Activation of special protection system during blackout

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Abstract

Technical aspects of the blackout that happened on January 12, 2003 in southern part of Croatia (HR) and Bosnia Herzegovina (BH) are analysed with respect to the role of the special protection system (SPS). Activation of the SPS during chronological sequence of blackout events represents main topic of this paper. The SPS is located at the northern 220 kV link between HR and BH systems and serves for their controlled emergency disconnection. It is shown here that its implementation and proper activation during the blackout prevented northern part of HR system from suffering voltage collapse. Real time measurements are found in several relays that belong to the SPS. These measurements are used as a basis while establishing sequence of events for the most probable blackout scenario. The scenario is simulated by using detailed dynamic model of concerned systems. Numerical analysis confirmed findings from data analysis based on various event recording listings. Root causes and consequences of the blackout are recognised and a set of countermeasures is proposed to the utilities in order to prevent its reoccurrence.

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 localised interruption of customer supply [1]. It represents a series of severe disturbances 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 behaviour of HR system, but 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 realised 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 for learning most important lessons to applying available countermeasures and preventing reoccurrence of similar incidents [5-6].

Numerous technical aspects of the blackout that happened on January 12, 2003 are analysed in [1]. 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 analysed in detail with respect to all relevant events recorded in collected documentation [7]. Generic description of the blackout from the system operators' viewpoint is given in [8]. Recognition of advantages that are made by installation and proper coordination of the special protection system (SPS) are set as the main objective in this work. The SPS is installed at the northern 220 kV link between HR and BH systems (OHL 220 kV Đakovo – TPP Tuzla). It primarily serves for controlled separation of 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 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. Activation of the SPS is first analysed 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 [9]. 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.

Root causes and consequences of the blackout

In order to recognise the system state before the blackout, general transmission network configuration is shown depicting severed southern area around bus Velebit 400 kV that was hit by weather storms (Fig. 1). Network state is endangered not only in HR system, but in 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 realised over these two systems.

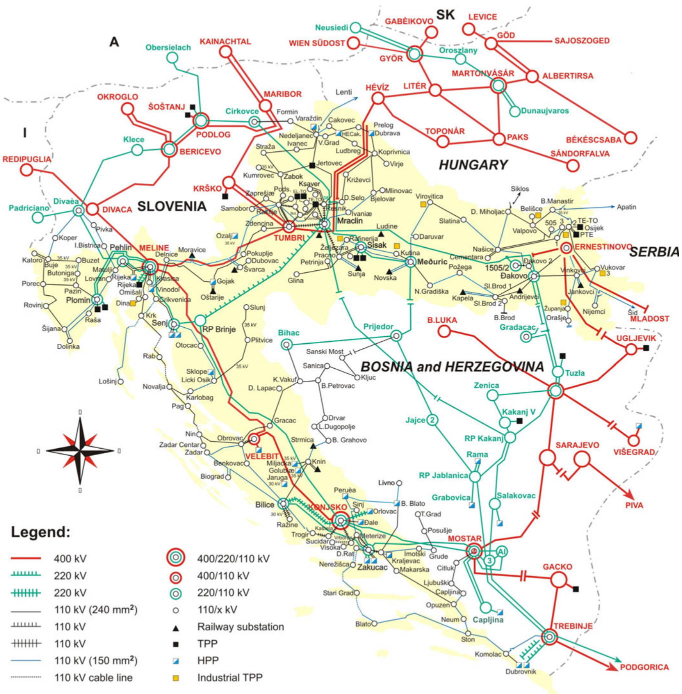

Figure 1 General network configuration of the HR system

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, show/wind storms, and frequent line outages caused by automatic re-closing. 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 quality of regional interconnection 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 lines were outaged. From one side, Dalmatia was connected to the BH system over OHLs 220 kV Zakučac – Mostar, DV 220 kV Konjsko – Mostar, and further through the BH system over OHL 220 kV Đakovo – TE 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 is less significant for the southern interconnection due to small value of 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. Balanced operation is achieved by coordinated schedule of generating plants. However, this is not quite simple to fulfil in longer time period.

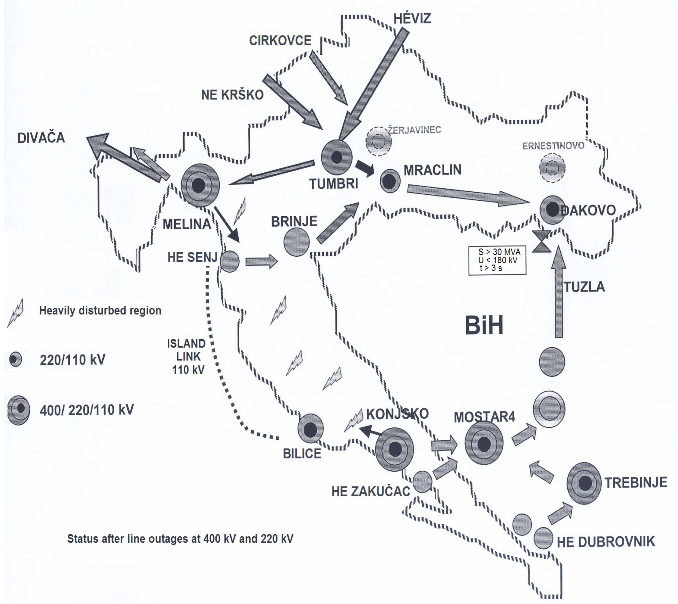

Figure 2 Deteriorated network configuration of the HR system

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 and the other in Dalmatia. Slavonian connecting point is located at 220 kV bus Đakovo at the northern link OHL 220 kV Đakovo – TPP Tuzla. Dalmatian connecting point comprises OHLs 220 kV Konjsko – Mostar and 220 kV Zakučac – Mostar, what with OHL 220 kV Konjsko – Zakučac makes common 220 kV loop of linked buses Zakučac, 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 unfavourable circumstances the critical sequence of events may be recognised that at the end caused the blackout.

During January 11 and 12, 2003, multiple activation of single phase line re-closing was registered on OHL 400 kV Konjsko – Velebit. That line was switched on/off many times upon temporary faults. Due to need for enhancement of the system security, the intention was to outsource voltage to the pumped-storage HPP Velebit by operating OHL 400 kV Konjsko – Velebit. That was needed to support auxiliary supply circuits in the HPP Velebit should it be synchronised to the system.

The blackout happened on Sunday, January 12, 2003 at 16:44 hours. 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).

The balance between generation and load in wider regions of Dalmatia and BH points out to regionally balanced operation in conditions of deteriorated system security due to initial unavailability of transmission lines. The northern 220 kV link (OHL 220 kV Đakovo – 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. Before the incident, the HR system was situated at 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 500-600 MWh/h. Loading level in the HR system was changed nearly 500 MW; load power fell from 2060 MW to 1560 MW. Besides, the incident initially caused change of generation power in the HR system of 540 MW; generating power fell from 1940 MW to 1400 MW. 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.

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 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. Such a short restoration time is possible due to large proportion of hydro generation. This blackout lasted for nearly 2 hours. 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. 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 nearly $ 2.375,000. Since the blackout happened on Sunday, the damage might have somewhat smaller value. Damage on infrastructural equipment due to weather storms was significantly larger.

Short circuit on OHL 400 kV Konjsko – Velebit near bus Velebit is recognised as the triggering event that initiated the blackout due to problems with protection rope (Fig. 3). That line was switched on shortly before (at 16:34) from Konjsko side and supplied uni-directionally 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 off OHL 400 kV Konjsko - Velebit at 16:43:58.998 hours. This is concluded due to continuously present initialisation of protection systems in buses Konjsko, Zakučac and Bilice (even after activation of the breaker). Initialisation of southern HPPs protections from unsymmetrical conditions supports this too.

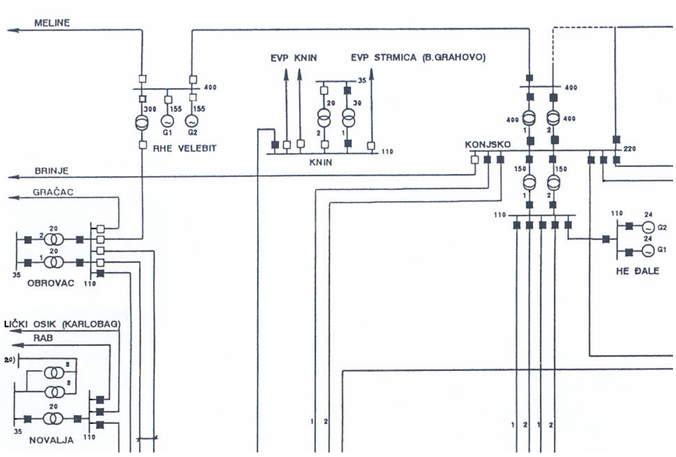

Figure 3 Location of the initial disturbance that caused the blackout

Spreading of the disturbance is not efficiently localised 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. Shortly afterwards (within 30 s), it caused cascading outages of lines (distant protection) and power plants (protection from unsymmetrical loading) in Dalmatia. The blackout appeared as a final consequence.

On the basis of analysed 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. In Table 1, field records are given above simulation times that are given 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.

All generators in Dalmatia were outaged within 30 s from the initial disturbance. Due to large power unbalance, power flows were increased over the island 110 kV link and the northern 220 kV link (OHL 220 kV Đakovo – TPP Tuzla towards Tuzla). Due to overloading, the island 110 kV link was first broken at the section OHL 110 kV Novalja – Pag. Then, the only connection left between two main HR regions was the northern 220 kV link which experienced additionally increased loading. Shortly afterwards it was outaged due to activation of the SPS. The SPS (coordinated with undervoltage load shedding) disconnected that link in bus 220 kV Đakovo due to impending voltage collapse and thereby prevented Slavonia from the blackout that already spread in Dalmatia and BH.

Table 1 Sequence of events in the HR system during the blackout (field records are given above simulation times that are given in round brackets)

TIME (hh:mm:ss)	EVENT
16:43:58.603 (10.000 s)	Three phase short circuit at uni-directionally supplied OHL 400 kV Konjsko – Velebit (80 km from Konjsko).
16:43:58.998 (10.395 s)	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.
16:44:00.474 (11.871 s)	In HPP Dubrovnik breaker activation (off) at OHL 220 kV Plat – RP Trebinje. Outage of generator G2/120 MVA/220 kV in HPP Dubrovnik.
16:44:01.224 (12.621 s)	In HPP Zakučac breaker activation (off) at generator G3/150 MVA/220 kV.
16:44:01.627 (13.024 s)	In HPP Đale breaker activation (off) at generator G2/24 MVA/110 kV.
16:44:02.499 (13.896 s)	In HPP Đale breaker activation (off) at generator G1/24 MVA/110 kV.
16:44:02.879 (14.276 s)	In HPP Zakučac breaker activation (off) at OHL 220 kV HE Zakučac – Konjsko.
16:44:03.175 (14.572 s)	In HPP Zakučac breaker activation (off) at generator G2/120 MVA/220 kV.
16:44:05.049 (16.446 s)	In bus Nin breaker activation (off) at OHL 110 kV Nin – Pag (breakage of the island 110 kV link).
16:44:05.051 (16.448 s)	In bus Novalja breaker activation (off) at OHL 110 kV Novalja – Pag (breakage of the island 110 kV link).
16:44:07.995 (19.392 s)	In HPP Čapljina breaker activation (off) at generator G2/240 MVA/220 kV; 1.5 s before outage of OHL 220 kV Đakovo - TPP Tuzla (the only simulated BH event)
16:44:08.339 (19.736 s)	In HPP Zakučac breaker activation (off) at OHL 220 kV Zakučac – Bilice.
16:44:09.495 (20.892 s)	In Đakovo breaker activation (off) at OHL 220 kV Đakovo–TPP Tuzla (breakage of the northern 220 kV link).
16:44:12.031 (23.428 s)	In HPP Dubrovnik breaker activation (off) at OHL 110 kV Plat – Komolac. Outage of generator G1/120 MVA/110 kV in HPP Dubrovnik.
16:44:13.196 (24.593 s)	In HPP Zakučac breaker activation (off) at generator G1/120 MVA/110 kV.
16:44:16.656 (28.053 s)	In bus Vrboran breaker activation (off) at OHL 110 kV Konjsko – Vrboran (1/2).
16:44:16.665 (28.062 s)	In bus Vrboran breaker activation (off) at OHL 110 kV Konjsko – Vrboran (2/2).
16:44:17.132 (28.529 s)	In bus Vrboran breaker activation (on) at OHL 110 kV Konjsko – Vrboran (2/2).
16:44:17.169 (28.566 s)	In bus Vrboran breaker activation (on) at OHL 110 kV Konjsko – Vrboran (1/2).
16:44:17.226 (28.623 s)	In bus Vrboran breaker activation (off) at OHL 110 kV Konjsko – Vrboran (1/2).
16:44:17.232 (28.629 s)	In bus Vrboran breaker activation (off) at 110 kV Konjsko – Vrboran (2/2).
16:44:17.258 (28.655 s)	In bus Konjsko at 110 kV side breaker activation (off) at ATR1 220 kV / 110 kV.
16:44:17.261 (28.658 s)	In bus Konjsko at 220 kV side breaker activation (off) at ATR2 220 kV / 110 kV.
16:44:17.279 (28.676 s)	In bus Konjsko at 110 kV side breaker activation (off) at ATR2 220 kV / 110 kV.
16:44:17.284 (28.681 s)	In bus Konjsko at 220 kV side breaker activation (off) at ATR1 220 kV / 110 kV.
16:44:17.582 (28.979 s)	In bus Makarska breaker activation (off) at OHL 110 kV Makarska – Opuzen.
16:44:18.064 (29.461 s)	In bus Makarska breaker activation (on) at OHL 110 kV Makarska – Opuzen.
16:44:18.456 (29.853 s)	In bus Blato breaker activation (off) at OHL 110 kV Blato – Ston.
16:44:19.120 (30.517 s)	In bus Blato breaker activation (on) at OHL 110 kV Blato – Ston.
16:44:22.467 (33.864 s)	In HPP Zakučac breaker activation (off) at generator G4/150 MVA/110 kV.
16:44:31.724 (43.121 s)	In HPP Peruća breaker activation (off) at generator G1/26 MVA/110 kV.

Special protection system (SPS)

Being properly designed and coordinated, the SPS has the first class significance. If a protection relay of an individual element is treated as the first line of system defence from disturbances, and a back-up relay as the second one, then the SPS represents the last defence line. When the first and the second defence 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 SPS mostly focuses at alleviation of consequences or their localisation.

In 220 kV bus Đakovo 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 Đakovo – 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 Đakovo 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 Đakovo 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 – Đakovo 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).

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

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

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

The first signal that revealed system stability problems was related to detection of power swings along OHL 220 kV Đakovo – Mraclin. The signal was registered in bus Đakovo at the protection terminal bay 220 kV Mraclin at 16:44:01.648 hours. Figure 4 depicts recordings of swings that belong to the phase voltages and currents at protection terminal bay 220 kV Mraclin in bus Đakovo with start at 16:44:01.448 hours. During following two seconds that are memorised 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 5 depicts recordings from the protection terminal bay 220 kV Mraclin in bus Đakovo at OHL 220 kV Đakovo – Mraclin started at 16:44:05.655 hours. Simultaneous voltage decrease and current increase points out to impending voltage collapse in the 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 – Našice (northern Slavonia) and N.Gradiška – Požega – Sl.Brod (southern Slavonia) and along 220 kV OHLs Đakovo – TPP Tuzla and Đakovo – Mraclin. These activations point out to voltage collapse and significant increase of power flows along the paths. Simultaneously, OHL 110 kV Požega – Sl.Brod was switched off in bus Požega 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 Požega. Precisely 3 seconds after continuously satisfied conditions, the SPS was activated to switch off OHL 220 kV Đakovo – TPP Tuzla on the basis of the voltage value in 220 kV bus Đakovo 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 protection 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. Underimpedance relays are set at 70 Ω for the line bay 110 kV Našice and 55 Ω for 110 kV Virovitica. Table 2 lists values of currents and voltages in bus Virovitica that were registered at that moment.

Table 2 Values of currents and voltages registered in bus Virovitica

TS Virovitica 110 kV registered values of currents and voltages on 12/01/2003 at 16:44 hours				
Time (internal clock)	Phase	Voltage (kV)	Current (A)	Apparent power (MVA)
16:43:03.191	L1	44.8	652.7	
	L2	43.4	659.3	85
	L3	43.7	629.0	
16:43:04.662	L1	41.2	662	
	L2	39.8	662	81
	L3	43.0	633	

At 16:44:09.444 hours, the undervoltage load shedding was applied in bus Požega according to the same criteria (voltage less than 90 kV, current flow from bus N. Gradiška larger than 400 A). It disconnected 15 MW of consume in bus Požega. Afterwards, the distant relay was activated in 2nd zone on OHL 110 kV S. Brod – Požega 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. Gradiška registered at that moment.

Table 3 Values of currents and voltages registered in bus N. Gradiška

TS N. Gradiška 110 kV registered values of currents and voltages on 12/01/2003 at 16:44 hours				
Time (internal clock)	Phase	Voltage (kV)	Current (A)	Apparent power (MVA)
16:43:36.125	L1	60.12	502.8	
	L2	60.02	525.2	91
	L3	59.65	495.3	
16:43:39.287	L1	46.60	767,5	
	L2	47.51	784.3	108
	L3	46.73	745.1	

Shortly afterwards the SPS was activated at OHL 220 kV Đakovo – TPP Tuzla in the line bay 220 kV Tuzla at 16:44:09.495 hours. All three criterions were satisfied which caused switching off of the circuit breaker at the line bay 220 kV Tuzla in bus Đakovo on OHL 220 kV Đakovo – TPP Tuzla. It happened 3.373 seconds after registration of the first signal in Slavonian network. Data analysis of available chronological events from protection terminals located at bays 220 kV Tuzla and 220 kV Mraclin in 220 kV bus Đakovo 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 Đakovo registered voltages 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 Đakovo – TPP Tuzla in direction of Tuzla. Following listing witnesses about that:

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LOCATION OF PART
Organiz      HEP PRP OS
Station      TS DJAKOVO
Obj/Bay      VP TUZLA
Unit         REL531A V1.0 C  Line protection terminal
Mod/Part     REL531A DRP-TRIP  Fault locator - Trip values ...
REL531  DRP-TRIP  Monitor Screen 3 of 3
DREP NO.49  - TRIP VALUES
Date,Time = 03-01-12 16:44:09.415         ł Trig Signal = TRIP-GTRIP     ł

    ł               ł  PreFault Condition     łł  Fault Condition        ł
    ł Analog. Input ł Magnitude  ł Phase      łł Magnitude  ł Phase      ł

    ł U1            ł 61.4    kV ł 0.0   deg  łł 59.8    kV ł 358.2 deg  ł
    ł U2            ł 54.9    kV ł 237.7 deg  łł 55.3    kV ł 232.3 deg  ł
    ł U3            ł 56.2    kV ł 123.4 deg  łł 53.1    kV ł 118.8 deg  ł
    ł U4            ł 0.3     kV ł 25.4  deg  łł 0.3     kV ł 76.7  deg  ł
    ł U5            ł 0.1     kV ł 231.9 deg  łł 0.1     kV ł 231.9 deg  ł

    ł I1            ł 1976.1  A  ł 18.2  deg  łł 1930.4  A  ł 17.9  deg  ł
    ł I2            ł 2001.1  A  ł 255.5 deg  łł 1923.2  A  ł 255.7 deg  ł
    ł I3            ł 1919.3  A  ł 136.6 deg  łł 1876.6  A  ł 137.1 deg  ł
    ł I4            ł 11.3    A  ł 156.0 deg  łł 15.1    A  ł 108.6 deg  ł
    ł I5            ł 2.6     A  ł 324.9 deg  łł 2.6     A  ł 322.5 deg  ł

    ł f             ł 49.90   Hz ł            łł            ł            ł
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Approximately 2 s before registration of shown measurement from the line bay 220 kV Tuzla, the relay at the line bay 220 kV Mraclin in bus Đakovo 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 network and protection systems were deactivated. Consumes in buses Slatina and Požega 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 Đakovo, the circuit breaker was switched on at the line bay 220 kV Tuzla (16:49:54.268 hours). At 17:34 hours on OHL 220 kV Đakovo – 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 Đakovo which confirmed proper design of the SPS. That was not a 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 interesting time dependences of voltage magnitudes and power flows in the north-eastern part of the HR system were graphically recorded during the blackout. Figure 6 shows time dependence of voltage magnitude in 220 kV bus Đakovo. 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 7 shows time dependence of active power flow on OHL 220 kV Đakovo – Mraclin, whereas Figure 8 shows the flow on OHL 220 kV Đakovo – TPP Tuzla. Their larger variability appeared in period between 16:43 and 20:30 hours when Dalmatia suffered from the blackout. Complete transient process is not seen due to larger time sampling.

Upon thorough data analysis based on available recordings and listings it is concluded 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 Đakovo – 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.

Time domain simulation scenario of the blackout

In simulation phase of the blackout analysis it is necessary to check out quality of established computer 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 recognise 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.

Calculations are carried out on the basis of established sequence of events to help analyse technical problems associated to the blackout. This 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 analysed 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. After that, the initial steady state that preceded the blackout is numerically analysed followed by simulation of the chronological sequence of events according to established blackout scenario during approximately 30 s.

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 buses voltage deviations are between +5% and +10%, or -5% and -10%. In the system state that preceded the blackout there were neither problems with overloadings nor with voltage regulation.

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 overloadings. 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. Most important influence to criterion fulfilment comes from regionally balanced system operation due to minimised power exchanges between the HR and BH systems as well as between the regions of the HR system. In the northern part of the HR system which was not hit by the blackout, the (N-1) criterion was not fulfilled (largest overloading: 136% in Slavonia, location: Đakovo).

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 realisation of small power exchanges (<100 MW) happening 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 lose synchronism provided that they would have been removed within standard activation time of concerned breakers. They are mostly larger than 0.3 s, and it does not point out to problems with respect to keeping generator angle stability during first swing upon temporary three-phase short circuit. Simultaneously, subtransient three-phase short circuit currents are smaller than concerned breaker capabilities in these buses. Short circuit power at the interface between generating plants and the network 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) defined by concerned breaker activation and at least 6 times larger value of the three-phase short circuit power at the interface between generating plant and the network than the installed nominal active power.

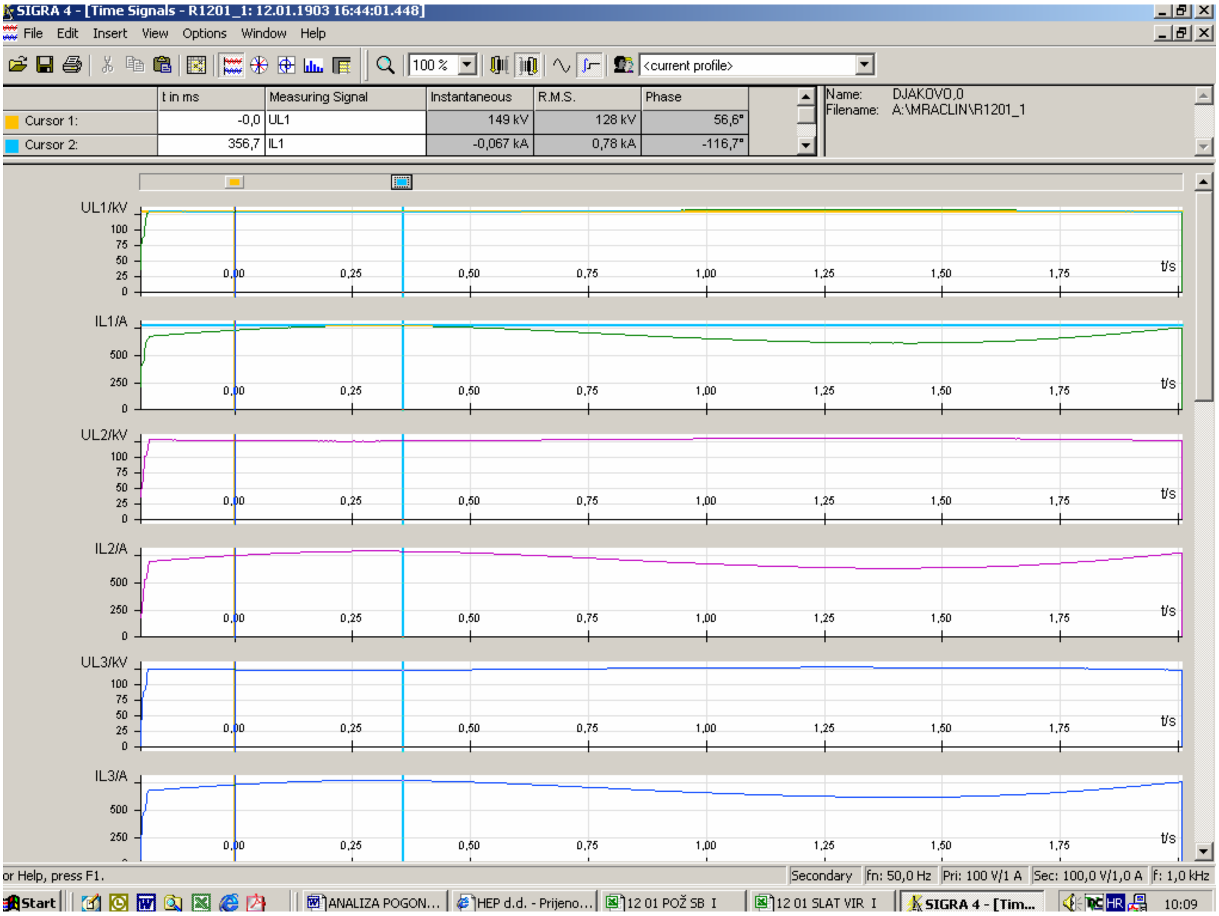

Figure 4 Voltages and currents during power swings on OHL 220 kV Đakovo – Mraclin in Đakovo at bay 220 kV Mraclin

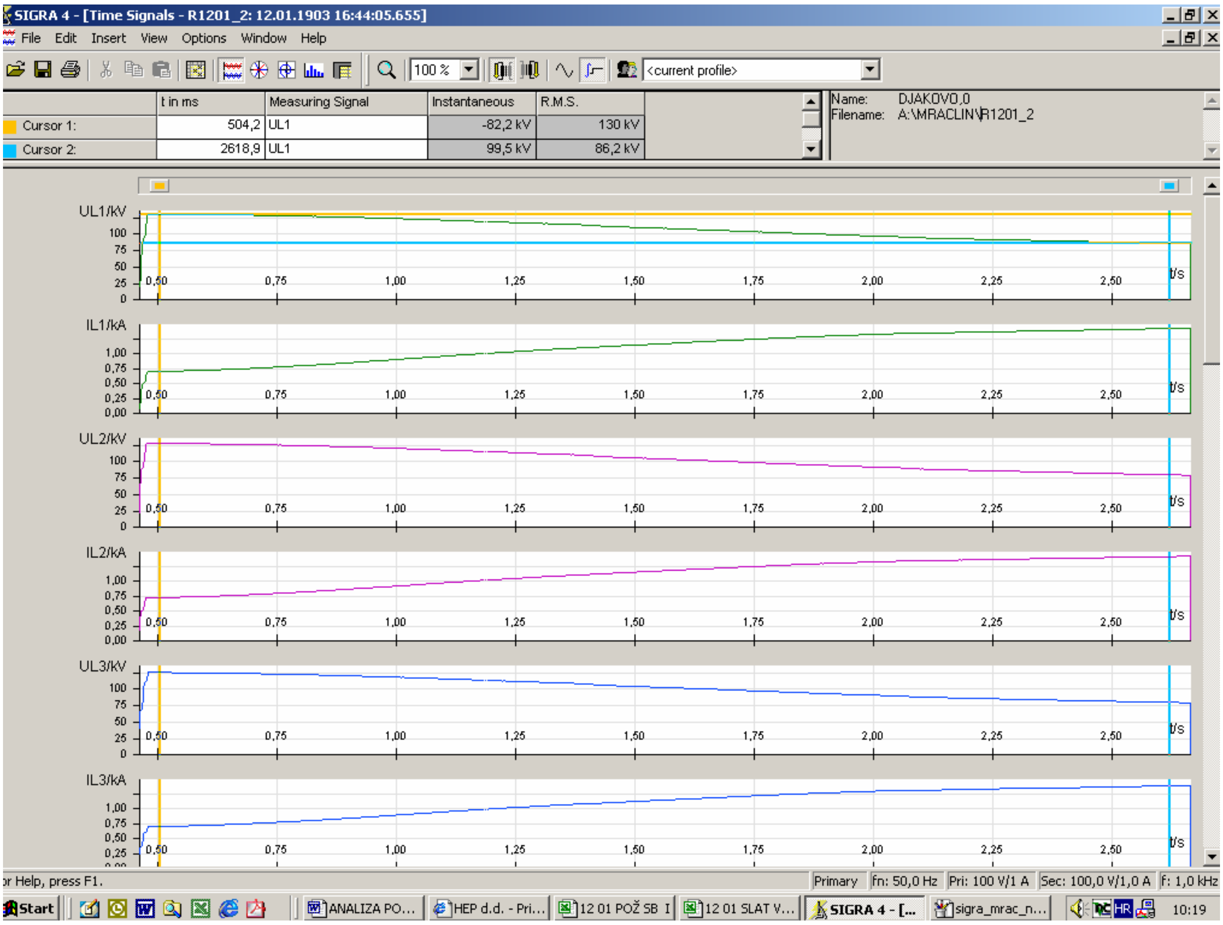

Figure 5 Voltage decrease and current increase on OHL 220 kV Đakovo – Mraclin in Đakovo at bay 220 kV Mraclin

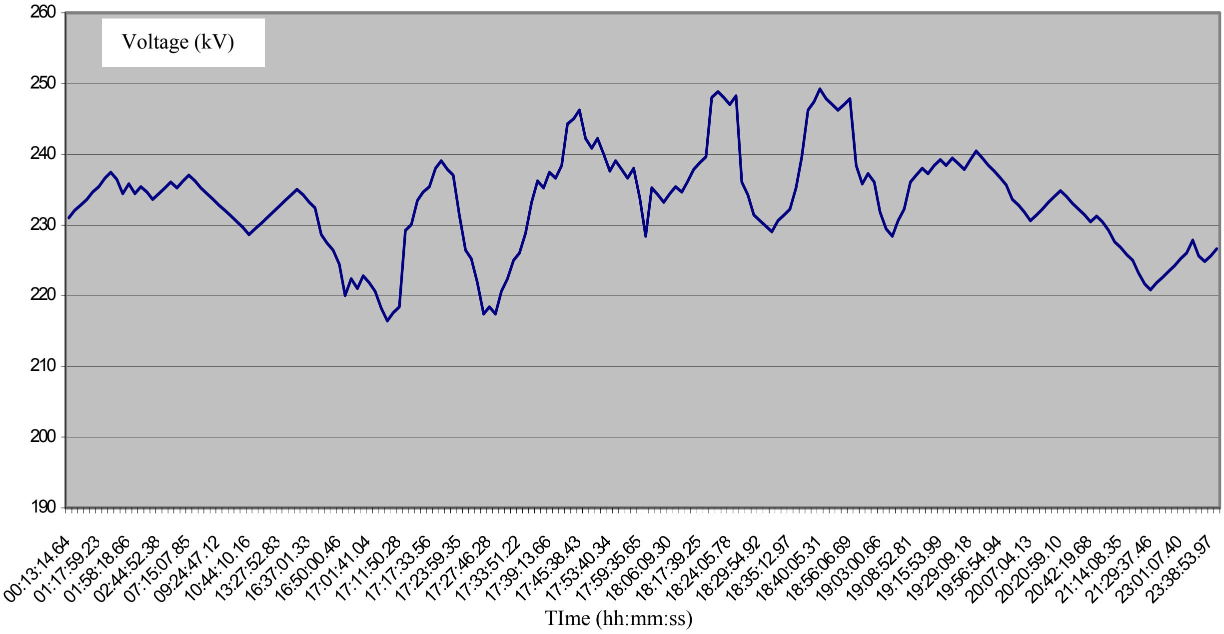

Figure 6 Voltage magnitude in 220 kV bus Đakovo during the blackout in Dalmatia on January 12, 2003

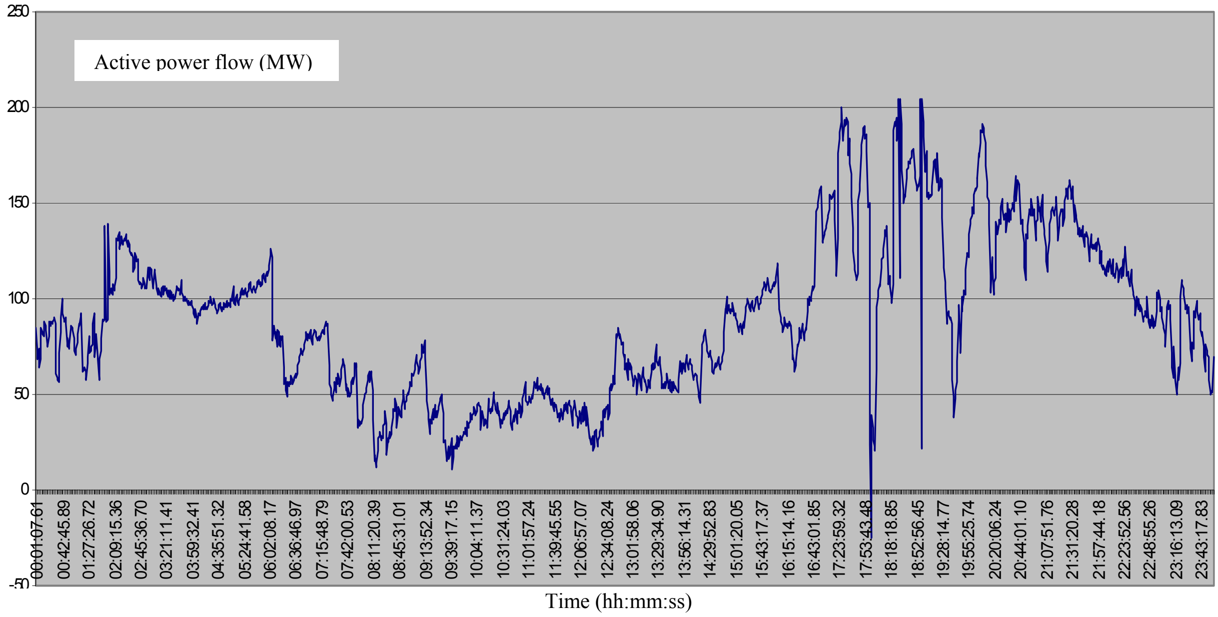

Figure 7 Active power flow along OHL 220 kV Đakovo - Mraclin during the blackout in Dalmatia on January 12, 2003

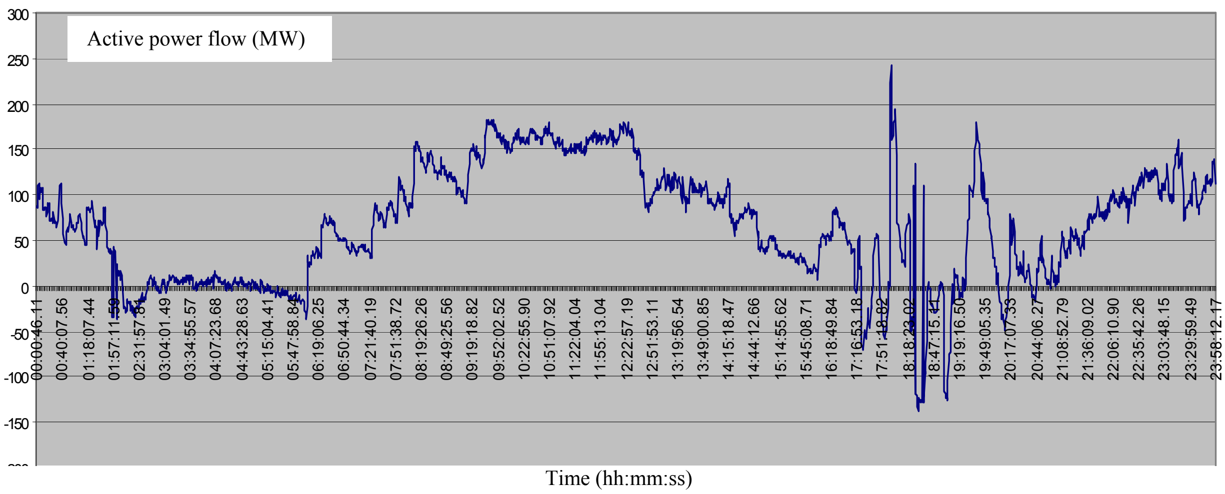

Figure 8 Active power flow along OHL 220 kV Đakovo – TPP Tuzla during the blackout in Dalmatia on January 12, 2003

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 fulfil 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.

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 analysed with respect to recognised 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 from field records. It is supposed that there are no outages in the BH system during simulated sequence (with the only exception of one generator in HPP Čapljina). 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 realised by adding inverse and zero impedances at the fault location in order to create 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 Đakovo – Mraclin was registered in 220 kV bus Đakovo at protection terminal in bay 220 kV Mraclin. Figure 4 shows field recordings of voltage and current swings in phases at protection terminal 220 kV Mraclin in 220 kV bus Đakovo 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 5 shows field recordings from protection terminal in 220 kV bus Đakovo at line bay 220 kV Mraclin on OHL 220 kV Đakovo – Mraclin beginning at 16:44:05.655 hours. At the time instant of switching-off activation, the relay in 220 kV bus Đakovo at line bay 220 kV Tuzla on OHL 220 kV Đakovo – TPP Tuzla registered sharp voltage drops at 53.1 kV to 59.8 kV (phase values, 0.418 pu and 0.471 pu) and current increases 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 Đakovo – TPP Tuzla at the time instant 16:44:09.495 hours.

Responses of bus voltages along northern 220 kV link (Mraclin – Đakovo – TPP Tuzla) besides oscillatory behaviour exhibit also sharp continuing voltage drop in 220 kV bus Đakovo down to nearly 0.50 pu in the period just before disconnection of OHL 220 kV Đakovo – TPP Tuzla (Fig. 9). After disconnection of the northern link, voltage magnitude in 220 kV bus Đakovo 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 Đakovo – 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. 10). Responses of power flows on OHL 220 kV Đakovo – Mraclin during simulated sequence of events (Fig. 11) 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. 12). 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. 13).

Responses of voltages in network buses across Dalmatia (Fig. 14) 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. 15).

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 Đakovo – TPP Tuzla (the northern link) has a key effect on responses of bus frequency in separated system parts (Fig. 16). 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.

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 blackout is primarily analyzed on the basis of collected chronological event listings and real-time recorded responses by relays concerned. Analytical findings are used to point out to available countermeasures aimed for alleviation of consequences.

Numerical analysis contains first security estimation of the initial steady-state to show awareness and preparedness of the system operators to deteriorated system conditions. 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.

Starting electromechanical oscillations are recognised as stabilised 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 Đakovo – 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 Đakovo which contains disconnection of OHL 220 kV Đakovo – 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.

Blackouts 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.

To that end, post-mortem analysis and report shall be 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.

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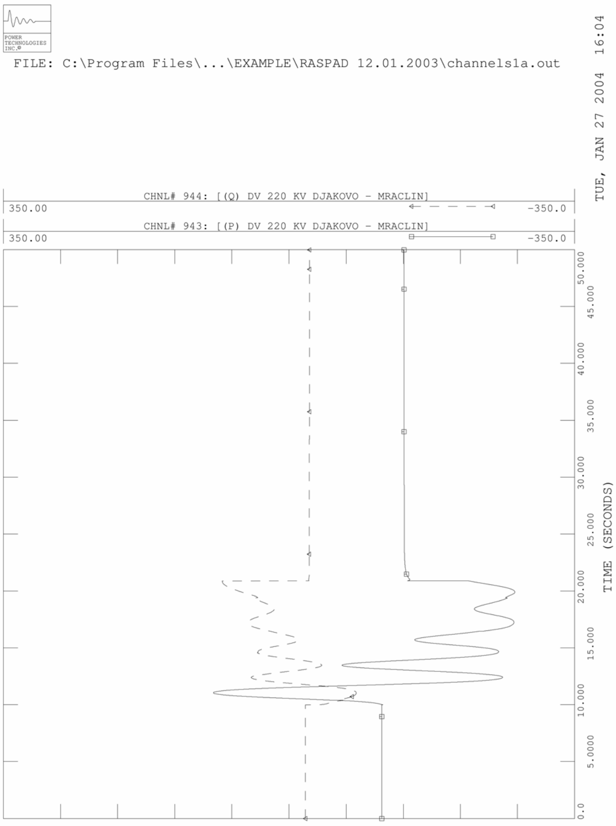

Figure 11 Power flows along OHL 220 kV Đakovo – Mraclin

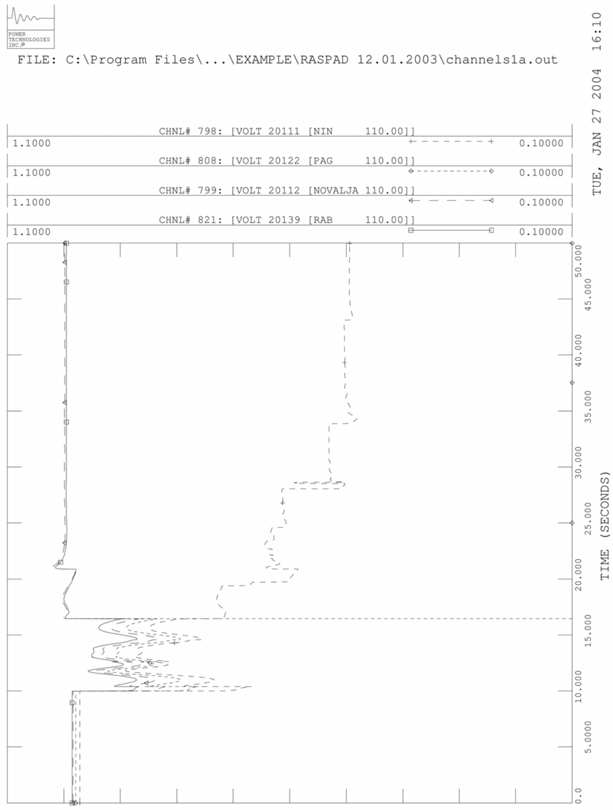

Figure 12 Voltage magnitude in buses along the island 110 kV link (Rab – Novalja – Pag – Nin)

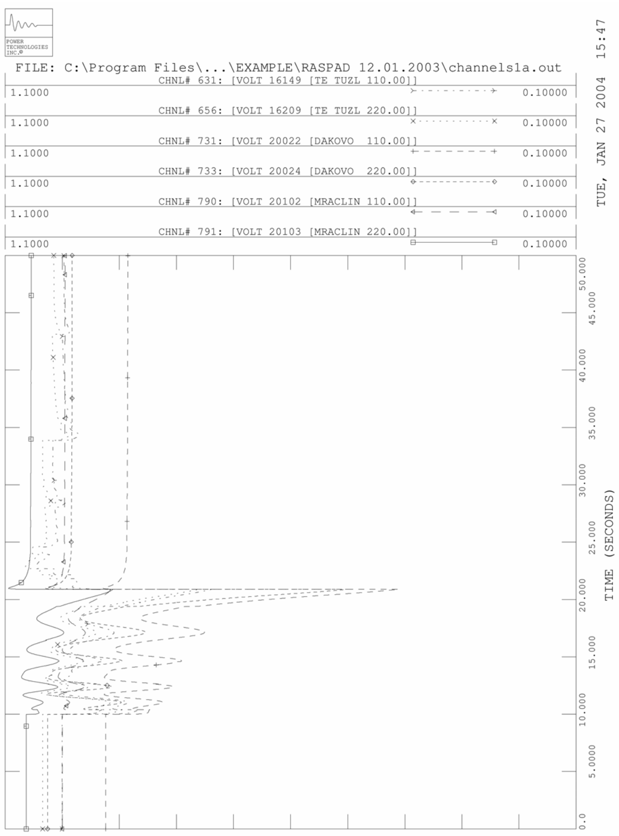

Figure 9 Voltage magnitude in buses along the northern 220 kV link (Mraclin – Đakovo – TPP Tuzla)

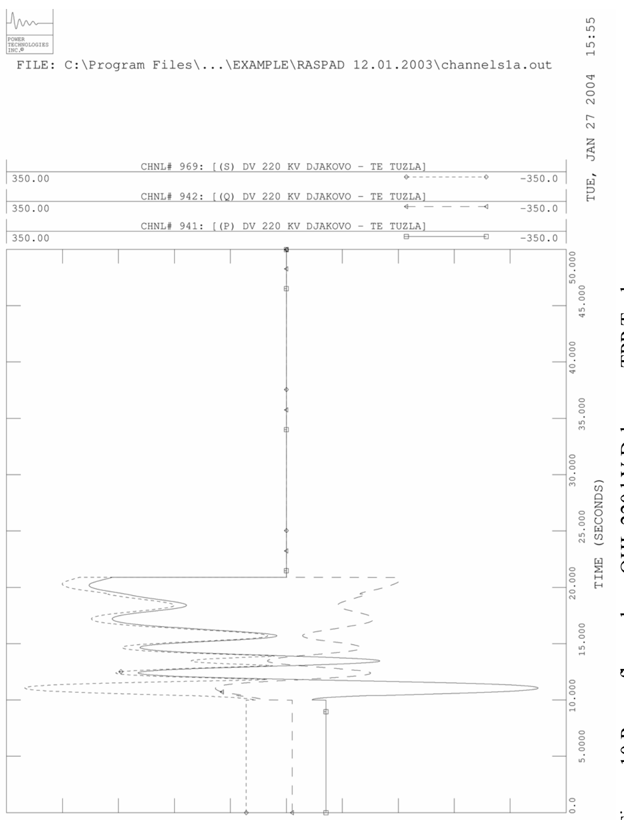

Figure 10 Power flows along OHL 220 kV Đakovo – TPP Tuzla

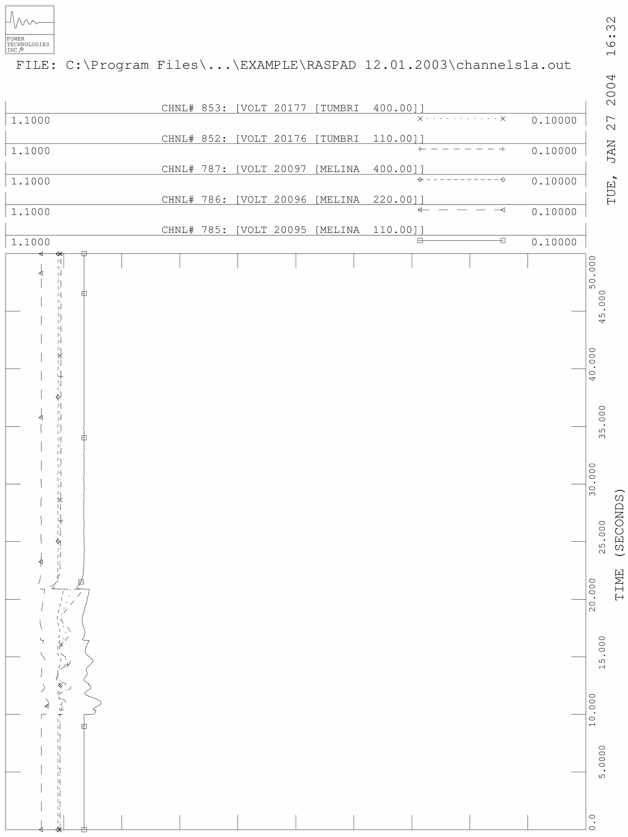

Figure 15 Voltage magnitude in network buses of the northern part of the HR system

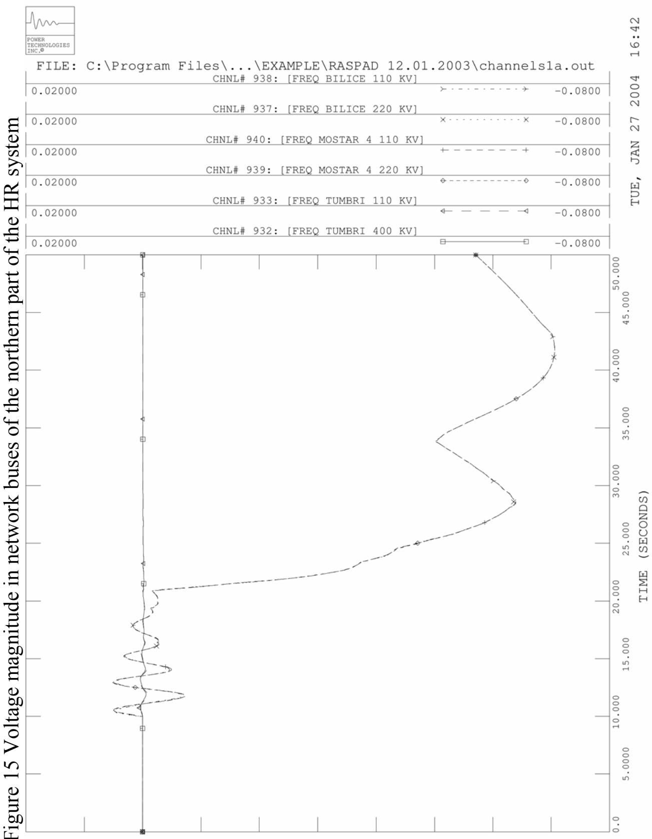

Figure 16 Frequency in buses of the southern and northern parts of the HR system

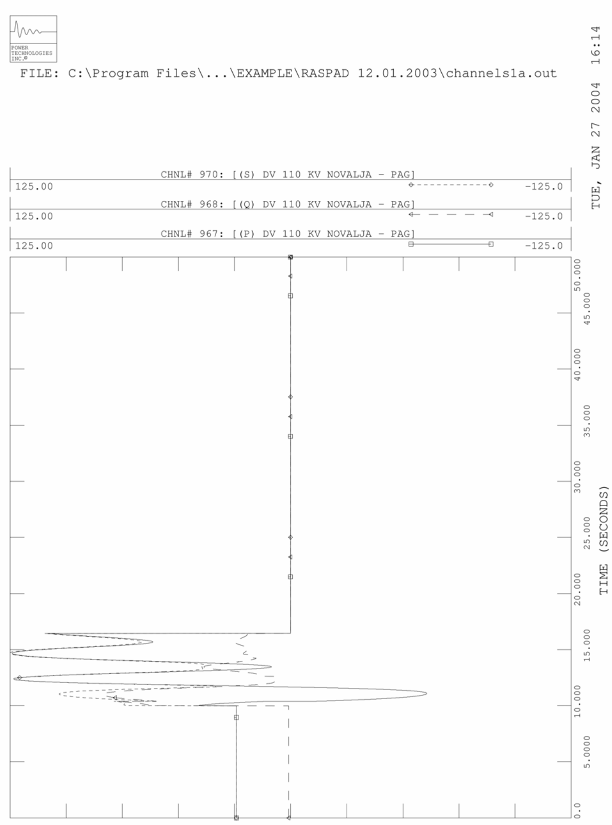

Figure 13 Power flows along OHL 110 kV Novalja – Pag

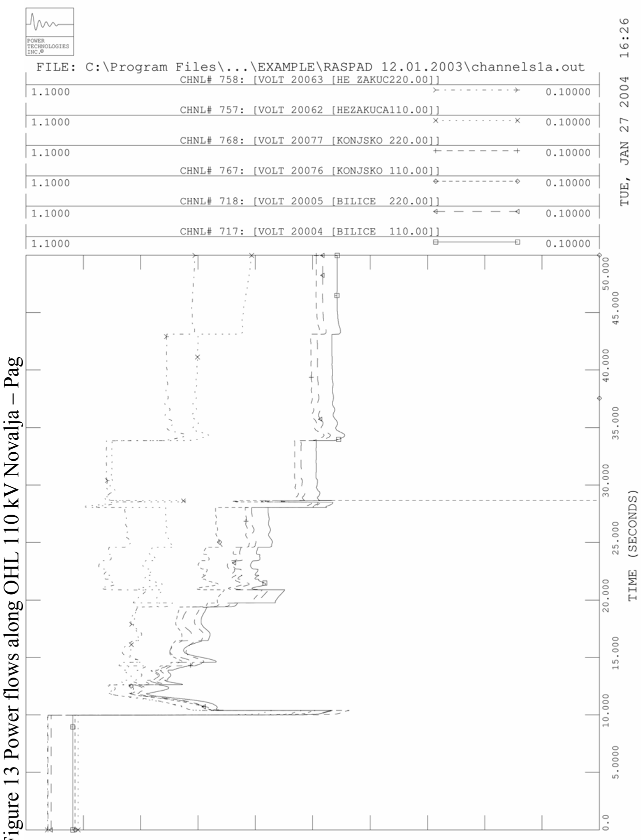

Figure 14 Voltage magnitude in network buses of the southern part of the HR system