UCTE synchronous system. Founding of CENTREL in 1992 by power utilities of the Czech Republic, Hungary, Poland and Slovakia, the significant part of former CDO (Central Dispatch Organization) started with intensive technical, organizational and financial preparations in order to fulfill conditions for the synchronous connection with UCPTE, which followed in late 1995 (which caused the expansion of the UCTE synchronous area in the biggest extent so far) so that CENTREL members joined the UCPTE associate membership.

Since the remotest western part of the Ukrainian network around Burštin region is significantly linked with these systems, the procedure for its synchronous connection with UCPTE was set in motion (and formally successfully completed in 2003 following the period of testing and trial operations as well as an affirmative report by the appropriate UCTE-CENTREL/Ukraine Technical Committee).

Radical changes of the European electric power system provoked by the EU Directive 96/92/EC on the common rules for the internal market in electricity [3] have left their mark within UCPTE as well. Amendments to the Articles of Association of 1997 and 1999 introduced, among others, changes in membership (legal instead of physical entities), working language (English instead of French and German) and operational focus (focus on transmission network). The letter 'P' was removed from the name (along with all the activities connected with the generation, which were transferred to EURELECTRIC, a UNIPEDE's successor).

In order to achieve a better adjustment to the changed environment, but also retain the continuity of existing successful performance, the 'old' UCTE was dissolved in May 2001 on its 50th anniversary and the 'new' UCTE was set up by 33 founders from 20 European countries.

Brussels was elected the head office and the new Articles of Association were adopted. This is a process of creating one of the biggest synchronous systems in the world (2004.), which safely and reliably supplies 400 million people with about 2200 TWh per year (13.2% of which are cross-border energy flows i.e. 11.5% taking only those within UCTE under consideration), peak load of 344 GW and 200,000 km of lines with more than 510 GW installed capacity in power plants.

2.1 Review of preparations, organization and reconnection preconditions

The activities relating to the reconnection project commenced after signing the Memorandum of Understanding in Lisbon. After long discussions and meetings, the UCTE Steering Committee founded the Executive Team in Zagreb in 2002 with its fundamental aim to prepare and carry out the project of connecting or electrical linking of then existing two European synchronous zones. Project leaders were representatives of the Croatian and Czechian TSOs.

So-called "DVG Study" made by UCTE under the direction of German power utility represented a good preparatory ground [4]. The main downside of the study was the absence of Ernestinovo substation due to a belief that Croatia would not be able to prepare its network infrastructure for some time in future. Therefore, the plan, according to that study, was the reconnection but not including the Ernestinovo substation and by-passing Croatia. After several meetings and uncertain situations Croatia earned the trust of the UCTE Steering Committee and it was given short deadlines to rehabilitate its system, which meant: the construction of two new 400 kV substations, reconstruction of all accompanying overhead lines as well as the construction of the new ones within the Croatian network topology. The deadline was June 2004.

Terms for the construction and the preparation of the Croatian network were heavily controlled and continuously reported to the UCTE Steering Committee. The project success also depended on the development of infrastructural reconstruction in BIH. Through the Power III Program employees of Bosnian power utility managed to reconstruct 400/110 kV Mostar substation on time as well as accompanying overhead lines 400 kV line Mostar – Sarajevo [5] was a particular problem, but thanks to everybody's dedication what seemed almost impossible was achieved, which represented a significant contribution of BIH experts to this project.

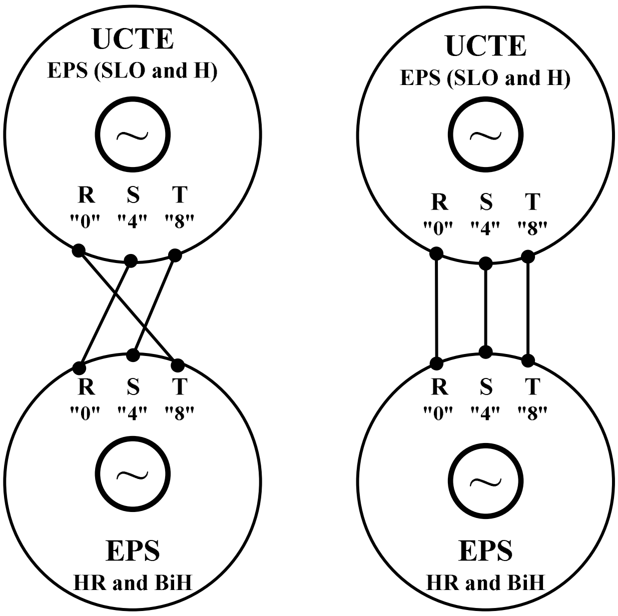
It should be accentuated that the main reconnection precondition was zero exchange of energy on the D day. Organization and regulation hierarchy was set in a manner not to disturb the project implementation.

2.2 Conducting an appropriate physical switch of phase conductors

HEP performed final activities of complex project of harmonizing phase sequences on the Croatian and UCTE electric power system interface on September 2004. HEP carried out detailed and comprehensive preparations and undertook all measures for the successful implementation of such a complex and risky project. Specifically, it was about interfacing systems which encompass all connecting lines between the Croatian, Slovenian and Hungarian electric power systems. To put it more simply, as it is clearly shown in Fig. 1, to harmonize phase sequences on this interface meant to conduct an appropriate physical switch of phase conductors ('transposition') on most favorable points of each connecting line between the Croatian, Slovenian and Hungarian electric power systems. This problem has existed since 1943. For this reason the electric power systems of Croatia and BIH were at one point on that very day in island operation.

3 Analysis

Simultaneousness of production and consumption of electrical energy in electric power system puts demand on continues leveling of the production output and the consumption needs, in terms of amount, time and space. An important feature of electrical energy is that it cannot be stored and has to be entirely consumed immediately upon its production. In case of disparity between the production variations and consumption variations, in case of isolated operation of one system frequency will vary, whereas in case of parallel operation of several systems frequency and exchange power will vary.



LEGEND: EPS − Electric Power System
BIH − Bosnia and Herzegovina
H − Hungary
HR − Croatia
SLO − Slovenia

Fig. 1 The interface between the Croatian and UCTE (Slovenian and Hungarian) electric power systems before (left) and after (right) harmonizing phase sequences

Electric power systems operate synchronously to each other within a major electric power system; frequency and exchange power among them are maintained in accordance with the known regulation principles. In line with the current electric power system development concepts, big generating units in the power plants are used and their size will get even bigger in the future. Exploitation of big production units has certain advantages, but causes problems as well. In operation of a certain large generating unit, it is very important to know how long both static and dynamic stability can be maintained after the unit outage. The another issue, in outage cases, is related to presence of "spinning reserve", i.e. to regular operation of the regulation system frequency – exchange power. As phenomena in frequency – power regulation are quite slow, an appropriate mathematical model for investigation of phenomena can be established, which can refer both to single system elements, as well as to the whole system. Theory of small oscillations [6] can be applied.

3.1 Basic stability considerations

The experiences related to connecting of electrical power systems indicate that the major stability issue was oscillation [7] of frequency values in range from 0.1 Hz to 0.5 Hz The oscillations can take several minutes and cause system breakdown.

The oscillations are considered mechanical [8]; they can be approximately analyzed by means of an appropriate linear model. Moment and speed are considered phasors during periodic oscillations.

Linearized equation referring to movement of the generating unit rotor is as follows:

$$M\Delta\omega + D\Delta\omega = \Delta T_m - \Delta T_e \tag{1}$$

Where are:

$M\Delta\omega$ – moment of acceleration,
$D\Delta\omega$ – mechanical attenuation moment,
ΔT_m – input mechanical moment (moment of driving unit),
ΔT_e – output electrical moment (synchronous generator electromagnetic moment),
$\Delta\omega$ – $\frac{d(\Delta\omega)}{dt}$.

The stated designations refer to unit values. The other parameters are: rotation speed ω (in p.u.), inertion constant M (s), mechanical attenuation coefficient D (in p.u.) and time t (s).

The rotor rotation speed ω is converted into p.u. units, by means of the following equations:

$$\omega = \frac{1}{\omega_b}\frac{d\delta}{dt}; \qquad \Delta\,\omega = \frac{1}{\omega_b}\frac{d\Delta\delta}{dt} \tag{2}$$

Where are:

ω_b – reference synchronous rotation speed,
δ – rotating moment angle in el. radians.

As mechanical attenuation of machines in big electric power systems is negligibly low in comparison with the one needed for attenuation of oscillations inside the system, $D\Delta\omega$ can be disregarded. Due to inertia of turbine regulator, it is taken $\Delta T_m = 0$, therefore only electromagnetic moment has a synchronous component which is designated $K_1\Delta\delta$.

The equation (2) in a frequency range is as follows:

$$(M_s^2 + K_1\omega_b) = 0, \qquad \Delta\omega = s\frac{\Delta\omega}{\omega_b} \tag{3}$$

The solution providing non-attenuated original mechanical frequency is:

$$s = \pm j\omega_n; \qquad \omega_n = \sqrt{\frac{K_1\omega_b}{M}} \tag{4}$$

It is to note that $\Delta\omega$ is in p.u., whereas ω_n and ω_b are in radians/s. K_1 is within the range from 0.5 to 1, M is within the range from 5 to 10, ω_n is order of magnitude $\sqrt{0.2\pi f}$ rad/s, whereas f_n is order of magnitude $\frac{\omega_n}{2\pi}$ (Hz).

Definitions of stability had been changed throughout the written sources, until two of them got widely accepted: transient stability in case of major disturbances and static stability in case of minor disturbances. But, regardless of stability definition, sometimes it is very difficult to determine which disturbances are major and which are minor ones, as it is dependent on stability control capability as well.

Stability can be analyzed using mathematical definition of static field. Static field does not alter with time. If strictly considered, there is no electromagnetic field which does not vary with time. There is a general tendency to bring all calculations to linear and static, i.e. to stable ones. Time variability is established according to certain parameter of reference. Let's consider that voltage and current vary harmonically over time, as per sinus law, at frequency of 50 Hz. The values and their effects, i.e. field, will undergo phase change by 180° in one-hundredth of second.

Phase variation of 5° can be considered negligile. It refers to time of $2.8\cdot10^{-4}$ s. Therefore, if the values are monitored in so short time period, their variability will not be technically determined. The observer has selected that reference time; each phenomenon is static to observer if the variation, e.g. by 1%, is observed in reference time. Electromagnetic phenomena spread by speed of light, i.e. $3\cdot10^{5}$ km/s. Within the time of $2.8\cdot10^{-4}$ s the mentioned phenomenon will spread to the distance of 80 km.

Approach to definition of stability varies throughout the references, particulary it refers to difference between static and dynamic phenomena. These phenomena often overlap; in most references as well as in UCTE Operation Handbook [9], stability [10], is defined and categorized as follows:

Static stability – refers to stability related to small and incremental load variations, the system maintains stability with conventional excitation and regulation, in terms of synchronous generators in power plants.

Dynamic stability – refers to stability related to relatively small and sudden load variations; in these terms, the system can be described by means of linear differential equations and can be stabilized using so called linear and continuous additional stability supervision. A typical example are low-frequency oscillations of extensive electric power systems and torsion oscillations of the turbogenerating unit in case of subsynchronous resonancy of transmission lines with capacitive compensation.

Transient stability – refers to stability of electric power system exposed to sudden and hazardous disturbances which exceed capacities of linear and continuous additional stability regulators. The system can "lose" stability at its first swinging, particulary if no effective protection was used. For analysis of transient stability and determining the regulaton, the system must be described by means of non-linear differential equations.

Non-linear stability – is a mathematical notion referring to a general stability matter in technical field, it is not closely related to electric power system only. The system shall be described by means of non-linear equations, but not necessarily be means of non-linear differential equations. Analysis of static stability using equal-area criterion and analysis of transient stability by means of Lyapun's direct method [11] are often applied in research of non-linear stability.

Stability of electric power system is a system capability, with a given state at the operation start, to return to a regular balanced state exposing the system to disturbance.

Stability is a balance state of the opposed powers; instability arises in case when disturbance leads to permanent instability between the opposed sides.

The electric power system is an exceptionally non-linear system which acts in a permanently variable environment; loading, generator outage, topology and key operation parameters vary continuously. When exposed to transient disturbance, the system stability depends on the disturbance type as well as on the operation start state.

Disturbance [12], (cause of instability) can be: minor or major. Minor disturbances referring to load variation happen continuously, the system adapts to the variable conditions. The system shall operate in satisfactory manner and successfully fulfill the demand in these circumstances. Also, it must withstand numerous major disturbances like short circuit in the power-transmission line or outage of a big production unit. After transient disturbance, if the electric power system is stable, it will reach the new balance state while keeping its integrity; automatic control and possible human factor in control will finally bring the system back into the normal state.

On the other side, if the system is unstable, the system runaway or its wear-out will happen; e.g. progressive increase of the generator rotor angle divergence or progressive decrease of the busbar voltage. An unstable system can cause cascade outages and interruptions in operation of the major part of the electric power system.

Response of electric power system to disturbances can influence various equipment; e.g. failure of critical element along with the protective relay operation will cause variation of energy flows, network busbar voltage and rotor speed; voltage variation will excite voltage regulators in the transmission network generators; variation of generator speed will excite primary actuators, whereas voltage and frequency variations will influence the system load different ways, depending on their individual properties.

Furthermore, the equipment used for protection of certain devices can respond to variation of system variables and that way affect operation of the electric power system. A typical up-to-date electric power system is therefore a highly multi-variable process whose operation is affected by numerous devices of different response rates and properties. The electric power system can be brought to instability due to different causes, depending on system topology, type of operation and disturbance.

The stability matter has been always related to maintenance of synchronous operation. As electric power systems rely on synchronous equipments for production of electrical energy, an indispensable prerequisite to assure satisfactory system operation is that all synchronous devices keep in step. This stability aspect is affected by the generator rotor angle dynamics and by the energy angle.

Instability can happen even if there is no loss of synchronism. E.g. the system consisting of a generator which drives an induction motor can become unstable due to the load voltage drop. In that case, the issue is stability and voltage regulation, but not keeping the synchronism. This type of instability can also happen in case of load involving a wide area within a big system.

If discrepancy between load and production is big, generators and regulators of primary actuator become significant, as well as system regulator and special protection regulators. If not properly coordinated, the system frequency can become unstable, whereas the generating units do not follow the load, which results by interruption of system operation (breakdown). It is one more case whereby the units can stay synchronized (unless their operation is enabled by means of protections, e.g. subfrequent) and the system gets unstable.

Because of huge scope and complexity of the stability issues, the simplified prerequisites must be considered, specific issues must be analyzed, thereby using appropriate number of the system presentation details.

3.2 Basic and progressive mathematic model for analysis of dynamics

Operation of all electric power systems is obligatorily planned one day ahead (D+1). Among other things, operation of the medium-loaded production is defined, as well as amount and source of regulating power. Depending on planned function and technical possibilities, certain power plants can be basically divided into three groups:

1) power plants with limited aperture for supply of driving machine (turbine) with operating medium,
2) power plants with so called "free regulators" participating primary regulation frequency regulation and,
3) backup power plants whose output is significantly influenced by a network (secondary) regulator.

Mathematic model of certain components in the system has proved quite complex structure of those components; therefore, in order to make (allowed) simplifications, there are certain prerequisites and disregards to start from:

- regulating of the generator excitator and reactive power will not be taken into consideration,
- rapid electromagnetic phenomena on electric lines, as well as initial and transient phenomena in generators will be disregarded,
- only electromechanical transient phenomena in generators will be taken into consideration (mechanical transient phenomena in turbine regulating devices including driving units – turbines will be disregarded),
- operation of the network (secondary) regulator will be taken into consideration,
- dynamic stability of the system, i.e. of particular generators will have lower significance compared to phenomena in regulation frequency-exchange power of the electric power system.

Mathematical model has a prerequisite of one frequency in a whole system, which means that single swings of rotors of the electrical generating units are disregarded. For each electrical generating unit *n*, in certain system *m*, the following swing equation can be established:

$$T_{mmn} = \frac{d(\Delta f)}{dt} = \frac{f_n}{S_{Gmn}}\left(\Delta P_{Tmn} - \Delta P_{Gmn}\right) \qquad (5)$$

Where are:

T_{mmn} – mechanic time constant of the generating unit n in the system m (s),
Δf – minor frequency variation (Hz),
f_n – rating system frequency (Hz),
S_{Gmn} – rating power of the generating unit n in the system m (Hz),
ΔP_{Tmn} – minor variation of the driving unit mechanical power (MW),
ΔP_{Gmn} – minor variation of the generator electric power (MW).

In solving this matter, it is suitable to use appropriate equivalent model for all electrical generating units in one system, which is possible within the linearization procedure. In that case, certain simplifications shall be introduced.

Firstly, there is no need to establish an exact model comprising the turbine regulating devices, water feeding equipment at the water turbines, as well as an exact model of steam generators at the thermal power plants. Research has shown that the phenomena related to driving units and their regulating devices can be described by means of the following differential equation:

$$T_{Rm\delta 1} \cdot T_{RmP_r} \frac{d^2(\Delta P_{Tm})}{dt^2} + \\ + \left(T_{Rm\delta 1} + T_{RmP_r}\right) \frac{d(\Delta P_{Tm})}{dt} + \Delta P_{Tm} \\ = \left(\Delta P_{UNPm} - K_{Tm}\Delta f\right) + \\ + \frac{d}{dt}\left(T_{Rm\delta 1}\Delta P_{UNm} - T_{RmP_r} K_{Tm}\Delta f\right) \qquad (6)$$

Where are:

$T_{Rm\delta 1}$ – regulating member time constant, taking frequency variations into account (s),
T_{RmP_r} – regulating member time constant, taking adjustment of the target turbine power value into account (s),
ΔP_{UNPm} – summarized adjustments of the target power values at all turbine regulators (MW),
K_{Tm} – regulating energy of the system m (MW/Hz).

In the process of automatic secondary regulation frequency – power, one of control parameters involving the turbine regulation system in the backup power plant is provided by the secondary regulator which, at an overall level, can be performed as a PID regulator with the following differential equations:

$$T_{RM} = \frac{d\left(\Delta P_{UNPm}\right)}{dt}$$

$$T_{RM} = -\left(\Delta P_{Rm} + K_{Rm} \cdot \Delta f + D_m + \frac{d(\Delta f)}{dt}\right)$$

$$-T_{RM} \cdot p_m \frac{d}{dt}\left(\Delta P_{Rm} + K_{Rm} \cdot \Delta f + D_m + \frac{d(\Delta f)}{dt}\right) \quad (7)$$

Where are:

T_{RM} – time constant, adjusted at the regulator (s),
ΔP_{Rm} – minor variation of exchange power in the system m (MW),
K_{Rm} – regulating energy adjusted at the regulator (MW/Hz),
p_m – P – member of the regulator,
D_m – D – member of the regulator.

In order to take into account all electrical generating units in the system m, it is to start from the following equations:

$$S_{Nm} = \sum_{n \in \phi} S_{Gmn} \qquad (8)$$

$$T_{mm} = \frac{\sum_{n \in \phi} T_{mmn} S}{S_{Nm}} \qquad (9)$$

$$T_{mm} = \frac{d(\Delta f)}{dt} = \frac{f_n}{S_{Nm}}\left(\sum_{n \in \phi} P_{Tmn} - \sum_{n \in \phi} P_{Gmn}\right) \qquad (10)$$

For each system m, an additional equation (11) can be established, which presents relation between minor loading variations ΔP_{OPTm}, minor variations of generator power and of exchange power ΔP_{Rm}.

$$\sum_{n \in \phi} \Delta P_{Gmn} = \Delta P_{OPTm} + \Delta P_{Rm} \qquad (11)$$

Minor variations of mechanical power of all driving machines n in the system m can be presented as:

$$\sum_{n \in \phi} \Delta P_{Tmn} = \Delta P_{Rm} \qquad (12)$$

Further to the preceding equations, the following swing equation can be obtained:

$$T_{mm} = \frac{d(\Delta f)}{dt} = \frac{f_n}{S_{Nm}}\left(\Delta P_{Tmn} - \Delta P_{OPTm} - \Delta P_{Rm}\right) \qquad (13)$$

In case N systems operate parallel to each other, then, besides N equations (13), the below power balance equation shall be established:

$$\sum_{m=1}^{n} \Delta P_{Rm} = 0 \tag{14}$$

Based on (N+1) equations (13) and equation (14), the values of $\Delta P_{R1},\ldots,\Delta P_{Rn}$ and Δf are obtained. If the equation (15) is established for total power of generating units in all systems S_N, the equation (16) for the average mechanical time constant T_m and coefficient γ_m in accordance with (17), an independent equations' system (18) is obtained.

$$S_N = \sum_{m=1}^{n} S_{Nm} \tag{15}$$

$$T_m = \frac{\sum_{m=1}^{n} S_{Nm}}{S_N} \tag{16}$$

$$\gamma_m = \frac{T_{mm} S_{Nm}}{S_N} \tag{17}$$

$$T_m = \frac{d(\Delta f)}{dt} = \frac{f_n}{S_N}\left(\sum_{m=1}^{N} \Delta P_{Tm} - \sum_{m=1}^{N} \Delta P_{OPTm}\right) \tag{18}$$

$$\Delta P_{Rm} = \left(\Delta P_{Tm} - \Delta P_{OPTm}\right) - \gamma_m \left(\sum_{m=1}^{N} \Delta P_{Tm} - \sum_{m=1}^{N} \Delta P_{OPTm}\right) \tag{19}$$

The equations (18), (6) and (7) constitute a mathematic model which can be used for performing the phenomena analysis in one of electric power systems operating synchronously, as well as in case of outage of major generating units during the secondary regulation process frequency – exchange power.

3.3 Static and dynamic analysis

Transit analysis and the analysis of capacity flows, short circuits and N-1 were conducted within the DVG study but, as before mentioned, the project was carried out without the Ernestinovo substation so that results were only partially applicable. Therefore, analyses with domestic experts who succeeded in analytical presentation of key analysis that showed the possibility of reconnection with the ever present risk were carried out. Programs that were used were DAM from the Faculty of Electrical Engineering and Computing and PSS/E. Several models were developed depending on the expected network configuration, hydrological conditions and expected project realization date.

It was extremely difficult to decide which model is acceptable, the risk was huge. Empirical data and opinions by most experts were to start with the implementation on a significant condition to stop trading on that day i.e. to stop electricity exchange between TSOs in the reconnection.

Dynamic behaviour; angle analysis, voltage stabilities, frequency oscillations, changes of capacity flows in a short time period were analitically observed using several software programs during the preparation itself, but mostly during the DVG study.

During the reconnection the dynamic behaviour was observed by monitoring the response of the above stated parametres using the installed state-of-the-art WAMS (wide area monitoring system) equipment in several junction points in Switzerland, Croatia and Greece. ETRANS, the Swiss operator, helped significantly. Interarea electromechanical and frequency oscillations were observed. However, the system was maintained in a matter of few minutes and by further connection on lower 220 kV and 110 kV voltage levels reached the stability zone.

4 Performance of reconnection

The key steps of the reconnection [13] are shown in Table 1.

The sequence of connecting interconnection lines is shown in Fig. 2.

As no problems in system operation were observed by TSOs involved in the process during the test run commencing on October 31 2004, the test run, which was not approved for commercial contracts between former 1st and 2nd UCTE synchronous zone, was rated successful. For the period between November 1 2004 and the end of 2004, UCTE issued the recommendation regarding the gradual increase of trade volume directed from the former 2nd UCTE zone towards the former 1st UCTE zone (monthly increase by 30% to complete NTC values).

5 Post-reconnection analysis

In general, the operation of interconnected electric power systems enhances technical possibilities required for safe system operation by using increased flexibility of the regulation connected system by interlinked (interconnected) lines. In more accurate terms, the parallel connection of two or more electric power systems achieves a bigger stability and operational availability of connected systems.

Table 1 The key steps of the reconnection on October 10, 2004

Time/ command	**Key steps**
Preparation.	All interconnecting overhead lines ready for operational use and idle.
The command to Bucurest.	To take over the frequency regulation in 2nd synchronous zone (Romania regulates the frequency, Greece, Bulgaria and EKC only the exchange).
The command to Budapest.	To discontinue the pluralistic CENTREL regulation and to assume the regulation by itself.
9:34	After fulfilling conditions $\Delta U<$ 20kV; $\alpha< 10°$; 0.03 Hz < $f_{II} - f_{I}$ < 0.05 Hz in Arad substation, Sandorfalva overhead line was connected (RESYNCHRONIZATION was carried out).
9:41	Subotica overhead line connected to Sandorfalva substation.
9:48	Command to all synchronous zone block 2 controllers to restore the LFC regulation mode.
9:58	Podgorica overhead line connected to Trebinje substation. Prior to the resynchronization, this overhead line had the biggest voltage difference (over 60 kV) which activated all compensation equipment in Croatia, the operating compensation generator in BIH was CHE Čapljina, and in Montenegro the aluminum factory was put out of operation for a few minutes in order to raise voltage.
10:07	Rosiori overhead line connected to Mukačevo substation.
10:20	Mladost overhead line connected to Ernestinovo substation.
10:58	220 kV Trebinje - Peručica, 220 kV Višegrad - Požega and 110 kV Trebinje - H. Novi overhead lines connected.
11:00	Main coordinators announced the successful completion of the reconnection.

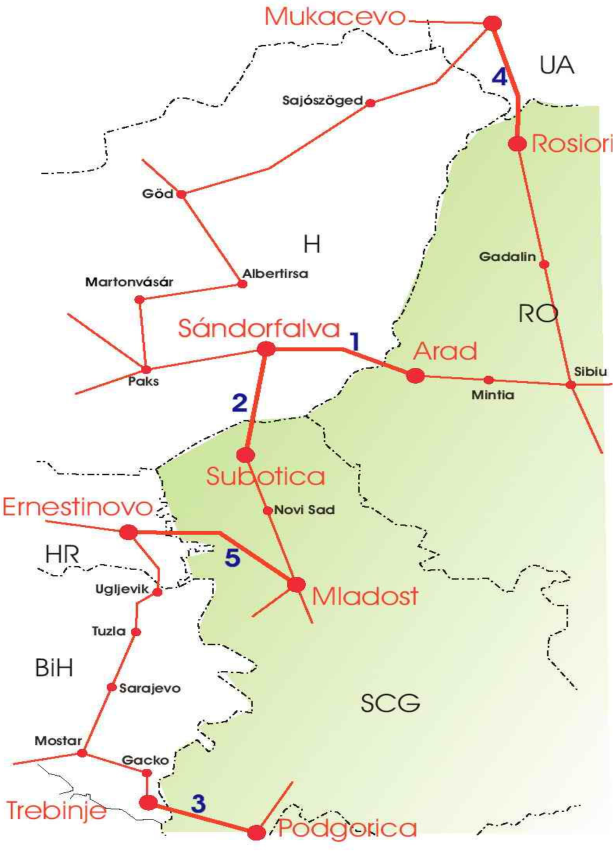


Fig. 2 The sequence of connecting interconnection lines

For executing such a task previous theoretical and experimental research is required, which is to show the manner in which each system individually and jointly as a whole will dynamically behave during parallel connection.

The control centers Laufenburg (Switzerland) and Brauwieller (Germany) conducted the first UCTE synchronous zone. The Croatian electric power system was coordinated from the Laufenburg coordination center. The second synchronous zone was, apart from connected countries, joined by Romania and Bulgaria. The process of UCTE reconnection was graded a high-risk because it was the first time the two big synchronous systems were connected, lacking similar prior experience and threatened by both systems' complete breakdown. The Executive Team, founded by the UCTE Steering Committee's decision, was given a task to prepare and carry out the reconnection of the UCTE synchronous zones. Following 2-year-long preparations the reconnection was successfully led and conducted from the National Dispatch Center in Zagreb on October 10, 2004 with the participation of all key transmission system operators. From the technical and economic point of view, the huge contribution of the reconnection to increased security of the UCTE system, increased electricity trading volume, electricity market opening and stimulating further development of internal EU electricity market was observed. TSOs are service providers for all market participants and as such significantly contribute to the development of electricity market preserving safety restrictions.

Since the reconnection enlarged the entire UCTE system, inter area oscillation in the connected UCTE system was expected and supported by measurement results. The reconnection has also created preconditions for enabling the remote-distance electricity trade via the integrated ITC (inter TSO compensation) mechanism. The rise in the total electricity trading volume also resulted in a gradual increase of trading schedules by TSOs in order to secure a continual safe system operation.

5.1 Positive effects for the Croatian electric power system

In broad terms, positive technical effects for the Croatian electric power system are the following:

- increased electricity transmission,
- improved voltage conditions,
- decreased share of technical losses in electricity transmission.
- increased reliability of electricity supply to customers (more supply routes, availability of the entire 400 kV network ...), and
- increased system security and disturbance resistance.

Positive economic effects of the Croatian electric power system can also be identified:

- doubled total cross-border electricity trading volume in Croatia (import, export, transit),
- increased revenues and savings for several reasons (e.g. due to decreased technical losses achieved savings of about 1/5 of investment in a reconstructed 400/110 kV Ernestinovo substation), and
- the need (and costs) for the reactive power compensation in the Croatian transmission network for the purpose of improving total voltage conditions was reduced after the reconnection.

Furthermore, need for additional generation of reactive power was decreased as well as the need to invest into compensation equipment. Insulation stress in HV facilities was decreased due to an improvement of voltage conditions with a positive long-term effect regarding the expected equipment life time which lessened the congestion possibilities on cross-border lines by redistributing incoming electricity flows into the Croatian electric power system onto reconnection connected lines. Total net transmission capacity (NTC) on the interface has been increased by approximately 500 MW, which enabled the electricity trading intensification. Circular flows from Hungary towards Slovenia have remained almost unchanged. New circular flows between Serbia, Croatia and BIH have appeared.

Summarizing, positive reconnection effects (both technical and economic) for the Croatian electric power system that are outlined in this paper can be expanded in broad terms onto the connected UCTE system.

6 Conclusion

The electric power system of each area is a very complex dynamic system in technical terms which can be faced with one of the following states: stationary (normal) operating state, transient operating state, emergency operating state or outage.

The results of reconnection of former two UCTE synchronous zones carried out on October 10, 2004 are extremely positive and affirmative. In general, the positive effects are the following:

1) Technical effects;

- the frequency stability (reduced number and quantity of frequency deviation) was increased in the connected UCTE system,
- the compulsory primary reserve in accordance with the UCTE rules was decreased,
- the required value of the regulation constant (Kr) was reduced, and
- emergency support by neighboring TSOs in case of an outage was increased.

2) Economic effects;

- increased capability of operational optimization with reduced total costs,
- increased total electricity trading volume (access to cheap surplus in the former 2nd UCTE zone), and
- the contribution to the development of the regional electricity market (REM) and Internal Electricity Market (EU IEM).

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