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APPLICATION OF THE DIGITAL PROTECTION IN THE TRANSFORMER SUBSTATION 35/10kV WITH ISOLATED NEUTRAL ON THE 10kV SIDE

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INTRODUCTION

The purpose of this paper is to describe digital relay protection system installed in Vinča 35/10kV transformer substation and significant network events that occurred in the first 6 months of substation operation after its reconstruction. The substation was completely reconstructed during summer of 2003 including replacement of the primary and the secondary equipment. New bays with vacuum circuit breakers and digital protection system have been installed. Two types of digital relays have been used: feeder or transformer over-current protection and transformer differential protection. New AC/DC auxiliary power supply unit with digital bay control unit had been also installed. All relays are connected via RS485 communications link with substation's central computer which also maintains communications with Operations Center. Thankfully to enhanced possibilities of a new digital protection system and software packages for relay configuration and network events analysis, we were able to trace down and analyze various faults and network events and confirm correct operation of the new protection system.

TRANSFORMER SUBSTATION

Primary equipment

Vinča transformer substation contains two Dy5, 35/10kV transformers, one 8MVA and the other 4MVA. Power system network on the 10kV side is isolated, and on the 35kV side is grounded in the source substations. There are seven 35kV bays: two transformer, two incoming, two outgoing feeders and one tiebreak. 10kV switchgear consists of two transformer/measuring bays, four outgoing feeders, tiebreak bay and service transformer bay. Second phase expansion has been planned in the future that will include grounding of the 10kV star point of the transformers through the resistor. Installed circuit breakers are vacuum type.

Secondary equipment

DC auxiliary power supply unit has been equipped with bay control unit that performs miscellaneous monitoring and alarm functions. It sends alarm to the station computer if any of the following occurs: main battery fuses failure, earth-fault in the DC circuit, DC circuit breakers tripping, rectifier/inverter failure, outside gate open and substation doors open. It also takes measurement of the DC voltage and sends it to the main station computer with alarms via RS485 link. Bay control units had been installed in the AC auxiliary power supply bay, and tiebreak bays in 10kV and 35kV switchgear. Those units have monitoring, local/remote signalization and remote breaker operation functions, i.e. they don't have any protection function.
In each transformer, outgoing or incoming feeder bay we have digital over-current relay mounted. Each 35kV transformer bay also contains differential protection relay. Some of the most important features of these devices are given bellow:

- Event log containing all operational indications from specific bay like: fault occurrence (only the information that fault happened; fault record is contained in the trip log), switching operations, etc. Events are stored in the memory buffer according to FIFO (first in first out) rule. The buffer can hold up to 200 time-stamped events.
- Trip log where each event that produced trip signal is stored as a separate file. Eight most recent fault events can be stored, again according to FIFO rule. Primary fault currents can be read and all records are time-stamped with reference to the moment of the relay pick-up.
- Instantaneous primary and secondary analogue input values, maximums and minimums of which can be recorded in a settable time period.
- Time signals for each fault stored in the trip log. Total length of records that can be stored in the memory is five seconds. Trigger for the record starting can be either trip or pick-up signal. Record length for single fault, time before and after the trigger, as well as the trigger itself are configurable through the configuration software.
- Self-check and watchdog procedures.

Relay configuration

Configuration of the relays and bay control-protection units is executed through configuration software package that can also be used for read out and visualization of the fault data. Additional software is used for visualization and evaluation of the fault records. Possibilities of the aforementioned software packages are wide, so we will stay focused on the protection functions activated, their settings and fault analysis.

Feeder protection settings on 10kV. Following protection functions in the over current relay on the 10 kV feeders have been activated:

- Two stages of the definite-time over-current protection 50-1 and 50-2.
- Two stages of negative sequence definite-time over-current protection function 46-1 and 46-2.
- Two stages of the definite-time directional sensitive ground fault protection 50Ns, its pickup depending on the pick-up of the displacement voltage element and sensitive over-current element.
- Considering the protected feeders are overhead lines with high probability of temporary faults, Automatic Re-closing (AR) function 79 has been activated on all outgoing feeder relays. AR function will be activated by the pick-up of one of the following protection functions: 50-1, 50Ns-1 and 50Ns-2, other functions bearing no influence on it. Two cycles have been activated, first being set as fast AR (dead time 1,50 sec.) and second as a slow AR (dead time 100 sec) cycle.

Feeder protection settings on 35kV. There are no protection functions activated on the incoming 35kV feeders. Following protection functions in the over current relay on the 35kV outgoing feeders have been activated:

- Two stages of the definite-time phase over-current protection 50-1 and 50-2.
- One stage of the definite-time ground over-current protection 50N-1.
- AR function is activated on one outgoing feeder. It is started by the trip signal from the 50N-1 function with only one 1,5 sec. cycle active.
- Function Switch On To Fault is activated by the simultaneous occurrence of the relay pick-up (either 50-2 or 50N-1) and Manual Close signals. In this case all time delays are ignored and trip is instantaneous.

Transformer protection on 10kV. Following protection functions on the transformer relays have been activated in the over current relays on 10kV side:

- Two stages of the definite-time over-current protection 50-1 and 50-2. Former is active for Circuit Breaker Fault (CBF) function. It functions in conjunction with 50-2 function from the faulted 10kV outgoing feeder relay that sends blocking signal for 250 ms, enough for fault clearing on that feeder. If the fault is not cleared after 250 ms, transformer relay trips its breaker and sends CBF signal.
- Two stages of the definite-time directional sensitive ground fault protection 50Ns-1 and 50Ns-2.
- Displacement voltage protection.

Transformer protection on 35kV. Following protection functions on the transformer relays have been activated in the over current relays on the 35kV side:

- One stage of the definite-time over-current protection 50-1 serves as backup overload protection.
- One stage of the definite-time ground fault element 50N-1 is used for transformer tank protection.
- For the purpose of inrush restraint second harmonic content in the signal is monitored.

Differential protection relay is directly connected to CT's on both sides of power transformer i.e. there is no need for any matching transformers. All calculations of the differential and restraining quantities are done in the relay according to the ratio and phase displacement of the protected power transformer. Two stages have been configured, 87-1 and 87-2, latter being set to send a trip signal in the case of very high fault current disregarding any restraining conditions. Differential protection is blocked in the case of detecting 2^{nd} harmonic content in the current on the power up of the transformer.

SUBSTATION OPERATION

In the first 6 months of the operation of the substation several faults occurred. Enhanced functionality of the protection system enabled thorough analysis of those events, verification of successful protection system operation and in some cases minimized damage during faults. Software package that supports the analysis of fault records had been used for that purpose. Using the measured values recorded in the fault record, the package calculates additional values, such as positive-sequence impedances, r.m.s. values, etc. These measured and calculated variables and binary signals can be graphically prepared for display in the following views:

- Time signals
- Vector diagrams
- Circle diagrams
- Harmonics
- Table
-

Any number of diagrams can be assigned to a view, and any number of signals to a diagram. Signal-specific values of the displayed variables can be read at the corresponding instants using the two cursors. The signals can be displayed either as primary or secondary values. Convenient zoom functions let you set the optimum size to display the value path in all views. The properties of views, diagrams and signals, e.g. colors, line style, scale, etc. can be set individually using dialog boxes.

Network events

Two records exist for each network event presented. First is the report from analysis program where we can see waveforms of selected quantities, pick-up and trip signals generated by the relay. Second report is extracted from trip log for the specific fault. From that report we can see exact sequence of events for the specific fault.

Fault in the protected zone. This fault occurred on the cable end in the phase A of the 35kV transformer bay H01 on December 20th 2003 at 15:58. Insulation on the cable end failed and energized cable core came in the contact with grounded cable shield wires. Figures 1 and 2 show record from the trip log and time signals of the fault respectively, downloaded from the differential protection device. On the basis of these records fault has been correctly located before visual inspection.

00301	Power System fault	14 - ON	20.12.2003 15:58:15.175
00302	Fault Event	14 - ON	20.12.2003 15:58:15.175
00501	Relay PICKUP	ON	0 ms
05631	87 Differential protection picked up	ON	0 ms
05681	87-1 Phase A (without Tdelay)	ON	20 ms
00511	Relay GENERAL TRIP command	ON	20 ms
05691	87 TRIP by 87-1	ON	20 ms
05701	Diff. curr. Ph. A at trip without Tdelay	9,57 I/InO	23 ms
05704	Restr.curr. Ph. A at trip without Tdelay	9,69 I/InO	23 ms
05702	Diff. curr. Ph. B at trip without Tdelay	0,00 I/InO	23 ms
05705	Restr.curr. Ph. B at trip without Tdelay	0,02 I/InO	23 ms
05703	Diff. curr. Ph. C at trip without Tdelay	0,00 I/InO	23 ms
05706	Restr.curr. Ph. C at trip without Tdelay	0,03 I/InO	23 ms
00576	Primary fault current I A Side1	0,66 kA	50 ms
00577	Primary fault current I B Side1	0,00 kA	50 ms
00578	Primary fault current I C Side1	0,00 kA	50 ms
00579	Primary fault current I A Side2	0,00 kA	50 ms
00580	Primary fault current I B Side2	0,00 kA	50 ms
00581	Primary fault current I C Side2	0,00 kA	50 ms
05681	87-1 Phase A (without Tdelay)	OFF	119 ms
05631	87 Differential protection picked up	OFF	159 ms

Figure 1: Trip log record for the fault on December 20th 2003

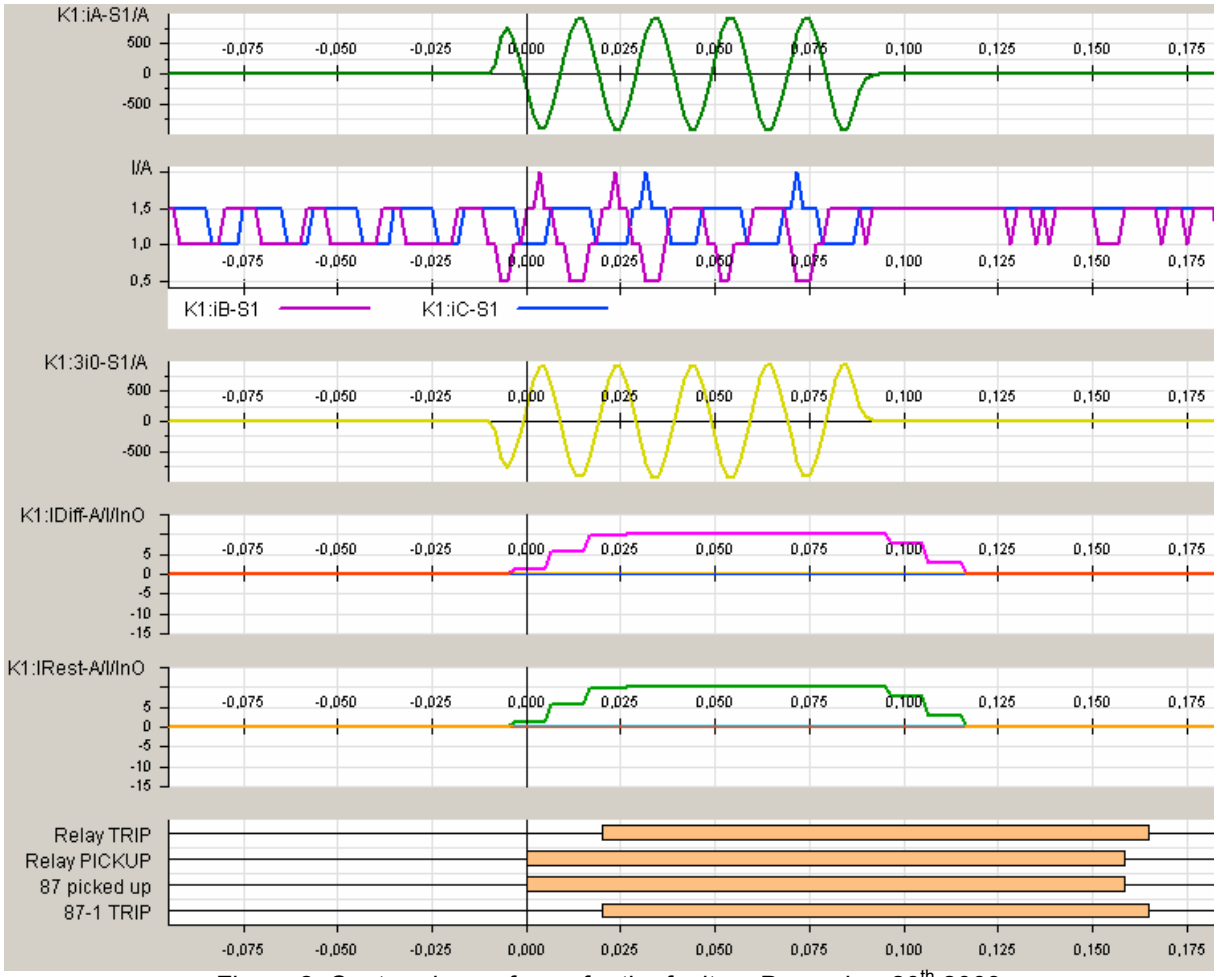

Figure 2: Captured waveforms for the fault on December 20th 2003

Switch onto fault. This fault occurred in the outgoing 35kV bay on December 7th 2003. The grounding disconnect switch on the cable end failed mechanically and remained in the grounded position, indicator showing OPEN position at the same time. The circuit breaker was directly closed on the grounded cable. All protections in the 35kV network are with time delays for the purpose of protection coordination. Therefore it can be said that SOTF function in this case prevented occurrence of higher level damage.

00301	Power System fault	7 - ON	07.12.2003 12:58:49.998
00302	Fault Event	8 - ON	07.12.2003 12:58:49.998
00501	Relay PICKUP	ON	0 ms
01761	50(N)/51(N) O/C PICKUP	ON	0 ms
01765	50N/51N picked up	ON	0 ms
01762	50/51 Phase A picked up	ON	0 ms
01763	50/51 Phase B picked up	ON	0 ms
01764	50/51 Phase C picked up	ON	0 ms
01810	50-1 picked up	ON	0 ms
01834	50N-1 picked up	ON	0 ms
01831	50N-2 picked up	ON	0 ms
01800	50-2 picked up	ON	10 ms
00511	Relay GENERAL TRIP command	ON	18 ms
01791	50(N)/51(N) TRIP	ON	18 ms
01833	50N-2 TRIP	ON	18 ms
01831	50N-2 picked up	OFF	24 ms
01765	50N/51N picked up	OFF	29 ms
01834	50N-1 picked up	OFF	29 ms
02785	79 - Auto-reclose is dynamically BLOCKED	ON	35 ms
02863	79 - Lockout	ON	35 ms
00533	Primary fault current Ia	1,89 kA	44 ms
00534	Primary fault current Ib	1,91 kA	44 ms
00535	Primary fault current Ic	1,89 kA	44 ms
01765	50N/51N picked up	ON	105 ms
01834	50N-1 picked up	ON	105 ms
01800	50-2 picked up	OFF	114 ms
01765	50N/51N picked up	OFF	126 ms
01762	50/51 Phase A picked up	OFF	126 ms
01763	50/51 Phase B picked up	OFF	126 ms
01764	50/51 Phase C picked up	OFF	126 ms
01810	50-1 picked up	OFF	126 ms
01761	50(N)/51(N) O/C PICKUP	OFF	126 ms
01834	50N-1 picked up	OFF	126 ms
00301	Power System fault	7 - OFF	07.12.2003 12:58:50.133

Figure 3: Trip log record for the SOTF on December 7th 2003

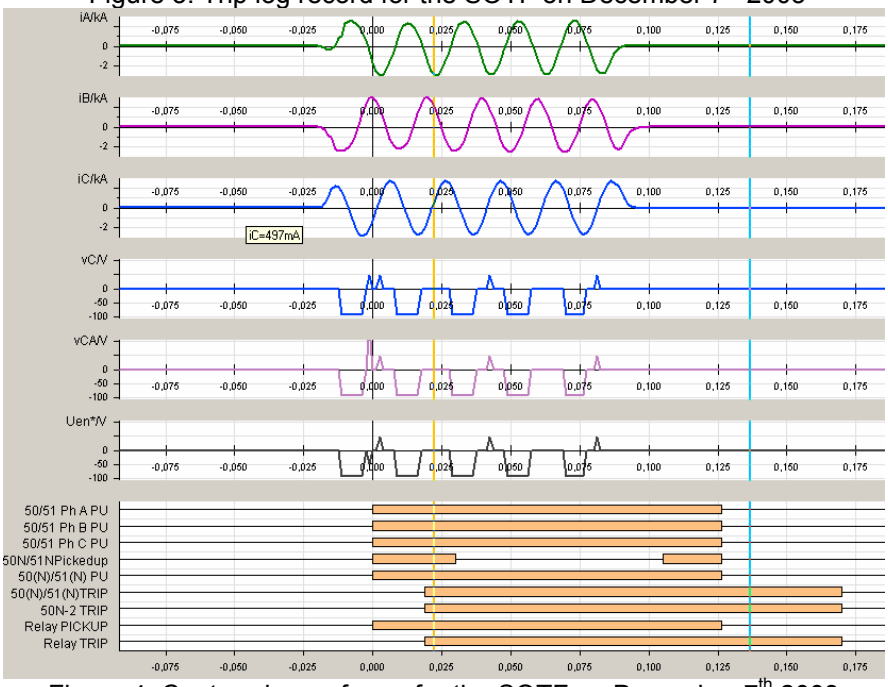

Figure 4: Captured waveforms for the SOTF on December 7th 2003

High resistance earth fault. This event occurred in the 10kV transformer bay K04 on March 14th 2004. Insulation on the cable end failed and high impedance ground fault occurred with low fault current which could not be detected by the differential protection. Fault was cleared by 64 (displacement voltage) protection after 6 seconds.

00301	Power System fault	15 - ON	14.03.2004 23:27:08.038
00302	Fault Event	15 - ON	14.03.2004 23:27:08.038
00501	Relay PICKUP	ON	0 ms
01215	64 displacement voltage pick up	ON	0 ms
01276	Sensitive Gnd fault in forward direction	ON	0 ms
01221	50Ns-2 Pickup	ON	3678 ms
01224	50Ns-1 Pickup	ON	3678 ms
01221	50Ns-2 Pickup	OFF	3758 ms
01221	50Ns-2 Pickup	ON	3798 ms
01221	50Ns-2 Pickup	OFF	3838 ms
01224	50Ns-1 Pickup	OFF	4078 ms
01221	50Ns-2 Pickup	ON	4474 ms
01224	50Ns-1 Pickup	ON	4474 ms
01221	50Ns-2 Pickup	OFF	4514 ms
01224	50Ns-1 Pickup	OFF	4594 ms
01224	50Ns-1 Pickup	ON	4958 ms
01224	50Ns-1 Pickup	OFF	4998 ms
01224	50Ns-1 Pickup	ON	5038 ms
01224	50Ns-1 Pickup	OFF	5158 ms
01224	50Ns-1 Pickup	ON	5238 ms
01221	50Ns-2 Pickup	ON	5278 ms
01221	50Ns-2 Pickup	OFF	5318 ms
01224	50Ns-1 Pickup	OFF	5438 ms
01224	50Ns-1 Pickup	ON	5478 ms
01224	50Ns-1 Pickup	OFF	5558 ms
01224	50Ns-1 Pickup	ON	5678 ms
00511	Relay GENERAL TRIP command	ON	6000 ms
01217	64 displacement voltage element TRIP	ON	6000 ms
00533	Primary fault current Ia	0,14 kA	6025 ms
00534	Primary fault current Ib	0,16 kA	6025 ms
00535	Primary fault current Ic	0,14 kA	6025 ms
01215	64 displacement voltage pick up	OFF	6117 ms
01224	50Ns-1 Pickup	OFF	6117 ms
00301	Power System fault	15 - OFF	14.03.2004 23:27:14.158

Figure 5: Trip log record for the fault on March 14th 2004

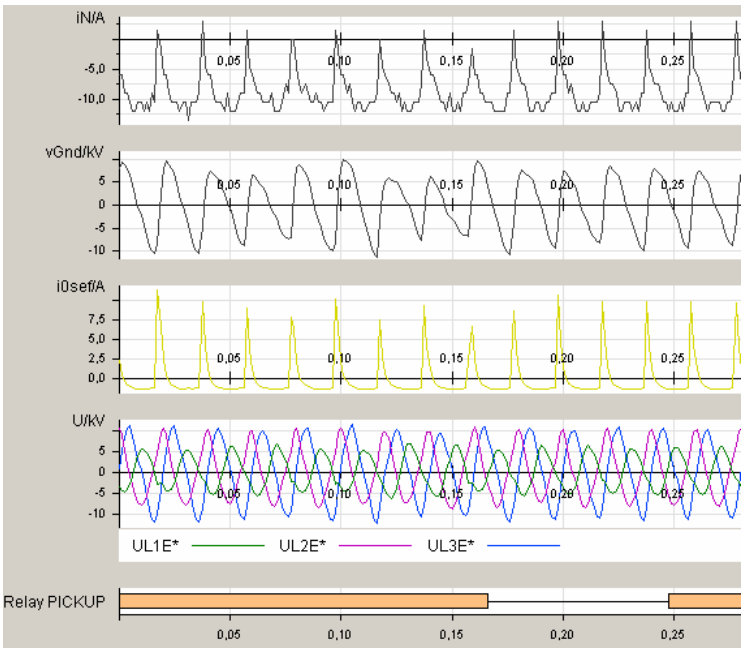

Figure 6: Captured waveforms for the fault on March 14th 2004

Loss of one phase. This event occurred on the incoming 35kV cable bay H06 on November 30th 2003. Protection on that relay is disabled due to he fact it is strictly incoming line in terms of energy flow. Therefore record shown on the figure 8 is taken from the event log. This event was preceded by the fault on the adjacent outgoing line which was cleared by the relay in the H07 bay, trip log for that fault shown on the figure 7. The fault is detected by the relay in H06 as "Failure: Current Balance".

00301	Power System fault	4 - ON	30.11.2003 15:01:36.474
00302	Fault Event	4 - ON	30.11.2003 15:01:36.474
00501	Relay PICKUP	ON	0 ms
01761	50(N)/51(N) O/C PICKUP	ON	0 ms
01765	50N/51N picked up	ON	0 ms
01764	50/51 Phase C picked up	ON	0 ms
01810	50-1 picked up	ON	0 ms
01834	50N-1 picked up	ON	0 ms
01831	50N-2 picked up	ON	0 ms
01762	50/51 Phase A picked up	ON	105 ms
01800	50-2 picked up	ON	116 ms
00511	Relay GENERAL TRIP command	ON	502 ms
01791	50(N)/51(N) TRIP	ON	502 ms
01836	50N-1 TRIP	ON	502 ms
02801	79 - in progress	ON	508 ms
00533	Primary fault current Ia	1,46 kA	524 ms
00534	Primary fault current Ib	0,00 kA	524 ms
00535	Primary fault current Ic	1,77 kA	524 ms
01800	50-2 picked up	OFF	597 ms
01831	50N-2 picked up	OFF	606 ms
01765	50N/51N picked up	OFF	617 ms
01762	50/51 Phase A picked up	OFF	617 ms
01764	50/51 Phase C picked up	OFF	617 ms
01810	50-1 picked up	OFF	617 ms
01761	50(N)/51(N) O/C PICKUP	OFF	617 ms
01834	50N-1 picked up	OFF	617 ms
02879	79-A/R multi-phase reclosing sequence	ON	621 ms
02844	79 1st cycle running	ON	621 ms
02851	79 - Close command	ON	2113 ms
00302	Fault Event	5 - ON	30.11.2003 15:01:38.685
00501	Relay PICKUP	ON	2211 ms
01761	50(N)/51(N) O/C PICKUP	ON	2211 ms
01765	50N/51N picked up	ON	2211 ms
01834	50N-1 picked up	ON	2211 ms
01764	50/51 Phase C picked up	ON	2220 ms
01810	50-1 picked up	ON	2220 ms
01831	50N-2 picked up	ON	2220 ms
01763	50/51 Phase B picked up	ON	2495 ms
01800	50-2 picked up	ON	2505 ms
01762	50/51 Phase A picked up	ON	2650 ms
01831	50N-2 picked up	OFF	2658 ms
01765	50N/51N picked up	OFF	2669 ms
01834	50N-1 picked up	OFF	2669 ms
00511	Relay GENERAL TRIP command	ON	3002 ms
01791	50(N)/51(N) TRIP	ON	3002 ms
01805	50-2 TRIP	ON	3002 ms
00533	Primary fault current Ia	1,85 kA	3030 ms
00534	Primary fault current Ib	1,85 kA	3030 ms
00535	Primary fault current Ic	1,83 kA	3030 ms
01765	50N/51N picked up	ON	3097 ms
01834	50N-1 picked up	ON	3097 ms
01800	50-2 picked up	OFF	3104 ms
01765	50N/51N picked up	OFF	3115 ms
01762	50/51 Phase A picked up	OFF	3115 ms
01763	50/51 Phase B picked up	OFF	3115 ms
01764	50/51 Phase C picked up	OFF	3115 ms
01810	50-1 picked up	OFF	3115 ms
01761	50(N)/51(N) O/C PICKUP	OFF	3115 ms
01834	50N-1 picked up	OFF	3115 ms
02862	79 - cycle successful	ON	12112 ms
00301	Power System fault	4 - OFF	30.11.2003 15:01:48.593

Figure 7: Trip log record in the H07 outgoing bay

After unsuccessful re-close attempt the fault was cleared again and definite trip was sent. After that, one phase was lost on the overhead incoming line in H06 which can be seen as "Failure: Voltage Balance" signal. Since the breaker in the H07 opened, there is no current in the incoming line, and protection in the source substation does not trip.

	Prekidac	CLOSE	27.11.2003 11:12:49.258
00163	Failure: Current Balance	ON	30.11.2003 15:01:37.146
00161	Failure: General Current Supervision	ON	30.11.2003 15:01:37.146
00160	Alarm Summary Event	ON	30.11.2003 15:01:37.146
00163	Failure: Current Balance	OFF	30.11.2003 15:01:37.748
00161	Failure: General Current Supervision	OFF	30.11.2003 15:01:37.748
00160	Alarm Summary Event	OFF	30.11.2003 15:01:37.748
00163	Failure: Current Balance	ON	30.11.2003 15:01:38.872
00161	Failure: General Current Supervision	ON	30.11.2003 15:01:38.872
00160	Alarm Summary Event	ON	30.11.2003 15:01:38.872
00163	Failure: Current Balance	OFF	30.11.2003 15:01:39.594
00161	Failure: General Current Supervision	OFF	30.11.2003 15:01:39.594
00160	Alarm Summary Event	OFF	30.11.2003 15:01:39.594
00167	Failure: Voltage Balance	ON	30.11.2003 15:01:40.186
00160	Alarm Summary Event	ON	30.11.2003 15:01:40.186
	Rucno komandovanje prekidacem	ON	01.12.2003 23:39:24.950
	Prekidac	Intermediate P...	01.12.2003 23:39:24.988
	Prekidac	OPEN	01.12.2003 23:39:24.996
	Kolica	Intermediate P...	01.12.2003 23:39:41.924
	Kolica	OFF	01.12.2003 23:39:43.020
	Prekidac	Intermediate P...	01.12.2003 23:40:14.106
00167	Failure: Voltage Balance	OFF	02.12.2003 06:38:10.672
00160	Alarm Summary Event	OFF	02.12.2003 06:38:10.672

Figure 8: Event log record in the H06 incoming bay

CONCLUSION

In the first six months of the operation, number of faults and network events occurred in the Vinča substation. New digital protection system employed in the substation with its greatly improved functionality enabled detailed analysis of all these events and helped us to reach firm conclusions on the causes of these events. At the same time correct operation of the digital protection was verified. We believe that electromechanical or static protection systems in similar conditions could not stand up to the level of protection achieved by new digital protection. Furthermore since old systems lack any of the analysis tool contained in digital relays software, it would be much harder to reach meaningful conclusions for the abovementioned network events.