Causes, analyses and countermeasures with respect to blackout in Croatia on January 12, 2003

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Abstract – Causes, analyses and countermeasures of the blackout that happened on January 12, 2003 in southern part of Croatia (HR) and Bosnia Herzegovina (BH) are presented here. First, root causes and consequences of the blackout are recognized through data analysis based on all relevant documentation obtained from different sources within HR and BH systems. Then, numerical analysis is conducted to provide additional insight during blackout evolution. Analytical findings are used to point out on available countermeasures aimed for alleviation of consequences in each of different blackout phases as well as for prevention of future incidents. A set of countermeasures is proposed to the utilities in order to prevent its reoccurrence. Role of system operators and special protection system (SPS) during chronological sequence of the blackout events are discussed in more details.

Index Terms – blackout, cascading outages, voltage collapse, short circuit, breaker malfunction, system operators

I. INTRODUCTION

Power systems in Croatia and Bosnia Herzegovina are seriously damaged due to war atrocities in previous decade. To large extent they fall outside of infrastructural planning criteria. Their operational performances have therefore deteriorated. Almost every bad weather situation during winter peak loading conditions makes security risks highly increased with respect to interconnected transmission systems. In such conditions during January 2003, the incident appeared with final consequence of widespread regional blackout and localized interruption of customer supply [1]. It represents a series of severe disturbances and faults which caused cascade outages of system elements.

Root causes and consequences of this blackout are numerous and serious. They point out to the need for better coordination of interconnected systems operation. This includes not only dynamic behavior of the HR system, but the BH one as well due to a fact that they make a common electromechanical unit [2]. Concerning transient phenomena that are uncontrollably spread over both systems, it is necessary to treat this blackout as impetus towards enhancement of security level at which these systems are operated [3]. System security has emerged as one of basic problems, especially with regard to expected UCTE reconnection which will be realized mainly over these two systems. This work is primarily orientated towards recognition of needs for conducting combined type of blackout analysis; data and numerical [4]. Blackouts serve as sources to learn lessons and apply countermeasures to prevent reoccurrence of similar incidents [5-6].

Numerous technical aspects of the blackout that happened on January 12, 2003 are analyzed in [1]. That project study contains results of data analysis of the blackout sequence followed by static and dynamic numerical approach. It is applied in order to mutually relate findings. The blackout was confined to southern part of Croatia (called Dalmatia) and a part of Bosnia Herzegovina which was at that time connected to the first UCTE synchronous zone. Root causes, consequences and countermeasures are analyzed in detail with respect to all relevant events recorded in collected documentation. The role of the system operators and the activation of the special protection system (SPS) during chronological sequence of the blackout events are discussed in more details.

The role of the system operators is primarily analyzed on the basis of collected chronological event listings and real-time recorded responses by relays concerned. The analysis contains security estimation of the initial steady-state to show awareness and preparedness of the system operators to deteriorated system conditions. Analytical findings are used to point out to available countermeasures aimed for alleviation of consequences in state restoration phase. Advantages that are made by installation and proper coordination of the special protection system (SPS) are recognized as well. The SPS is installed at the northern 220 kV link between HR and BH systems (OHL 220 kV Dakovo – TPP Tuzla). It primarily serves for controlled separation of the HR and BH systems upon detection of potentially unstable local voltage magnitudes in the north-eastern part of Croatia (called Slavonia). The SPS is coordinated with undervoltage load shedding in Slavonian load buses. By activation of this system, a classical voltage collapse scenario was avoided in Slavonia due to the blackout in Dalmatia and BH.

Blackout analysis is based on all relevant documentation obtained from different sources within HR and BH systems. The blackout is first analyzed on the basis of collected chronological event listings and real-time recorded responses by relays concerned. Then, static and dynamic computer model is established based on the system state that was exercised before the incident. Chronological sequence of events during blackout evolution is set on the basis of chronological listings and relay recordings in order to conduct numerical analysis. The analysis contains security estimation of the initial steady-state and system trajectory in time-domain [7]. It significantly contributes to recognition of root causes and consequences during blackout evolution. Analytical findings are used to point out on available countermeasures aimed for alleviation of consequences in each of different blackout phases as well as for prevention of future incidents.
II. SYSTEM CHARACTERISTICS

In order to recognize the system state before the blackout, the general transmission network configuration is shown depicting severed southern area around bus Velebit 400 kV that was hit by weather storms (Fig. 1).

![Fig. 1 General network configuration of the HR system](image)

Network state is endangered not only in the HR system, but in the BH one as well, due to insufficiently recovered war damages in previous decade. In 2004, the 110 kV/220 kV/400 kV transmission network of Croatian Power Utility will be completely reconstructed and reinforced. Moreover, the BH network is supposed to be reconstructed at 220 kV and 400 kV levels. This will make sufficient infrastructural preconditions for the UCTE reconnection that will be mainly realized over these two systems.

In the first half of January 2003, the HR system suffered from serious damages along the southern power interconnection (OHLs 400 kV Meline – Velebit – Konjsko and OHLs 220 kV Meline – Senj – Brinje – Konjsko). Supply of electrical energy was significantly severed due to bad weather conditions in wider Adriatic area and especially in its southern part of Dalmatia. Bad supply conditions are even further deteriorated due to low ambient temperatures, snow/wind storms, and frequent line outages caused by automatic reclosing. Along the southern power interconnection, lines at 400 kV and 220 kV voltage levels represent the only links with firm transit capability between cities of Rijeka and Split. Without them, existing 110 kV network is not capable to assure sufficient quality of regional interconnection at transmission level and keep local consumers supplied.

Because of extremely bad weather situation followed by high winds, low temperatures, icing rain and snow, due to various fault reasons 7 transmission lines were out of operation in Dalmatia before the blackout (Fig. 2). At the southern interconnection, 400 kV and 220 kV voltage levels were outaged. From one side, Dalmatia was connected to the BH system over OHLs 220 kV Zakuca – Mostar, DAV 220 kV Konjsko – Mostar, and further through the BH system over OHL 220 kV Dakovo – TPP Tuzla (northern link) to north-eastern part of the HR system (Slavonia). From the other side, Dalmatia was connected to the north-western part of the HR system over 110 kV island link Rab – Novalja – Pag – Nin. The island link has a limited transmission capability which does not enable larger regional power exchanges.

In the southern part, the (N-1) criterion aimed for the system security estimation may be fulfilled depending on loading level of OHL 400 kV Melina – Velebit – Konjsko. Its outage influences system security in Croatia. Fulfillment of the criterion depends on schedule of generating units in Dalmatia and availability of rotational reserve. If the line is outaged at its loading level larger than 200 MW (empirical data related to steady-state conditions of minimal engagement of generating plants in Dalmatia), the loading power is dominantly redistributed over OHL 220 kV Brinje – Konjsko. Afterwards, it also becomes jeopardized due to possible thermal overloading. If there is a sufficient amount of rotational reserve, the system operator can prevent cascading outages along the southern interconnection conditioned that its increased awareness is duly enforced during such period. Certainly, this action of the system operator is realizable provided that various protection systems have not reacted faster and caused cascading outages in wider region. Generally, fulfillment of the (N-1) security criterion is not an issue with appropriate operation of generating units in HPP Zakuca and HPP Velebit.

The island link is less significant for the southern interconnection due to small maximum power throughput. It becomes more significant when consume supply is to be restored after the incident. Then, Dalmatian HPPs need outsourced voltage for starting-up purposes. Upon breaking up of the southern interconnection at 400 kV and 220 kV voltage levels, operation of the island link at 110 kV level may be viable provided balanced power exchange between different regions concerned. Balanced operation is achieved by coordinated schedule of generating plants. However, this is not quite simple to fulfill in longer time period.

Outages of OHL 400 kV Melina – Velebit – Konjsko and OHL 220 kV Brinje – Konjsko make operation of the system in Croatia significantly worsened due to following:
• At an hourly and daily basis it is necessary to continually carry out agreed schedule in regard to UCTE with allowed deviation of ±20 MW. In case of permanent outages in the transmission network this task is achievable by balancing powers between northern and southern parts, simultaneously providing that loading level of OHL 220 kV Dakovo – TPP Tuzla stays within requested limits.

• It is necessary to continually keep balanced operation along OHL 220 kV Dakovo – TPP Tuzla which shall not disturb stated constraints and cause permanent deviation in regard to UCTE on hourly basis.

• These permanent outages in the transmission network isolate reversible pumped-storage HPP Velebit that is connected at 400 kV voltage level. HPP Velebit is capable to inject 2x135 MW into the network or in pumping regime to draw 2x130 MW from the network. Its reactive power compensating mode is useful when higher network voltages should be corrected during system light loading conditions at night.

• Disturbances with temporary nature can also jeopardize operation of both systems (HR and BH).

• Engagement of the HPPs in Dalmatia shall enable not only realization of requested schedule, but also correction of line loadings along the southern interconnection (sometimes even along the northern link OHL 220 kV Dakovo – TPP Tuzla) simultaneously keeping planned levels at smaller water accumulations.

• Outage of each TPP generating power plant additionally jeopardizes established system steady-state, disturbs power flows, causes congestions in transmission network, requests rearrangement of limited amounts of gas among the plants or even their fuel replacement (gas to oil-fired TPPs).

• Low ambient temperatures and strong winds from north significantly increase consumption of electrical energy especially in Dalmatia for space heating purposes.

• Large and important consumer of electrical energy is located in southern part of the BH system (EAL Mostar) which uses electrical energy for electrolysis in aluminum production. Its supply is realized from buses Mostar 3 and Mostar 4. In normal operation this consumer continually draws power between 160 MW and 190 MW. It is a stable consumer with long term delivery contracts of aluminum export. Since its production process includes aluminum melting among other things, it is sensitive to longer supply disruptions. Allowed pause may last up to 2 hours without posing larger consequences to production process. Otherwise, significant damages could appear. For comparison, consumed electrical energy of EAL Mostar on a daily basis equals combined generation of three newly built HPPs at nearby river Neretva (HPP Salakovac, HPP Grabovica, HPP Mostar) which are not capable to keep maximum production throughout the whole day. Therefore, EAL Mostar is a consumer that needs secure permanent supply which is independent of direction from which electrical energy comes.

By looking at the HR and BH systems as at common electromechanical unit, two connecting points may be treated as the most important; one in Slavonia (northern one) and the other in Dalmatia (southern one). Slavonian connecting point is located at 220 kV bus Dakovo at the northern link OHL 220 kV Dakovo – TPP Tuzla. Dalmatian connecting point comprises OHLs 220 kV Konjsko – Mostar and 220 kV Zakuca – Mostar, what with OHL 220 kV Konjsko – Zakucac makes common 220 kV loop of linked buses Zakuca, Konjsko and Mostar. Before the blackout, the second point was connected to the north-western part of the HR system through the island 110 kV link with limited transfer capability. Large generation disturbances in Dalmatia such as outage of large HPPs bring additional loading of the northern 220 kV link and the island 110 kV link. In such unfavorable circumstances the critical sequence of events may be recognized that at the end caused the blackout.

III. BLACKOUT ROOT CAUSES AND CONSEQUENCES

The blackout happened on Sunday, January 12, 2003 at 16:44 hours. The system operators succeeded to balance power exchange of the HR system and its regions. Shortly before the blackout, the HR system was relatively well balanced against UCTE (power exchange amounted 173 MW / -70 Mvar, power transit amounted 741 MW / 169 Mvar). Against the BH system, the HR system was well balanced too (power exchange amounted 5 MW / -23 Mvar). Generation in Dalmatia was balanced with load. In the time of the incident, total consumption in Dalmatia was approximately equal to 490 MW (nearly 80% of maximum loading level equal to 633 MW). Total loading of the HR system (consume + losses) was equal to 2023 MW (peak value around 2700 MW).

According to excerpts from SCADA system, the balance between generation and load in wider regions of Dalmatia and BH points out that the system operators achieved regionally balanced operation in conditions of deteriorated system security due to initial unavailability of transmission lines. The northern 220 kV link (OHL 220 kV Dakovo – TPP Tuzla) was lightly loaded (30 MW / 4 Mvar from BH to HR), while in generating power plants there were 120 MW of rotational power reserve. Power loading level of interconnecting lines between the HR and BH systems during January 12, 2003 was between 10% and 25% of allowed thermal limit. The BH system mostly generated energy for its own needs. Scheduled power connected to the BH system (two utilities in the first UCTE zone) was equal to 730 MW in EPBiH and 280 MW in EPHZHB. Second generating unit in HPP Dubrovnik (HR), which is usually operated for the EPRS (third BH utility in the second UCTE zone), was at that time switched to the first UCTE zone through the BH system.

In general, total daily consumption on Sunday is lower than the one on any other working day. Consumption of electrical energy in time of the incident is situated between morning and evening peaks in daily consumption diagram
(Fig. 3). It is the point with relatively lower energy consumption in expectation of fast increase towards the evening peak. During next two hours, the system consumption should have been increased reaching the peak that would have been larger for approximately 500 MWh/h to 600 MWh/h. The incident caused change of loading level in the HR system in amount of approximately 500 MW; load power fell from 2060 MW to 1560 MW.

Frequency change at the time of the incident (16:44) was equal to 23 mHz. Unfortunately, it was not possible to find recordings of frequency response in the parts of the HR and BH systems that suffered from the blackout. These parts were disconnected from the large UCTE system and found in islanded operation which was kept for next 30 seconds.

During January 11 and 12, 2003, multiple activation of single phase line reclosing was registered along OHL 400 kV Konjsko – Velebit (Fig. 6). That line was switched on/off many times upon temporary faults. Due to need for enhancement of the system security, the intention of the system operators was to outsource voltage to the HPP Velebit by operating OHL 400 kV Konjsko – Velebit. That was needed to support auxiliary supply circuits in the HPP Velebit should it be synchronized to the system.

The incident initially caused change of generation power in the HR system of 540 MW; generation fell from 1940 MW to 1400 MW (Fig. 4). After the incident, whole southern part of the HR system was left without supply while expecting fast increase of consumption. Two utilities in the BH system that were in the first UCTE zone suffered total blackout.

On the blackout day, short circuit on OHL 400 kV Konjsko – Velebit near bus Velebit is recognized as the triggering event that initiated the blackout due to problems with protection rope. That line was switched in shortly before (at 16:34) from Konjsko side and supplied unidirectionally to outsource voltage to the HPP Velebit for supporting auxiliary supply and making preconditions for its starting-up. On the basis of various chronological listings, it is concluded that most probably one pole of the 400 kV circuit breaker at line bay Velebit located in bus Konjsko did not break fault current when switching out OHL 400 kV Konjsko - Velebit 9 minutes later at 16:43:58.998 hours. This is concluded due to continuously present (even after activation of the breaker) initialization of protection systems in buses Konjsko, Zakucac and Bilice. Initialization of protections from unsymmetrical conditions at the Dalmatian HPPs supports this conclusion.

Spreading of the disturbance is not efficiently localized in bus Konjsko 400 kV. Bus Konjsko 400/220/110 kV is the only one at 400 kV voltage level in the HR system not equipped with busbars protection and protection from breaker malfunctioning. These back-up protection systems would certainly provide isolation of the faulted location more efficiently in case of the main protection system malfunction. Unsymmetrical operating conditions were not removed by the back-up protection systems in 400 kV bus Konjsko. This shortly afterwards (within 30 s) caused cascading outages of lines (distant protection) and power plants (protection from unsymmetrical loading) in Dalmatia. The blackout appeared as a final consequence.
Total amount of energy not delivered to customers in southern Croatia during the blackout was equal to approximately 1270 MWh. At price of 0.09 $/kWh and by adding 22% of VAT, the financial loss of the utility due to non-delivered energy can be estimated to approximately 140,000 S. Damage for the society as a whole or value of non-delivered energy, if it is calculated at average price of 1.85 $/kWh which corresponds to ratio between gross domestic product and yearly energy consumption in Croatia, would amount to approximately 2,375,000 S. Since the blackout happened on Sunday, the damage might have somewhat smaller value. Damage on infrastructural equipment due to weather storms was significantly larger.

On the basis of analyzed chronological listings, the most probable chronological sequence of events is established that describes evolution of the blackout. Table 1 details time instants that belong to activation of the breakers at significant generators and lines in established chronology. The chronology is used to form scenario of the blackout sequence being simulated with computer dynamic model (times in round brackets). Conducted simulations help to estimate values of voltages and power flows which were present in times of the breakers activation in order to point out to eventual discrepancies in protection settings.

It is seen from Table 1 that all generators in Dalmatia were outaged within 30 seconds from the initial disturbance. Due to such large power unbalance, power flows were increased over the island 110 kV link and the northern 220 kV link (OHL 220 kV Dakovo – TPP Tuzla towards Tuzla). Due to overloading, the island 110 kV link was first broken at the section OHL 110 kV Novalja – Pag. Afterwards, the northern 220 kV link which was then the only connection between two main HR regions (southern and northern) experienced additionally increased loading. Shortly after that the northern 220 kV link was outaged due to activation of the special protection system which is installed in 220 kV Plat – Komolac. The SPS (coordinated with undervoltage load shedding) disconnected that link in bus Dakovo due to impending voltage collapse and thereby prevented Slavonia from the blackout that already spread in Dalmatia and BH.

In the HPP Zakucac, the initial event was first sensed at generator G4/150 MVA/110 kV followed by G3/150 MVA/220 kV as a signal to their excitation systems due to time limit of maximum excitation current. This HPP has 4 units in total, and these two are the bigger ones that are equipped with static excitation systems supplied from generator terminals. The other two have older rotational excitors. Generator G3/150 MVA/220 kV was first tripped off due to loss of excitation caused by asymmetry of thyristor valves. Generator G4/150 MVA/110 kV was tripped of as the last one of four units in HPP Zakucac despite the fact that it was the one which first sensed the initial disturbance. Approximately 24 seconds elapsed between the first signal and tripping-off of this unit. Detailed chronological listings pointed out that this generator spent at least 7.5 seconds in unstable operation changing polarity of excitation voltage between maximum (positive) and minimum (negative) ones.

<table>
<thead>
<tr>
<th>TIME (hh:mm:ss)</th>
<th>EVENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>16:43:38.603 (10.000 s)</td>
<td>Three-phase short circuit at uni-directionally supplied OHL 400 kV Konjsko – Velebit (80 km from Konjsko).</td>
</tr>
<tr>
<td>16:43:58.998 (10.395 s)</td>
<td>In Konjsko breaker activation (off) at OHL 400 kV Konjsko – Velebit. 3phSC into 1phSC by adding inverse and zero sequence impedances at the fault location.</td>
</tr>
<tr>
<td>16:44:00.474 (11.871 s)</td>
<td>In HPP Dubrovnik breaker activation (off) at OHL 220 kV Plät – RP Trebinje. Outage of generator G2/120 MVA/220 kV in HPP Dubrovnik.</td>
</tr>
<tr>
<td>16:44:01.224 (12.621 s)</td>
<td>In HPP Zakucac breaker activation (off) at generator G3/150 MVA/220 kV.</td>
</tr>
<tr>
<td>16:44:01.627 (13.024 s)</td>
<td>In HPP Dale breaker activation (off) at generator G2/24 MVA/110 kV.</td>
</tr>
<tr>
<td>16:44:02.499 (13.896 s)</td>
<td>In HPP Dale breaker activation (off) at generator G1/24 MVA/110 kV.</td>
</tr>
<tr>
<td>16:44:02.879 (14.276 s)</td>
<td>In HPP Zakucac breaker activation (off) at OHL 220 kV HE Zakucac – Konjsko.</td>
</tr>
<tr>
<td>16:44:03.175 (14.572 s)</td>
<td>In HPP Velebit breaker activation (off) at generator G2/120 MVA/220 kV.</td>
</tr>
<tr>
<td>16:44:05.049 (16.446 s)</td>
<td>In bus Nin breaker activation (off) at OHL 110 kV Nin – Pag (breakage of the island 110 kV link).</td>
</tr>
<tr>
<td>16:44:05.051 (16.448 s)</td>
<td>In bus Novalja breaker activation (off) at OHL 110 kV Novalja – Pag (breakage of the island 110 kV link).</td>
</tr>
<tr>
<td>16:44:07.995 (19.392 s)</td>
<td>In HPP Capljina breaker activation (off) at generator G2/240 MVA/220 kV; 1.5 s before outage of OHL 220 kV Dakovo - TPP Tuzla (the only simulated BH event).</td>
</tr>
<tr>
<td>16:44:08.339 (19.736 s)</td>
<td>In HPP Zakucac breaker activation (off) at OHL 220 kV Zakucac – Bilice.</td>
</tr>
<tr>
<td>16:44:09.495 (20.992 s)</td>
<td>In Dakovo breaker activation (off) at OHL 220 kV Dakovo - TPP Tuzla (breakage of the northern 220 kV link).</td>
</tr>
<tr>
<td>16:44:12.031 (23.428 s)</td>
<td>In HPP Dubrovnik breaker activation (off) at OHL 110 kV Plät – Komolac. Outage of generator G1/120 MVA/110 kV in HPP Dubrovnik.</td>
</tr>
<tr>
<td>16:44:13.196 (24.593 s)</td>
<td>In HPP Dubrovnik breaker activation (off) at generator G1/120 MVA/110 kV.</td>
</tr>
<tr>
<td>16:44:16.656 (28.053 s)</td>
<td>In bus Vbroran breaker activation (off) at OHL 110 kV Konjsko – Vbroran (1/2).</td>
</tr>
<tr>
<td>16:44:16.665 (28.062 s)</td>
<td>In bus Vbroran breaker activation (off) at OHL 110 kV Konjsko – Vbroran (2/2).</td>
</tr>
<tr>
<td>16:44:17.132 (28.529 s)</td>
<td>In bus Vbroran breaker activation (on) at OHL 110 kV Konjsko – Vbroran (2/2).</td>
</tr>
<tr>
<td>16:44:17.169 (28.566 s)</td>
<td>In bus Vbroran breaker activation (on) at OHL 110 kV Konjsko – Vbroran (1/2).</td>
</tr>
<tr>
<td>16:44:17.226 (28.623 s)</td>
<td>In bus Vbroran breaker activation (off) at OHL 110 kV Konjsko – Vbroran (1/2).</td>
</tr>
<tr>
<td>16:44:17.232 (28.629 s)</td>
<td>In bus Vbroran breaker activation (off) at 110 kV Konjsko – Vbroran (2/2).</td>
</tr>
<tr>
<td>16:44:17.258 (28.655 s)</td>
<td>In bus Konjsko at 110 kV side breaker activation (off) at ATR1 220 kV / 110 kV.</td>
</tr>
<tr>
<td>16:44:17.261 (28.658 s)</td>
<td>In bus Konjsko at 220 kV side breaker activation (off) at ATR2 220 kV / 110 kV.</td>
</tr>
<tr>
<td>16:44:17.279 (28.676 s)</td>
<td>In bus Konjsko at 110 kV side breaker activation (off) at ATR2 220 kV / 110 kV.</td>
</tr>
<tr>
<td>16:44:17.284 (28.681 s)</td>
<td>In bus Konjsko at 220 kV side breaker activation (off) at ATR1 220 kV / 110 kV.</td>
</tr>
<tr>
<td>16:44:17.582 (32.979 s)</td>
<td>In bus Makarska breaker activation (off) at OHL 110 kV Makarska – Opuzen.</td>
</tr>
<tr>
<td>16:44:18.064 (39.461 s)</td>
<td>In bus Makarska breaker activation (off) at OHL 110 kV Makarska – Opuzen.</td>
</tr>
<tr>
<td>16:44:18.456 (39.853 s)</td>
<td>In bus Blato breaker activation (off) at OHL 110 kV Blato – Ston.</td>
</tr>
<tr>
<td>16:44:19.120 (40.517 s)</td>
<td>In bus Blato breaker activation (on) at OHL 110 kV Blato – Ston.</td>
</tr>
<tr>
<td>16:44:22.467 (53.864 s)</td>
<td>In HPP Zakucac breaker activation (off) at generator G4/150 MVA/110 kV.</td>
</tr>
<tr>
<td>16:44:31.724 (63.121 s)</td>
<td>In HPP Peruc breaker activation (off) at generator G1/26 MVA/110 kV.</td>
</tr>
</tbody>
</table>
IV. RELIABILITY OF TRANSMISSION LINES

It is interesting to relate previous findings on the blackout to statistical analysis of transmission lines reliability [8]. Regarding constructional elements and mechanical parts the lines generally represent reliable elements of transmission network. They can keep up higher level of reliability by strictly applying rules and conducting good technical practice in the procedure of their installation and maintenance. Unfortunately, two factors negatively influence their reliability. The first one is related to very different geographical, weather and urban zones that they shall pass through, while the other one reflects their behavior during bad weather conditions. Frequency of line outages is several tens of times larger during bad weather conditions than in normal operating conditions. Fortunately, majority of disturbances have temporary character which most often does not heavily affects the system performance. Moreover, reparation of permanent faults mostly lasts relatively short. Difficulties appear due to a fact that bad weather conditions are frequent and intensive in localized regions. This makes larger number of lines in one area more prone to outages due to heavy disturbances.

Statistical data of transmission line disturbances come as a result of the analysis [8] that was carried out during period of 12 years which was considered as a sufficient enough to achieve statistically correct information. The analysis was based on statistics of permanent line disturbances at 110 kV, 220 kV and 400 kV voltage levels in that period. Permanent line disturbance denotes a disturbance that needed intervention of a field emergency team before line reconnection. Total number of permanent line disturbances equaled to 105 within given period. On a yearly basis, it varied from 1 to 20 with an average of 8.75/year. Disturbances had following distribution with respect to voltage levels:

<table>
<thead>
<tr>
<th>Voltage Level</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>110 kV</td>
<td>64.8 %</td>
</tr>
<tr>
<td>220 kV</td>
<td>27.7 %</td>
</tr>
<tr>
<td>400 kV</td>
<td>7.5 %</td>
</tr>
</tbody>
</table>

Previous percentages are proportionally related to total line lengths at specific voltage level with a rather small deviation at 110 kV (towards larger values) and 400 kV (towards smaller values).

On the basis of statistical analysis it was seen that there were characteristic regions with very large number of permanent line disturbances and the other ones with rare disturbances. The most severed region was shown to be Primorje, Gorski Kotar and Lika (mid-western part, area I) with 34.4 % of total disturbances. The second one was Dalmatia and southern parts of Bosnia Herzegovina and Monte Negro (area II) with 20.9 % of total disturbances. If only disturbances in Croatia should be accounted for then total number of disturbances equaled to 50, whereof 34 disturbances or 68 % were in area I, 12 disturbances or 24% in area II, and 4 disturbances or 8% in the other areas. Results showed that reliability was jeopardized especially during November, January and December with 65 % of all disturbances, while especially "quiet" months were May, September and October with only 0.9 %.

Appearance of simultaneous disturbances significantly varied depending on nominal voltage level. For example, at 110 kV level in 27 notifications there was 1 simultaneous disturbance, and in 1 notification as much as 10 simultaneous disturbances. At 220 kV level, there were 18 notifications with 1 simultaneous disturbance, and 2 notifications with 5 simultaneous disturbances. At 400 kV level, there were 4 notifications with 1 simultaneous disturbance, and 1 notification with 4 simultaneous disturbances. Appearance of simultaneous disturbances resulted with following probabilities (x denotes number of simultaneous disturbances and \( P(x) \) probability of their occurrence):

At 400 kV voltage level

\[
\begin{array}{c|c}
 x & P(x) \\
\hline
 0 & 0.260 \\
 1 & 0.352 \\
 2 & 0.230 \\
 3 & 0.102 \\
 4 & 0.033 \\
\end{array}
\]

At 220 kV voltage level

\[
\begin{array}{c|c}
 x & P(x) \\
\hline
 0 & 0.295 \\
 1 & 0.360 \\
 2 & 0.216 \\
 3 & 0.088 \\
 4 & 0.027 \\
 5 & 0.006 \\
\end{array}
\]

At 110 kV voltage level

\[
\begin{array}{c|c}
 x & P(x) \\
\hline
 0 & 0.112 \\
 1 & 0.246 \\
 2 & 0.268 \\
 3 & 0.195 \\
 4 & 0.106 \\
 5 & 0.047 \\
 6 & 0.017 \\
 7,8,9,10 & 0.007 \\
\end{array}
\]

Since previous distribution looked rather similar to the Poisson distribution, the largest number of simultaneous disturbances was theoretically computed. Its value fell around 6. Given data have represented a good source of information to network planners and system operators regarding transmission lines behavior. It has been noted that fulfillment of the (N-1) security criterion is jeopardized in winter period of year.

Analogously to occurrence of simultaneous disturbances, their duration was analyzed as well. Following results were obtained for duration of simultaneous disturbances at 110 kV level (x denotes number of simultaneous disturbances and \( P(x) \) distribution of their occurrence):

\[
\begin{array}{c|c}
 x & P(x) \\
\hline
 0 & 0.429 \\
 1 & 0.363 \\
 2 & 0.153 \\
 3 & 0.043 \\
 4,5,6,7 & 0.011 \\
\end{array}
\]
In 42.9% of time there was not a single permanent disturbance at 110 kV voltage level, whereas for example in 4.3% of time three lines appeared as permanently disturbed.

In case of raising a question whether or not this blackout was unpredicted or unexpected, the answer is certainly negative. Following similarities are notified by comparing basic information on the blackout to the previously given results of statistical analysis:

- The blackout happened in Dalmatia, one of two most endangered zones.
- The blackout happened in January, one of three most endangered months.
- There were 7 transmission lines simultaneously outaged shortly before the blackout, which is close to theoretical value of 6.

V. REGIONALLY BALANCED INITIAL STATE AS A SIGN OF SYSTEM OPERATORS AWARENESS

In order to minimize probability of blackout occurrence or consequences once it rolls on, each properly organized system shall fulfill some fundamental security measures to enable system operators dealing with such problem.

Analysis of reconstructed initial steady state just before the blackout points out to conditions of regionally well balanced system operation before the initial fault appeared. It is seen that the system operators applied appropriate measures to balance power exchange between regions of the systems and minimize eventual troublesome situations. Numerical calculations are carried out on the basis of data analysis to help analyze technical problems associated to the blackout. To that direction, detailed static and dynamic model of the HR and BH systems as well as of all surrounding systems is established at first. The initial steady state that preceded the blackout is numerically analyzed first and the findings are shown hereafter.

For the initial steady state, load flow computations are conducted at first, showing that there are neither thermally overloaded elements nor network buses with voltage deviations larger than ±10% of nominal values. In small number of network buses voltage deviations are between +5% and +10%, or -5% and -10%. In the system state that preceded the blackout there were registered neither problems with overloads nor with bus voltage magnitude deviations.

Contingency analysis of single outages in the initial steady state shows that the (N-1) security criterion was fulfilled in the southern part of the HR system (and in the BH system) that later on suffered from the blackout. System elements located in Dalmatia (and BH) are not classified as potentially critical since their single outages would not cause thermal overloading. Before the blackout, 7 transmission lines were out of operation in Dalmatia. However, that part of the HR system fulfilled the (N-1) security criterion even with such initial loss. The most important influence to fulfillment of that criterion comes from regionally balanced system operation with respect to minimized power exchanges between the HR and BH systems as well as within the regions of the HR system. The system operators were prepared and aware to deteriorating conditions. In the northern part of the HR system which was not hit by the blackout, the (N-1) criterion was not fulfilled (largest overloading of 136% in Slavonia, location: Dakovo).

Afterwards, available transmission capacity (ATC) values are computed between the HR and BH systems. The ATC values do not point out to particularly large problems in realization of smaller power exchanges up to 100 MW which was the case just before the blackout.

Critical fault clearing times near generating power plants are calculated for the initial system state. Three-phase short circuits would have not forced generators to loose synchronism provided that they would have been removed within standard activation time of concerned breakers. They are mostly larger than 0.300 s, and it does not point out to problems with respect to keeping the electromechanical stability of generator rotor angles during first swing upon temporary three-phase short circuit. Simultaneously, sub-transient three-phase short circuit currents are smaller than concerned breaker capabilities in these buses. Three-phase short circuit powers at the plant/network interface are larger than the minimum requirements. Just before the blackout, the system transient angle stability criterion was fulfilled with respect to the minimum critical fault clearing time (0.150 s) and at least 6 times larger value of the three-phase short circuit power at the plant/network interface than the installed nominal active power.

The three-phase short circuit at the initial location of the blackout should have been isolated by proper activation of concerned protection systems and circuit breaker. Since one pole of the breaker on OHL 400 kV Konjsko – Velebit did not fulfill request for switching off and since transformers TR 400/220 kV Konjsko were not disconnected, the disturbance spread from 220 kV bus Konjsko further into the network. Non-selective outages of nearby lines and generators were initiated due to significant asymmetries. Cascading outages could have been prevented by proper coordination of protection systems at the HR-BH border.

VI. THE SYSTEM OPERATORS ACTION DURING RESTORATION PERIOD

On the basis of analyzed chronological listings, the most probable chronological sequence of events is established that describes evolution of the blackout (Table 1). The chronology is used to form scenario of the blackout sequence being simulated with computer dynamic model.

All generators in Dalmatia were outaged within 30 s from the initial disturbance. Due to such large power unbalance, power flows were increased over the island 110 kV link and the northern 220 kV link (OHL 220 kV Dakovo – TPP Tuzla towards Tuzla). Due to overloading, the island 110 kV link was first broken at the section OHL 110 kV Novalja – Pag. Shortly afterwards, the northern 220 kV link which was then the only connection between two main HR regions (southern and northern) experienced additionally increased loading. Shortly after that the northern 220 kV link was outaged due to activation of the special protection
system which is installed in 220 kV bus Dakovo. The SPS (coordinated with undervoltage load shedding) disconnected that link in bus Dakovo due to impending voltage collapse and thereby prevented Slavonia from the blackout that already spread in Dalmatia and BH. Later on, the northern 220 kV link was switched in again in order to enable system operators to restore supply.

Active power flow along OHL 220 kV Dakovo – TPP Tuzla (Figs. 7-8) shows that its larger variability appeared between 16:43 and 20:30 hours. In that period Dalmatia and BH suffered from the blackout and the system operators tried to reestablish their supply partly through that link.

From that viewpoint it is interesting to reconstruct events related to active power exchange between HR and BH systems along OHL 220 kV Dakovo – TPP Tuzla, especially during restoration period from 16:45 till 18:45 hours (Fig. 9). During the blackout this OHL was first switched out, and then after a few minutes switched in to interconnect the HR and BH systems again and speed up restoration procedure.

Point 1 denotes outage of OHL 220 kV Dakovo – TPP Tuzla and the blackout appearance. Between points 1 and 2 the BH system drew starting amount of energy that was gradually increased. At 17:12 hours (point 2) the system load was suddenly increased to a twice larger value than previously noticed. At 17:15 hours, either previously connected load was shed or approximately 60 MW of generation was synchronized in the BH system (point 3). More probable is that a synchronized source in the BH system gave energy to the HR one within next 5 minutes.

At point 4 around 17:20 hours, larger consume was connected in the BH system which led to approximately 70 MW of power exchange. That increase was dominantly motivated by connection of consume in the middle part of the BH system which was decreased upon the intervention of the system operators due to the risk of decreased voltage magnitudes and reoccurring voltage collapse. Therefore, between points 5 and 7 the BH system load was gradually decreased with respect to the request of the system operators stating that consume should be connected in smaller steps in order to keep appropriate and balanced loading conditions along OHL 220 kV Dakovo – TPP Tuzla. Start-up of generating sources in the BH system should have been balanced with continuing load increase. The loading should have been realized in selective manner in order to match connected generation to load consume.

Between points 7 and 8 the load was probably shed in the BH system, while generated energy that none in the BH system could have used entered in the HR system. Between points 8 and 9, approximate consume of 50 MW was again connected to the BH system. Behind point 9, the largest power amount was delivered from the BH system to the HR one (245 MW). It is supposed that at point 9 large load shedding appeared in the BH system. Since none in the BH system could have used energy generated in the BH system, it entered into the HR system which tried to gradually decrease this exchange between points 9 and 10.

Behind point 10, the consume was reconnected in the BH system which started drawing energy from the HR system up to the maximum amount of 140 MW with tendency of further increase. That tendency was limited and stabilized by appropriate action of the system operators.

In the period of system restoration, aggregates of the HPP Zakucac (the largest hydro generating power plant in Croatia) exhibited problems related to black start capability (Fig. 10). Responses of total active power generation and individual generations of all four aggregates in the HPP Zakucac clearly depict three major periods associated to the blackout on January 12, 2003 between 16:00 and 20:00 hours (Figs. 11-12). The first period of more or less initial steady state is interrupted by the moment of the blackout which is clearly visible at 16:44 hours. The first period is followed by the second one which is characterized by unsuccessful attempts of resynchronization of the HPP Zakucac aggregates. Finally, after several such attempts the aggregates are successfully synchronized to the network.
which enabled increase of their loadings within the third period of state restoration.

Fig. 10 Connection of four aggregates within the HPP Zakucac

Within state restoration after the blackout, the system operators revealed that generators G1/120 MVA/110 kV and G2/120 MVA/220 kV in the HPP Zakucac exhibit unstable regulation mode of their speed governors while being isolated from the system and in islanded operation supplying own auxiliary load. This is recognized as the main contributing factor to unsuccessful attempts in the start-up procedure of islanded generators G1/120 MVA/110 kV and G2/120 MVA/220 kV. The HPP Zakucac is otherwise made capable for the black-start.

During November and December 2002 (a month before the blackout), the speed governor – turbine systems were reconstructed on generators G1/120 MVA/110 kV and G2/120 MVA/220 kV in the HPP Zakucac. The operation of the aggregates was checked out in each operating regime including the islanded operating mode. However, during final tuning procedure the key parameters of the regulating circuits were set as to maximally support parallel operation of the aggregates and the system in order to make the aggregates more stable while working on the stiff system.

Besides, a new protection system block was installed then at the aggregate G1/120 MVA/110 kV in the HPP Zakucac. Among the other things, new block comprised under and overfrequency protection as well. That protection system caused switching-out of the aggregate while being in islanded operating regime. In the same reconstructing period, new block with equipment aimed for synchronization is installed too. Since then, if the generator was in islanded operating mode it was not possible to switch-in the generator breaker from the control room, but to go to the switchyard and switch it in locally. It additionally slowed down the system operators activities on state restoration not to mention lack of proper information dissemination to the system operators.

That resulted with later resynchronization of these aggregates to the network which further on contributed to later state restoration after the blackout. Such situation points out to a necessity for the system operators to have a precise knowledge of the aggregates role in the system as well as to apply sound engineering rules while tuning parameters of various regulating circuits. Difficulties with the HPP Zakucac that were noticed during state restoration after the blackout initiated activities on retuning of the speed governor parameters in order to satisfy both operating regimes; islanded operation and operation to a stiff system. Moreover, activation of under/overfrequency protection at the aggregate G1/120 MVA/110 kV has been readjusted. It was decided to enable switch-in of the generator breaker from the control room.

VII. SPECIAL PROTECTION SYSTEM

Being properly designed and coordinated, the special protection system has the first class significance. If a protection relay of an individual element is treated as the first line of system defense from disturbances, and a back-up relay as the second one, then the special protection system represents the last defense line. When the first and the second defense lines can limit spreading of disturbances throughout the system and keep it isolated only at directly faulted system components, then it is quite likely that the system is able to withstand consequences. Application of the special protection system mostly focuses at alleviation of consequences or their localization.

In 220 kV bus Dakovo the HR system accepts larger or smaller amounts of energy from the BH system depending on its generation schedule. During a year the loading level of OHL 220 kV Dakovo – TPP Tuzla has variable values from a few tens of MW up to 220 MW. Direction of energy flow is from the BH system to the HR one. The other way of the energy flow appears very rarely due to the following:

- Bus Dakovo represent poor energy source (generation in Slavonia is mostly between 20 MVA and 40 MVA,
and its consume is even 10 times larger amounting to 256 MW just before the blackout),

- Bus Dakovo draws energy from 220 kV bus Tuzla (BH) and Mraclin (HR, further at Slovenian side from bus Cirkovce and at the HR southern side from buses Brinje and HPP Senj) and from 110 kV network,

- The northern power interconnection OHLs 220 kV Cirkovce – Mraclin – Dakovo is physically improvised due to unrecovered war damages and contains parts of 400 kV, 220 kV and 110 kV lines operated at 220 kV (such line structure causes appearance of significant limitations and makes bottlenecks in power transmission which furthermore limits bus Dakovo until complete network reconstruction).

Thus, in order to protect north-eastern part of the HR system, the special protection system has been installed in 220 kV bus Dakovo on OHL 220 kV Dakovo – TPP Tuzla with following activation conditions:

- Voltage in 220 kV bus Dakovo less than 180 kV,
- Power flow along OHL 220 kV Dakovo – TPP Tuzla larger than 30 MVA in direction to Tuzla, and
- Time to continuously satisfy previous two conditions is larger than 3 seconds.

In case of continuous voltage drop in 220 kV bus Dakovo below 180 kV and simultaneous power flow larger than 30 MVA along OHL 220 kV Dakovo – TPP Tuzla in direction to Tuzla during more than 3 seconds, the SPS shall initiate the circuit breaker at line bay Tuzla in bus Dakovo to switch-off OHL 220 kV Dakovo – TPP Tuzla.

The first signal that revealed system stability problems was related to detection of power swings along OHL 220 kV Dakovo – Mraclin. The signal was registered in bus Dakovo at the protection terminal bay 220 kV Mraclin at 16:44:08.484 hours. Figure 13 depicts recordings of swings that belong to the phase voltages and currents at protection terminal bay 220 kV Mraclin in bus Dakovo with start at 16:44:01.448 hours. During following two seconds that are memorized in the relay the swings are especially visible in response of the currents. After a few seconds of the power swings, the relay registered the start of continuous bus voltage magnitude drop all over Slavonian transmission network. Figure 14 depicts recordings from the protection terminal bay 220 kV Mraclin in bus Dakovo at OHL 220 kV Dakovo – Mraclin started at 16:44:05.655 hours. Simultaneous voltage decrease and current increase points out to impending voltage collapse in that region.

Simultaneous voltage decrease and current increase caused intensified activation/deactivation of distant protection systems in all three phases along 110 kV paths Virovitica – Slatina – Nasice (northern Slavonia) and N.Gradiška – Pozega – Sl.Brod (southern Slavonia) and along 220 kV OHLs Dakovo – TPP Tuzla and Dakovo – Mraclin. These activations point out to voltage collapse and significant increase of power flows along the paths. Simultaneously, OHL 110 kV Pozega – Sl.Brod was switched off in bus Pozega due to non-directional distant protection initiated by too high loading level at too low voltage magnitude. The same reasoning was applied to switch off transformer 110 kV / 35 kV in buses Slatina and Pozega. Precisely 3 seconds after continuously satisfied conditions, the SPS was activated to switch off OHL 220 kV Dakovo – TPP Tuzla on the basis of the voltage value in 220 kV bus Dakovo being less than 180 kV and power flow along the line in direction to Tuzla being larger than 30 MW. Shortly afterwards, voltage situation in Slavonia was improved, distant and undervoltage relays were deactivated.

At 16:44:08.484 hours, the undervoltage load shedding scheme was applied in bus Slatina according to criteria that the phase voltage should be less than 90 kV (0.709 pu) with previous current flow from bus Virovitica larger than 400 A. This action caused disconnection of 7 MW consume in bus Slatina. Activation of distant protection systems along the northern 110 kV path did not appear after outage of transformer in bus Slatina which confirmed decrease of the line loading level. Impedance drop just before the application of the load shedding amounted nearly 60 Ω, while afterwards the impedance was approximately equal to 70 Ω. Low impedance relays are set at 70 Ω for the line bay 110 kV Nasice and 55 Ω for the line bay 110 kV Virovitica. Table 2 lists values of currents and voltages in bus Virovitica that were registered at that moment.

At 16:44:09.444 hours, the undervoltage load shedding was applied in bus Pozega according to the same criteria (voltage less than 90 kV, current flow from bus N. Gradiska larger than 400 A). It disconnected 15 MW of consume in bus Pozega. Afterwards, the distant relay was activated in 2nd zone on OHL 110 kV S. Brod – Pozega to switch off circuit breaker in the line bay VP 110 kV S. Brod. Table 3 lists values of currents and voltages in bus N. Gradiska that were registered at that moment.

<table>
<thead>
<tr>
<th>Time (internal clock)</th>
<th>Phase</th>
<th>Voltage (kV)</th>
<th>Current (A)</th>
<th>Apparent power (MVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16:43:36.125</td>
<td>L1</td>
<td>60.04</td>
<td>525.2</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>L2</td>
<td>60.02</td>
<td>525.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L3</td>
<td>59.65</td>
<td>495.3</td>
<td></td>
</tr>
<tr>
<td>16:43:39.287</td>
<td>L1</td>
<td>46.60</td>
<td>767.2</td>
<td>108</td>
</tr>
<tr>
<td></td>
<td>L2</td>
<td>47.51</td>
<td>784.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L3</td>
<td>46.73</td>
<td>745.1</td>
<td></td>
</tr>
</tbody>
</table>
in 220 kV bus Dakovo revealed that bus Tuzla drew large amount of power (320 MVA) from Slavonian transmission network. At the moment of its activation, the relay at the line bay 220 kV Tuzla in 220 kV bus Dakovo registered voltage magnitudes of 53.1 kV to 59.8 kV (phase values, 0.418 pu and 0.471 pu) and current flows of 1876.6 A to 1930.4 A. This made power flow of nearly 320 MVA that was drawn along OHL 220 kV Dakovo – TPP Tuzla in direction of Tuzla. Following listing witnesses about that:

<table>
<thead>
<tr>
<th>LOCATION OF PART</th>
<th>Organizer</th>
<th>Relisys 785-DS</th>
<th>Station</th>
<th>TS DJAKOVO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obj/Bay</td>
<td>VP TULZA</td>
<td>REL531A DRP-TRIP Monitor Screen 3 of 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mod/Part</td>
<td>REL531A DRP-TRIP Fault locator - Trip values ...</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit</td>
<td>REL531A V1.0 C  Line protection terminal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Obj/Bay</td>
<td>VP TUZLA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Station</td>
<td>TS DJAKOVO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Organiz</td>
<td>HEP PRP OS</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Approximately 2 seconds before registration of shown measurement from the line bay 220 kV Tuzla, the relay at the line bay 220 kV Mraclin in bus Dakovo 220 kV registered voltage phase value of 86.1 kV and current phase value of 1.39 kA.

After these actions, voltage situation was improved in Slavonian transmission network and the protection systems were deactivated. Consumers in buses Slatina and Pozega were not supplied for less than 15 minutes. Activation of the SPS helped to avoid the blackout in Slavonia, while disconnected consumers were reconnected after 12 and 14 minutes. Approximately 6 minutes after the SPS activation in 220 kV bus Dakovo, the circuit breaker was switched on at the line bay 220 kV Tuzla (16:49:54.268 hours). At 17:34 hours along OHL 220 kV Dakovo – TPP Tuzla there was noted power flow of 121 MW in direction of Tuzla, but with voltage value of 220 kV in 220 kV bus Dakovo which confirmed proper design of the SPS. That was not single case since at 18:56 hours there was 117 MW, and at 18:59 hours 124 MW power flow in direction of Tuzla.

Several time dependences of voltage magnitudes and power flows in the north-eastern part of the HR system were graphically recorded during the blackout. Figure 15 shows time dependence of voltage magnitude in 220 kV bus Dakovo. It is seen that the voltage magnitude becomes variable after 16:43 hours when troubles in Dalmatia were noted. The voltage magnitude became balanced after 19:15 hours. Only during two very short time intervals the voltage magnitude dropped below 220 kV, while four times it was increased above 240 kV and nearly 250 kV. It is supposed that the moment when the voltage magnitude had dropped below 180 kV (activation of the SPS in Slavonia) was not recorded due to larger time sampling. Figure 16 shows time dependence of active power flow along OHL 220 kV Dakovo – Mraclin, whereas Figure 17 shows the flow along OHL 220 kV Dakovo – TPP Tuzla. Their larger variability appeared in period between 16:43 hours and 20:30 hours when Dalmatia suffered from the blackout. Complete transient process is not seen due to larger time sampling.

Thorough data analysis based on available recordings and listings pointed out that the activation of the special protection system was in line with settings and protection plans as designed in Slavonian transmission network. The operation of the north-eastern part of the HR system was successfully saved from the blackout by switching off the OHL 220 kV Dakovo – TPP Tuzla. This certainly prevented the blackout in Slavonia which in contrary might have been sensed in closer parts of the western UCTE area as well.

VIII. SIMULATION OF THE BLACKOUT SCENARIO

In simulation phase of the blackout analysis it is necessary to check out quality of established system model at first and then to eventually find adequate explanations of technical phenomena that have key positions in understanding of root causes of the blackout. Post-mortem analysis is a very challenging task due to the following:

1) Establishing time domain sequence of discrete events (switching operations),
2) Preparing model of the initial steady state of the system that appeared just before the first disturbance, and
3) Duplicating recorded system responses by using computer model.

Steps 1 and 2 request sublimation of larger quantities of data that should be obtained from different power utilities and regulating areas. In step 3, duplicating and model validation should be based on graphical recordings of the disturbances (if they exist at all). Most often it is usually shown already in the beginning that the usage of a standard model aimed for system planning gives normal system state when in reality it already exhibits characteristics of in-extremis state. Thus, it is necessary to recognize all insufficiencies of the model in advance. This enables conduction of enhanced computer representation of the system through collecting additional data on generators and loads in the network. After making intensive simulations it might be possible to reproduce sequence of events by using computer model. Verified simulations enable confirmation of conclusions drawn on the blackout.

Numerical calculations are carried out on the basis of established sequence of events to help analyze technical problems associated to the blackout. After that, it is pointed out to a necessity for establishing or revision of existing standards, guidelines and procedures to follow in emergency states. It is also shown as necessary to secure supervisory measures over conducting defined procedures. Collected and analyzed data associated with the blackout are used to form final report on the incident.

To that direction, detailed static and dynamic model of the HR and BH systems as well as of all surrounding systems is established at first. Such model is usable for conducting wide variety of planning studies or to estimate security level of the current system state while running its operation. After that, the initial steady state that preceded the blackout is numerically analyzed followed by simulation of the chronological sequence of events according to established blackout scenario during nearly 30 seconds.
Fig. 13 Voltages and currents during power swings on OHL 220 kV Dakovo – Mraclin in Dakovo at bay 220 kV Mraclin

Fig. 14 Voltage decrease and current increase on OHL 220 kV Dakovo – Mraclin in Dakovo at bay 220 kV Mraclin
Fig. 15 Voltage magnitude in 220 kV bus Dakovo during the blackout in Dalmatia on January 12, 2003

Fig. 16 Active power flow along OHL 220 kV Dakovo - Mraclin during the blackout in Dalmatia on January 12, 2003

Fig. 17 Active power flow along OHL 220 kV Dakovo – TPP Tuzla during the blackout in Dalmatia on January 12, 2003
For the initial steady state, it is already shown here that there in the system state that preceded the blackout there were not problems with overloading, inadequate voltage regulation, (N-1) security, available transfer capacity, critical fault clearing times and related short circuit level. Analysis of reconstructed initial steady state just before the blackout points out to conditions of regionally well balanced system operation before the initial fault appeared.

Responses of significant system variables are computed in time domain according to the blackout simulation scenario from Table 1. Responses of the variables are shown and analyzed with respect to recognized reaction of characteristic parts of the HR system (north vs. south) and individual system components. Responses are chosen to depict as good as it gets conditions in different parts of the HR and BH systems, which were left mutually disconnected during the blackout (Dalmatia and BH vs. northern part of the HR system).

Sequence of events which is simulated in time domain is described in Table 1. On the basis of established scenario, transient electromechanical process is simulated during first 30 s after the initial fault appeared. Only the events that happened in the HR system are simulated since only for these events the chronological registrations are collected in millisecond range. It is supposed that there are no outages in the BH system during simulated sequence (with the only exception of one generator in HPP Capljina). Time instant \( t=10.000 \) s in simulated sequence corresponds to the time instant \( t=16:43:58.603 \) (hh:mm:ss) of the initial short circuit appearance in real sequence. Afterwards, all time instants in simulated sequence are recomputed with respect to the time instant of the initial short circuit. Transfer from three-phase to single phase short circuit due to unsuccessful activation of the breaker in one pole is realized by adding inverse and zero impedances at the fault location in order to create there conditions of single phase short circuit. Impedances are defined according to computed values of three-phase and single phase currents, or actually their portions that come from the side of 400 kV bus Konjsko 400 kV since the line was uni-directionally supplied before the blackout.

According to the chronological recordings, the power swinging signal on OHL 220 kV Dakovo – Mraclin was registered in 220 kV bus Dakovo at protection terminal in bay 220 kV Mraclin. Figure 13 shows recordings of voltage and current swings in phases at protection terminal 220 kV Mraclin in 220 kV bus Dakovo beginning at 16:44:01.448 hours. During next 2 seconds that were recorded by the relay the swings are clearly visible especially in response of the currents.

After a few seconds of power swinging, continuous voltage decrease and current increase is registered in nearby network buses. Figure 14 shows recordings from protection terminal in 220 kV bus Dakovo at line bay 220 kV Mraclin on OHL 220 kV Dakovo – Mraclin beginning at 16:44:05.655 hours. At the time instant of switching-off activation, the relay in 220 kV bus Dakovo at line bay 220 kV Tuzla on OHL 220 kV Dakovo – TPP Tuzla registered voltages at 53.1 kV to 59.8 kV (phase values, 0.418 pu and 0.471 pu) and currents at 1876.6 to 1930.4 A.

Simultaneous voltage decrease and current increase is particularly characteristic for evolution of voltage collapse scenario. This activated the SPS which contained switching off the OHL 220 kV Dakovo – TPP Tuzla at the time instant 16:44:09.495 hours.

Responses of bus voltages along northern 220 kV link (Mraclin – Dakovo – TPP Tuzla) besides oscillatory behaviour exhibit also sharp continuing voltage drop in 220 kV bus Dakovo down to nearly 0.50 pu in the period just before disconnection of OHL 220 kV Dakovo – TPP Tuzla (Fig. 18). After disconnection of the northern link, voltage magnitude in 220 kV bus Dakovo is quickly recovered in a new steady state which is somewhat less than the nominal.

Responses of power flows (active P, reactive Q and apparent S) on OHL 220 kV Dakovo – TPP Tuzla (northern link) show that its disconnection in the blackout scenario happens after short-term power oscillations at a level of 300 MVA in direction to Tuzla (Fig. 19). Responses of power flows on OHL 220 kV Dakovo – Mraclin during simulated sequence of events (Fig. 20) confirm appearance of power swings that diminished after the disconnection of the link.

Responses of voltage magnitudes in buses along the island 110 kV link (Rab – Novalja – Pag – Nin) show clear regional separation of northern and southern parts of Dalmatia (Fig. 21). After its breakage, voltage magnitudes in northern buses along the island 110 kV link (Rab and Novalja) are quickly recovered to approximately nominal values. Bus Pag 110 kV at the moment of the breakage becomes left without supply since the outage of OHL 110 kV Novalja – Pag was preceded by the outage of OHL 110 kV Nin – Pag. In southern bus of the island 110 kV link (Nin) voltage magnitude is decreased to a very low level. Responses of power flows (active P, reactive Q and apparent S) on OHL 110 kV Novalja – Pag (the island link) also show that in the simulated sequence of events its disconnection happens after short-term power oscillations at the level larger than 100 MVA (Fig. 22).

Responses of voltages in network buses across Dalmatia (Fig. 23) undoubtedly show evolutionary sequence of events that led it into the blackout. Voltage magnitudes are decreased to a very low level in all buses located southern from bus 110 kV Novalja. In northern network buses (Tumbri and Melina) there are almost no significant voltage changes during the blackout (Fig. 24).

Mutual separation of different system regions (Dalmatia and BH vs. northern HR system) caused by disconnection of OHL 110 kV Novalja – Pag – Nin (the island link) and especially OHL 220 kV Dakovo – TPP Tuzla (the northern link) has a key effect on responses of bus frequency in separated system parts (Fig. 25). After the initial disturbance, damped electromechanical oscillations appear in both system parts with the only difference that the oscillations are larger in southern part than in the northern one. After breakage of the northern 220 kV link the system becomes separated into two parts (Dalmatia and BH in one and northern HR in the other). Frequency in the northern HR part is quickly stabilised. Frequency in the southern part (Dalmatia and BH) suffers from oscillatory instability.
IX. LESSONS LEARNED FROM BLACKOUTS

During 2003 there were 5 internationally well-known blackouts that within 6 weeks hit 112 million people in 5 different countries (Italia, USA, Great Britain, Denmark/Sweden and Finland). Blackouts did not waive around Croatia. In 2003 it suffered from 3 major blackouts. One of them is described here. Lessons learned on the basis of post-mortem analyses of these blackouts and some past ones are given hereafter in shortened basic form:

- Review procedures of tree trimming schedules along paths of transmission lines.
- Take care of each MW that can be generated and transmitted.
- Periodically test responses of generating units in simulated conditions of emergency states.
- Gas aggregates shall always be available or available for remote starting-up.
- Install alarms at each gas aggregates.
- Modify gas aggregates to enable realization of their black start capability (starting-up in no-voltage conditions) and supply of plant’s local load.
- Modify voltage regulation block in excitation system of gas aggregate in order to compensate reactive power produced by shunt capacitances of plant’s connecting cables.
- Explore possibilities for separation of generating units from the network and supply of plant’s local load rather than its emergency shutting-down.
- Introduce remote ‘one button’ control aimed for fast response.
- Introduce remote switching-in/switching-out/starting-up from dispatching center in emergency states.
- Establish checking procedures for plant’s main regulation circuits with respect to their proper designing, commissioning and monitoring.
- Conduct system tests in order to validate models in high loading conditions by comparing measured and modeled responses of fundamental system variables.
- Coordinate data collected on basis of conducted tests with data obtained from monitoring of real disturbances and conduct analysis on such coordinated data.
- Conduct additional analysis aimed for system model checking to increase quality level of parameterization with respect to real disturbances.
- Introduce system monitoring at key locations.
- Continually conduct monitoring and promote development of means for system oscillations analysis.
- Develop and use models aimed for evaluation of system stability in frequency domain.
- Organize workshops/seminars and provide consulting services to educate personnel for work on analytical software in frequency domain (MASS, PEALS, Prony).
- Enhance means aimed for direct modal analysis of system electromechanical oscillations.
- Provide technical overview of suggested regulation circuits that can significantly improve damping of system oscillations.
- Review computer models of system elements that participate in weakly damped oscillation modes.
- Develop and install advanced information network technology to measure and monitor system dynamic behavior.
- Investigate and develop advanced mathematical procedures aimed for extraction of information that belong to system dynamic behavior on the basis of conducted measurements.
- Exchange information on boundary regions of reactive power generation in a precise and timely adequate way to improve system models for planning and operation.
- Investigate and develop monitoring procedures for generator reactive power and voltage magnitude in order to determine generators that are not capable to follow operating requirements regarding Q-V limitations.
- Establish common standard for evaluation of steady-state generator operation as well as after disturbances (15-minute period) with respect to capability of reactive power generation; determine methodology, testing and operation requirements.
- Determine level of services that generators must provide with respect to reactive power generation in order to fulfill system security requirements.
- Periodically review and test boundary regions of reactive power generation in order to check generator’s capability to achieve declared values.
- Enable operating personnel with real-time indication of available reactive power generation from each generator (or group of generators) and other sources of reactive power as well as indication of reactive power reserve margin in critical buses. This enables maximization in usage of shunt capacitor banks during large power transits and increases availability of reactive power reserves that belong to elements with faster response.
- In voltage stability problems, necessarily analyze fast automatic switching of capacitor banks (shunt and series), direct disconnection of shunt reactors and loads as well as undervoltage load shedding.
- Develop and periodically review reactive power margin that serves as a basis for evaluation of system security with respect to realization of the largest allowed power transits.
- Review system voltage responses to disturbances.
- Add of modify devices for voltage regulation in system buses.
- Secure provision of information to operating personnel in clear and concise manner.
- Develop communication and visualization systems that provide operating personnel momentary information on changes of switching statuses of main components in own system as well as in neighboring ones.
- Introduce uninterruptible supply of communication systems to enable exact transfer of information on system state to control centers during emergencies.
- Introduce back-up supply in communication system.
- Install diesel-generator sets in power plants to independently supply own local and auxiliary loads.
- In dispatching centers, use dynamic determination of line loading levels and display data on outages to provide operating personnel fast and understandable information on availability of system elements as well as of operating conditions of each element.
- In dispatching centers, introduce such energy management system which enables operating personnel to have computer generated system responses to applied specific action together with expected results of such action.
- Establish procedure of real-time system security estimation in order to detect critical outages with respect to limitations related to thermal overloading, voltage magnitudes and stability.
- Establish timely synchronized monitoring of system during emergency states to evaluate security of interconnected system upon appearance of disturbances and develop adequate protection systems.
- Upon outages, system shall get back to reliable operating point within acceptable time period. Operating rules and guidelines need to be reviewed to define action plan for system restoration during acceptable time period.
- Decrease announced power transits down to secure level until having analytically proved loading limits or total transmission capability of system.
- Establish procedures for recognition of unusual system operating conditions and potentially dangerous scenarios of disturbance development in order to analyze them before they appear in real operation.
- Verify and correct grounding of transmission towers.
- Prepare procedures for proper handling with relays.
- Test proper functioning of protection systems in largest possible way.
- Check coordination of protection systems.
- Introduce back-up protection systems at critical elements.
- Periodically test system behavior during activation of protection schemes. When installing protection schemes it is necessary to conduct testing of complete protection system as well as testing of each individual component to verify acceptability of their activation.
- Continually upgrade protection systems with respect to coordination with infrastructural changes in system and enhance supervision over relays.
- At critical transmission lines install devices for recognition of disturbed states and connect them with automated systems for load shedding or generation disconnection if short term overloading capability is at risk. Time delay of activation shall have sufficiently large value to provide operating personnel some time to decrease line loading in some other way.
- Analyze activation of synchro-check relays during blackout.
- Review constraints related to phase angle that can prevent reconnection of main transmission lines during emergency states. Analyze blocking of synchro-check relays to enable direct connection of critical lines in order to preserve system stability in emergency states.
- Prepare criteria for controlled system separation to islanded regions in emergency situations.
- Avoid uncontrolled system separation to islanded regions.
- Review needs for controlled system separation to islanded regions. Operating guidelines shall point out to possible appearance of large unbalances between generation and load within islanded regions.
- Establish and maintain coordination of automatic load shedding to avoid total loss of supply in region that is separated from main network and in deficit with generation. Shedding shall be treated as auxiliary program and not as a replacement for proper system design.
- Install shedding program in such a way to enable operating personnel fast activation of disconnection of large blocks of power.
- Revise operating plans in emergency states.
- Stuff operating personnel teams in adequate and organizationally acceptable way in order to improve quality level of resolving emergency issues.
- Prepare and train procedures for resolving emergency states.
- Prepare and continually train procedures for fast state restoration.
- Prepare plan of state restoration in such way that loads can be connected to network shortly upon connection of appropriate transmission element (not waiting on a full network restoration for a load connection).
- Prepare procedures for reconnection with other networks.
- Prepare and train procedures of fast reaction of operating personnel on overloads.
- Conduct training programs of operating personnel for activation in emergency states.
- In training program introduce system simulator to train operating personnel for actions in normal and emergency states.
- Procedures and training programs of operating personnel shall include expectation, recognition and definition of emergency states.
Written guidelines and material used for operating personnel training purposes shall include criteria that are used for recognition of signs of disturbed states and countermeasures of disturbance spreading that shall be applied before transferring system in emergency state.

Procedures for decrease of line loading should not be based on conditions that are noticed in emergency states since these procedures in many cases can not be efficiently applied in requested time period that is available to operating personnel.

Determine operating guidelines for each piece of equipment.

Work on wider guidelines that can enable operating personnel direct load disconnection before fatal cascading sequence of events.

Operating personnel shall necessary accept responsibility for momentary reaction to restore normal system state.

Operating personnel permissions and responsibilities for applying momentary actions shall be specifically emphasized and protected upon sensing degradation of system state.

Procedures for risk estimation of voltage instability and procedures for improving existing training programs shall be reviewed to enhance estimation of future voltage problems before they appear or spread to nearby regions.

Specific details that are related to lessons learned from this blackout are given [1]. These details are of utmost importance in proper and adequate system operation. By resolving them, total security level of Croatian system can be significantly increased.

X. GUIDELINES FOR PROVISION OF MANDATORY EMERGENCY PLANS

This blackout gives solid impact to proceed with defining emergency procedures and forming general emergency plans of activities for each relevant party involved [9]. Plans for protection from large disturbances such as blackouts and system state restoration after a blackout shall be necessarily coordinated with valid legislative acts and included in grid codes at least at a level of definition of responsibility with respect to prevention and resolving of emergency situations.

Plan for protection from large disturbances shall be prepared for situations where malfunction of any key element happens in a chain generation - transmission - distribution - consumption. Such plan can not cover all possible system events, equipment faults or human errors. However, it shall be composed of measures that might be computer tested with regard to a wide variety of different and less probable events. Thus, it should be kept on mind that simultaneous disturbances can bring the system to the verge of total or partial blackout independently of valued technical, planning or operational aspects that define security level of system operation. This creates necessity of making and testing of system state restoration plans with an ultimate objective to re-establish normal state as fast as it is possible. The first task in such plan falls to the scope of countermeasures that limit spreading of a disturbance further from faulted area and decrease duration of emergency situation.

Post-mortem analysis and report is treated as one of significant measures that indirectly influence operational system security. Adequate report, based on careful and professional reconstruction and analysis of all events, provides an overview of causes, consequences and responsibilities for appeared events. Moreover, it points out to discrepancies that should be removed in order to prevent future blackouts. Therefore, it shall be mandatory defined which elements should be covered in such a report and to which level such analysis should be conducted.

In case of total or partial blackout, basic objective of the system operator is found in determination of priorities and directives that are aimed for system state restoration. It is necessary to define activities that fall to that scope. At first, current system state shall be recognized before starting to work on restoration. While restoring a system state, all operating constraints that can slow down restoration process should be detected and respected thoroughly. Upon detection of status of generating power plants it is necessary to detect status of transmission network according to precisely stated activities. Certainly, system state restoration procedures shall be activated as fast as it is possible. But, root cause of blackout should be known before that since extreme precaution should be applied otherwise. Moreover, in cases of system restoration due to heavy environmental disasters (earthquake, flood, fire…) it is necessary to send a field team to check status of telecontrolled power plants that have no operators.

System state restoration by using interconnecting lines is acceptable when fast voltage re-establishment accompanied with stable frequency is needed. The system operator in cooperation with the other parties is requested to find out possible ways for accepting the voltage from neighboring system operators and achieve agreement on emergency power exchange. The system operator, in consent with neighboring system operators, defines needed activities and approximate amount of power exchange (together with sequential start-up of own generating plants) to achieve acceptable voltage level in no-load conditions at bordering buses. Thus, the system operator shall make detailed plan of activities and consent operative agreements with neighboring system operators. Such plan shall include measures and procedures needed for activation in pre-specified emergency situations. The system operator decides on schedule of switching-in of individual transmission lines at 400 kV, 220 kV and 110 kV voltage levels, power transformers and compensating devices. It makes valid transmission network diagram and in coordination with distribution network operators sequentially synchronizes and connects system parts.

System state restoration by using own generating power plants is realizable in case that sufficient number of the plants with black-start capability is on the operator’s disposal. This approach is unavoidable in case that it is not possible to get voltage from external systems. It is more complicated and lasts longer, but with detailed procedures,
well trained personnel and adequate cooperation of interested parties it is achievable without larger problems.

It is interesting to note that during war period in last decade there were 42 total blackouts in Dalmatia and BH which were in common in isolated operating mode. Usual duration of system state restoration after a blackout was between 15 and 30 minutes with fulfilling of all constraints in generation, transmission and consumption of electrical energy. This blackout lasted for approximately 2 hours.

In order to achieve adequate speed of system state restoration all generating power plants shall have clearly defined guidelines and emergency procedures (Emergency Code). They shall be approved by the system operator. Upon starting-up of generating power plants, further state restoration shall be based on re-energizing of larger network portions before total reconnection of consumer loading. Reconnection of consumer loadings in short period represents significant element in restoration procedure. It requests valid coordination and backward confirmation of available generation capacities before taking larger consumer loadings.

It should be noted that reconnection of isolated system areas (especially those with directly connected generation) has advantage before re-establishment of services for end-users. If it is detected that due to status of the whole system re-synchronization of isolated areas should be delayed, then individual areas should be controlled in a balanced manner such that local consumption is matched to available generation. Priority before re-establishment of service for all end-users shall have energy needed for start-up of accessible generating power plants followed by supply of large cities.

XI. CONCLUSIONS

During 2003 there were 5 internationally well-known blackouts that within 6 weeks hit 112 million people in 5 different countries (Italia, USA, Great Britain, Denmark/Sweden and Finland). Blackouts did not waive around Croatia. In 2003 it suffered from 3 major blackouts. One of them is described here.

In the analysis of the blackout that happened on January 12, 2003 it is concluded that one pole of the circuit breaker in 400 kV bus Konjsko at line bay Velebit on OHL 400 kV Konjsko – Velebit did not break fault current when activated to switch off the line at 16:43:58.998 hours. The initial fault caused cascading outages of larger number of transmission lines and generators due to significant asymmetries which for a final consequence had the blackout in Dalmatia and Bosnia Herzegovina.

Data analysis of the blackout is based on all relevant documentation obtained from different sources within HR and BH systems. The role of neighboring system operators is primarily analyzed on the basis of collected chronological event listings and real-time recorded responses by relays concerned. The analysis contains security estimation of the initial steady-state to show awareness and preparedness of the system operators to deteriorated system conditions. Analytical findings are used to point out to available countermeasures aimed for alleviation of consequences in state restoration.

Analysis of reconstructed initial steady state just before the blackout points out to conditions of regionally well balanced system operation before the initial fault appeared. It is seen that the system operators applied appropriate measures to balance power exchange between regions of the systems and minimize consequences of eventually troublesome situations.

Within state restoration period, coordination of the neighboring system operators was of utmost importance. It is shown as necessary to provide the system operators all information concerning key infrastructural objects. Black-start capability of key hydro generating power plants has the most important role while reestabishing load supply. The system operators need to have properly disseminated information of every reconstruction taken on regulating circuits. Otherwise, it may additionally slow down the system operators activities on state restoration after the blackout.

From the numerical analysis part, it is seen that starting electromechanical oscillations are recognized as stabilized at first. Then with mutual separation of different system parts they become unstable in Dalmatia and BH. The separation is motivated by disconnection of OHL 110 kV Novalja - Pag (the island link) and especially OHL 220 kV Dakovo – TPP Tuzla (the northern link). After their outages, generators in Dalmatia and BH become disconnected from the network, while generators in the northern part of the HR system keep stable operation.

Activation of the special protection system in 220 kV bus Dakovo which contains disconnection of OHL 220 kV Dakovo – TPP Tuzla prevented spreading of the blackout to the north-eastern part of the HR system. After the outage of generator G1/120 MVA/110 kV in HPP Dubrovnik, fast voltage collapse would have happened even there if before that the northern 220 kV link was not switched off. After the outage of that generator, the power flow through the northern 220 kV link would have been further increased. This would have additionally decreased voltage magnitudes and caused faster blackout in the whole HR system.

Blacksouts give solid impact to proceed with defining emergency procedures and forming general emergency plans of activities for each relevant party involved. Plans for protection from large disturbances such as blackouts and system state restoration after a blackout shall be necessarily coordinated with valid legislative acts and included in grid codes at least at a level of definition of responsibility with respect to prevention and resolving of emergency situations.

XII. LITERATURE


