Loss of Excitation Protection Testing by Transient Playback of EMTP Simulation Results

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***Abstract*—Loss-of-excitation protection of a large synchronous generator was tested at the site by injecting simulated generator current and voltage signals obtained from the EMTP simulation for various fault scenarios. The protection operates on directional current principle with overcurrent / undervoltage control. In order to achieve proper coordination of the protection with the unit's underexcitation limiter a new setting of the protection was proposed. By recording the protection response during tests its correct operation has been proved. Finally, the validity of the new setting has been assessed by checking the protection operating characteristic during primary field tests.**

***Index Terms*— EMTP simulation, field test, generator protection, loss of excitation**

I. Introduction

Loss-of-excitation protection of a synchronous generator in parallel operation with other generators in a power system has duty to selectively detect partial or total loss of generator excitation due to any internal fault in the excitation system. It should rapidly disconnect the unit from the system in order to prevent damage to the generator and to avoid adverse impact to stability of nearby generators and of the entire power system, particularly in case of large generators. Internal faults in excitation system that would cause loss-of-excitation (LOE) condition may be loss of excitation system supply, short circuit or opening of the field circuit, or even, in certain cases, a sudden loss of AVR reference. In such cases the synchronous generator starts running as an induction generator, delivering active power to the system but also drawing large amount of reactive power from the system. Sustained operation in that regime is unacceptable because there is risk of excessive heating of parts of the generator stator and rotor. The unit loses transient stability so that, by convention, the entire power system becomes transiently unstable. There is also a danger of voltage collapse because the generator now requires reactive power instead of supporting the system voltage by its own reactive power production.

Transition from normal operation to loss-of-excitation condition would occur within several seconds, its duration depending on initial operating condition of the generator and on stiffness of the power system at the connection point.

Loss of field condition is usually detected by impedance relays that measure the impedance viewed from generator terminals, or by directional overcurrent relays combined with overcurrent /undervoltage control. Certain time delay is applied in order to avoid unnecessary tripping. If unit is not equipped with a dedicated pole slip protection, loss-of-excitation protection should also operate as a pole slip protection in case of loss of synchronism caused by external faults, i.e. with the excitation system of the protected generator being intact.

Automatic voltage regulators (AVRs) are generally equipped with underexcitation limiters (UEL) which normally prevent generator operation outside an allowable region in underexcitation. This region is usually limited by a curve determined by permissible heating which depends on generator construction. If properly coordinated, the curves limiting generator operation in underexcited region should be ordered, in direction of increasing capacitive reactive power, as follows: underexcitation limiter should operate first, loss-of-excitation protection operating characteristic should be behind the limiter and the construction-dependent limiting curve behind the protection characteristic. Naturally, taking into account total time delay of the LOE protection, the operating point at which the generator would actually be tripped will be behind the above mentioned LOE protection operating characteristic.

II. BACKGROUND AND MOTIVATION

Generating unit at Rijeka TPP is the largest single unit in Croatian power system (376 MVA, 20 kV). The power plant is situated near the town of Rijeka and is connected to 220 kV transmission network via two short transmission lines (Fig.1).

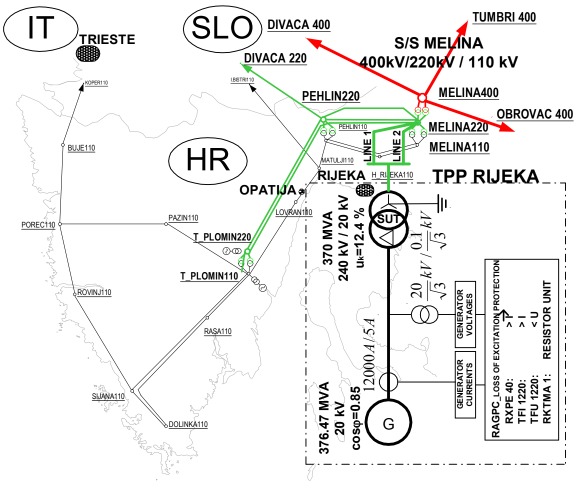

Fig. 1. Connection of TPP Rijeka to the power system

The generator is equipped with a static excitation system normally supplied from the unit auxiliaries 6 kV bus.

It had been noticed earlier, particularly during periodic testing of the excitation control system, that the loss-of-excitation alarm ("underexcitation") sometimes occurred with no fault in the excitation system and before the underexcitation limiter (with the setting for 2 and 3 bar pressure of the generator coolant) had operated. One likely explanation was poor coordination of UEL characteristic with loss-of-excitation protection characteristic. It was therefore decided to perform detailed tests of the loss-of-excitation protection.

A. Basic operating principle of the loss-of-excitation protection

Loss-of-excitation protection RAGPC at Rijeka TPP, considered in this paper, is solid state device consisting of a directional current relay with inverse time characteristic RXPE40, one overcurrent (TFI 1220) and one undervoltage (TFU 1220) relay and a resistor unit RXTMA1. Generator current in phase R and the three line voltages are taken as measurements. Reference voltage with a desired phase shift β is formed within the resistor unit (see Fig. 2) and is applied to the directional unit together with the R-phase generator current. Thus formed operating characteristic of the directional unit will be lying in the underexcited region of the generator capability chart, leaned towards the active power axis by the characteristic angle (α=90°-β). Time inverse characteristic of the directional unit RXPE40 is factory set and cannot be adjusted. The only parameter of the directional relay that can be set is its current threshold I_s (see Fig. 6) which is actually the generator current component in line with the reference voltage U_{SM} (Fig. 2) and which in fact determines the position of the operating characteristic in the generator capability chart.

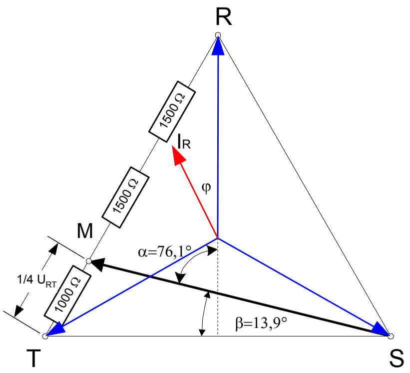

Fig. 2. Vector diagram showing forming of the reference voltage in the resistor unit RXTMA1

Upon operation of directional unit an alarm ("underexcitation") will be issued. If this condition persists and, at the same time, either overcurrent or undervoltage condition are fulfilled, the protection will trip the unit (signal: "loss of excitation"), as can be seen in Fig. 3.

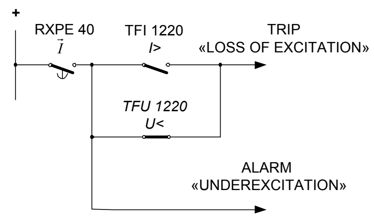

Fig. 3. Operation logic of RAGPC loss-of-excitation protection

B. Advanced Test Procedure

In routine tests each relay in the loss-of-excitation protection is tested separately by applying standard variable-amplitude current and/or voltage signals. This essentialy static method is quite useful for checking relay settings and functionality but it does not consider performance of the protection as a whole nor does it represent any power system dynamics.

Thankfully, capabilities of modern relay protection testing equipment and tools for computer simulation of power system dynamics enable us to concieve more advanced methods. The basic idea is to use a suitable power system model and to simulate selected fault scenarios. Voltage and current waveforms obtained from simulation in digital form are then converted in a modern relay protection testing device into appropriate analogue current and voltage signals that can be readily applied to the protection terminals, as if they were measurements from the real system, i.e. from secondary circuits of current and voltage transformers. Obviously, simulation program to be used must give instantaneous values of voltages and currents, which requires an EMTP program (in this particular case: LEC ATP).

Tests are done with generator at standstill and with all signals from and towards the plant disconnected. With simulated generator measurements applied simultaneously to all relays within the LOE protection it is possible to observe exact sequence of operation and to test the protection performance with realistic input signals that reflect power system dynamics during faults. Another great advantage of the method is that tests could be repeated at as many times as necessary.

C. Dynamic Models

An EMTP model of Rijeka TPP and its connection to the nearest 400/220/110 kV station Melina was prepared (see Fig. 1). The rest of the system was equivalenced at Melina so the EMTP model is basically of one-machine-infinite bus type.

As already mentioned, loss of excitation and asynchronous operation of a large generator has significant impact on surrounding system and nearby generators, so it seems justified to check system stability by means of a multimachine dynamic model used for standard stability analysis. Such programs use phasor representation of electric network so that the simulation results cannot be directly used for real protection testing by transient replay but can be compared with results from EMTP simulations for the same scenarios. In that way the EMTP model can be validated. The multimachine model used in this case has detailed representation of Croatian network at 400, 220 and 110 kV levels, while surrounding systems and one part of UCTE/CENTREL interconnection are represented at 400 and 220 kV levels.

III. Simulation Results

Loss of excitation was simulated as a sudden loss of field by setting field voltage to zero. A series of simulations with the generator at different initial operating points has been performed. LOE protection RAGPC was modelled with some simplifications (no hysteresis, ideal instrument transformers, time delay of the overcurrent relay fixed, etc.)

An example of simulation results obtained from the multimachine model is given in Fig. 4 and Fig. 5 for the case of permanent loss of excitation with the machine initially at 120 MW, 4.5 MVAr and with initial setting of the directional relay RXPE40. Trajectory of the generator current is given in Fig. 4 and time diagrams showing effective values of generator current and voltage are given in Fig. 5 along with the binary signals (from top to bottom):

a. generator current and the binary signal showing overcurrent relay operation (TFI1220)
b. generator voltage and undervoltage relay operation (TFU1220)
c. the measured component of the generator current relative to the directional relay RXPE40 threshold I_S and RXPE40 operation
d. trip signal of the RAGPC protection and the generator rotor angle

Time stamps given in Fig. 5 on the left, correspond to the time stamps shown on the trajectory of the generator current (Fig. 4) and they denote absolute time from the beginning of the simulation (pre-trigger time of 0.5 secs included).

It is interesting to compare results from the multimachine simulation with those from EMTP (Fig. 5). The directional relay picked up about 250 ms later in the EMTP simulation. Time delay of the directional relay is practically equal in both cases (0.99 secs in EMTP vs. 0.97 secs in the multimachine case). The undervoltage relay picked up roughly at the same time in both simulations (11.23 sec in EMTP vs. 11.18 sec in the multimachine case) and that was the necessary condition for the LOE (RAGPC) trip. On basis of this comparison and a number of other similar tests it may be concluded that for the purpose of this investigation the EMTP model reasonably well represents machine behaviour in parallel operation with the power system.

No actual trip action was simulated in either case, so that the generator in both simulations remained connected to the system. There is a difference between simulation results which is becoming more noticeable as the generator approaches the pole slip condition. This may be explained by different properties of the system dynamic equivalent used in the EMTP simulation compared to the full multimachine model with detailed representation of individual generators and their controls. It, however, does not affect the general conclusion about validity of the EMTP model for the purpose of the here presented testing of loss-of-excitation protection.

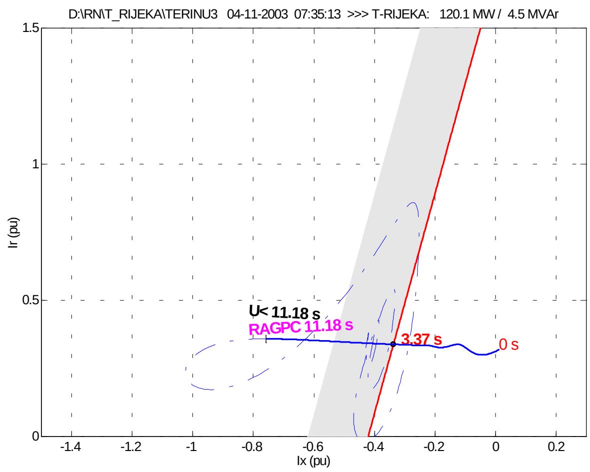

Fig. 4. Generator current trajectory observed following a sudden loss of excitation with the generator initially at 120 MW, 4.5 MVAr and initial setting of RXPE40, multimachine model simulation

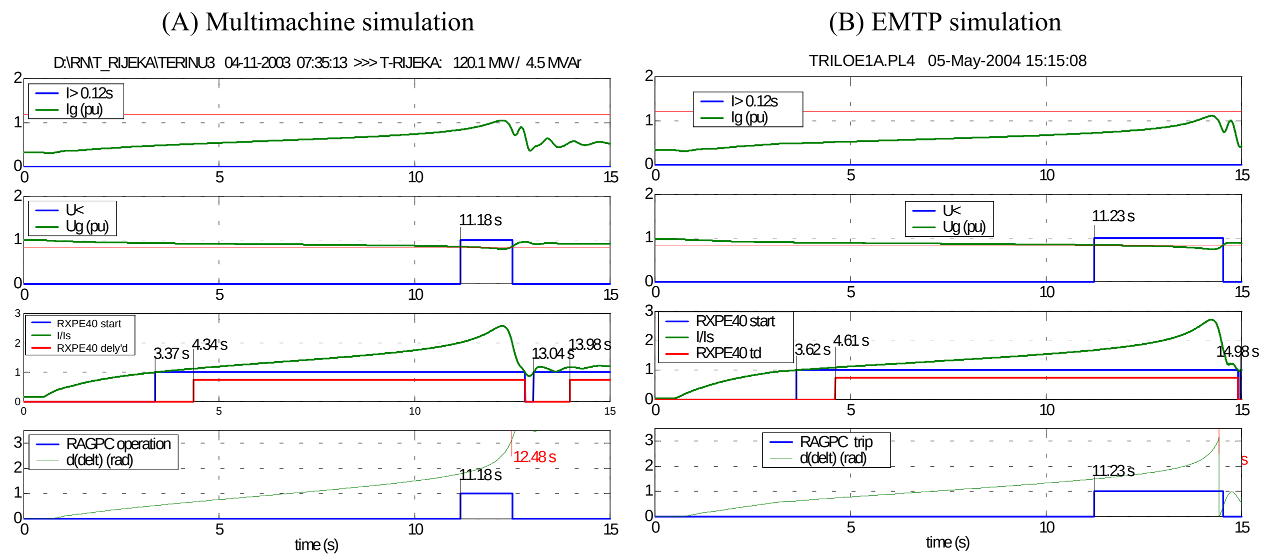

Fig. 5. Comparison of multimachine and EMTP simulation results of sudden loss of excitation with the generator initially at 120 MW, 4.5 MVAr and initial setting of RXPE40

IV. Field Test Results

In order to precisely determine actual thresholds and time delay characteristics of individual relays a set of standard secondary tests was done first. Both the initial and the new operating characteristics of the directional relay RXPE40 were checked in several points as well as its inverse time characteristic. Settings of the overcurrent relay TFI1220 and the undervoltage relay TFU1220 remained unchanged.

Both old and new operating characteristics of the directional relay are shown in the generator capability chart (Fig. 6). Operating characteristics of the underexcitation limiter and limits of permissible operating region of the generator are shown in the same diagram, both of them for three different levels of the generator coolant (i.e., hydrogen) pressure (Fig. 6).

These standard tests were followed by a series of tests in which simulated currents and voltages from EMTP were injected into the LOE protection by means of an Omicron CMC 156 device using its transient replay feature. List of tests / fault scenarios is given in Table 1. The case of a three-phase short circuit at the open end of one 220 kV line from TPP Rijeka to Melina, lasting 640 ms, is simulation of a real event which resulted in Rijeka generator being tripped by the loss-of-excitation protection.

Test results presented here (Fig. 7) are screen shots from the Omicron TransPlay software showing both injected voltage and current waveforms and various binary signals from the actual LOE protection at Rijeka TPP. These are, in form of horizontal bars, from top to bottom:

a. RXPE40 - operation of the directional relay
b. TFI1220 – operation of the overcurrent relay
c. TFU1220 – operation of the undervoltage relay (note that the signal is inverted: it is "1" when voltage is healthy and "0" when voltage falls below the threshold set at 84%)
d. RAGPC – trip signal from the LOE protection

Tab. 1. Overview of EMTP simulation scenarios / tests

TPP Rijeka initial cond. MW	MVAr	Fault type	Duration	Fault location
120	+22.5	LOE*	permanent	generator TPP-RIJEKA
220	-24.0	LOE*	permanent	
300	+37.0	LOE*	permanet	
220	-24.0	3-ph sh.circuit	150 ms	mid of the 220 kV transmiss. line TPP Rijeka – S/S Melina 220 II
300	+37.0	3-ph. sh.circuit	150 ms	
220	-24.0	L-L short circuit	150 ms	
300	+37.0	L-L short circuit	150 ms	
220	-24.0	3-ph sh.circuit	640 ms	end of the open 220 kV TL TPP Rijeka – Mel. II
300	+37.0	3-ph sh.circuit	640 ms	

*LOE – loss of excitation

Transient replay sequence test results are illustrated here for two cases of loss of excitation with the generator initially at 300 MW, 37 MVAr (Fig. 7), one with the old (initial) setting and the other with the new setting of the directional relay RXPE40. The difference between the old and the new settings can be observed from comparison of the relevant LOE binary signals which are shown simultaneously for both settings at the bottom of the Fig. 7 (generator current and voltage signals are equal in both cases and shown only once). With the new setting the directional relay operates later but the necessary condition (in this case: undervoltage) occurs at the same time as with the old setting and so does the RAGPC trip signal.

Operating points transiently reached by the generator at the moment of issuing the trip command by the LOE protection (with the new setting) are shown in the capability chart (Fig. 6).

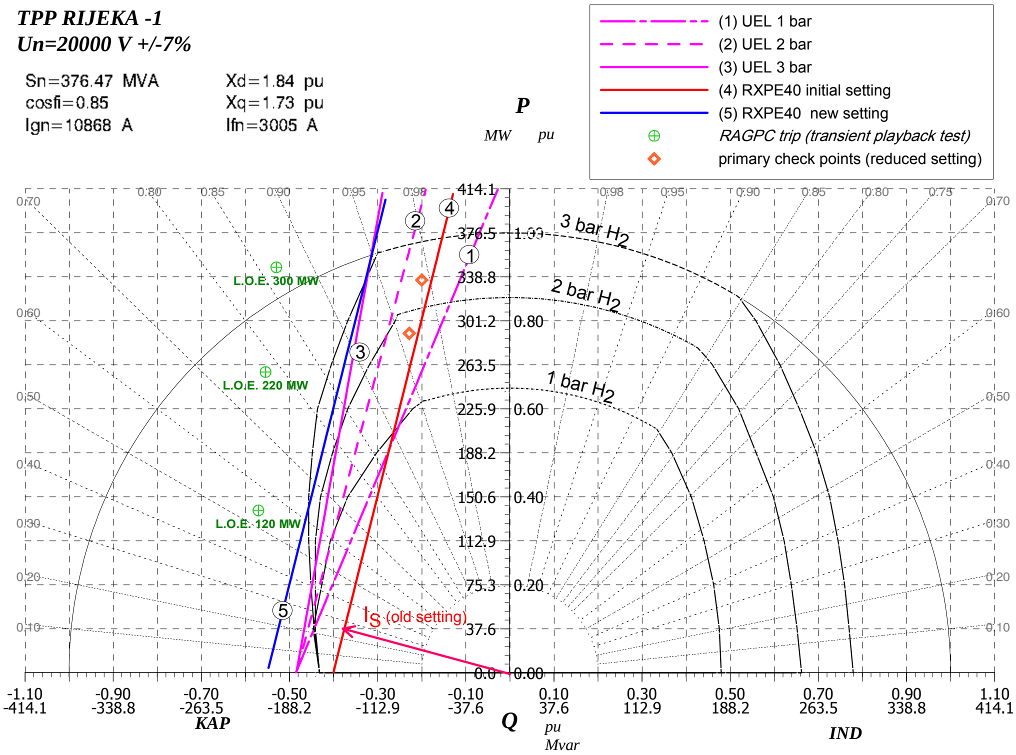

Fig. 6. Loss-of-excitation protection characteristics in the generator capability chart

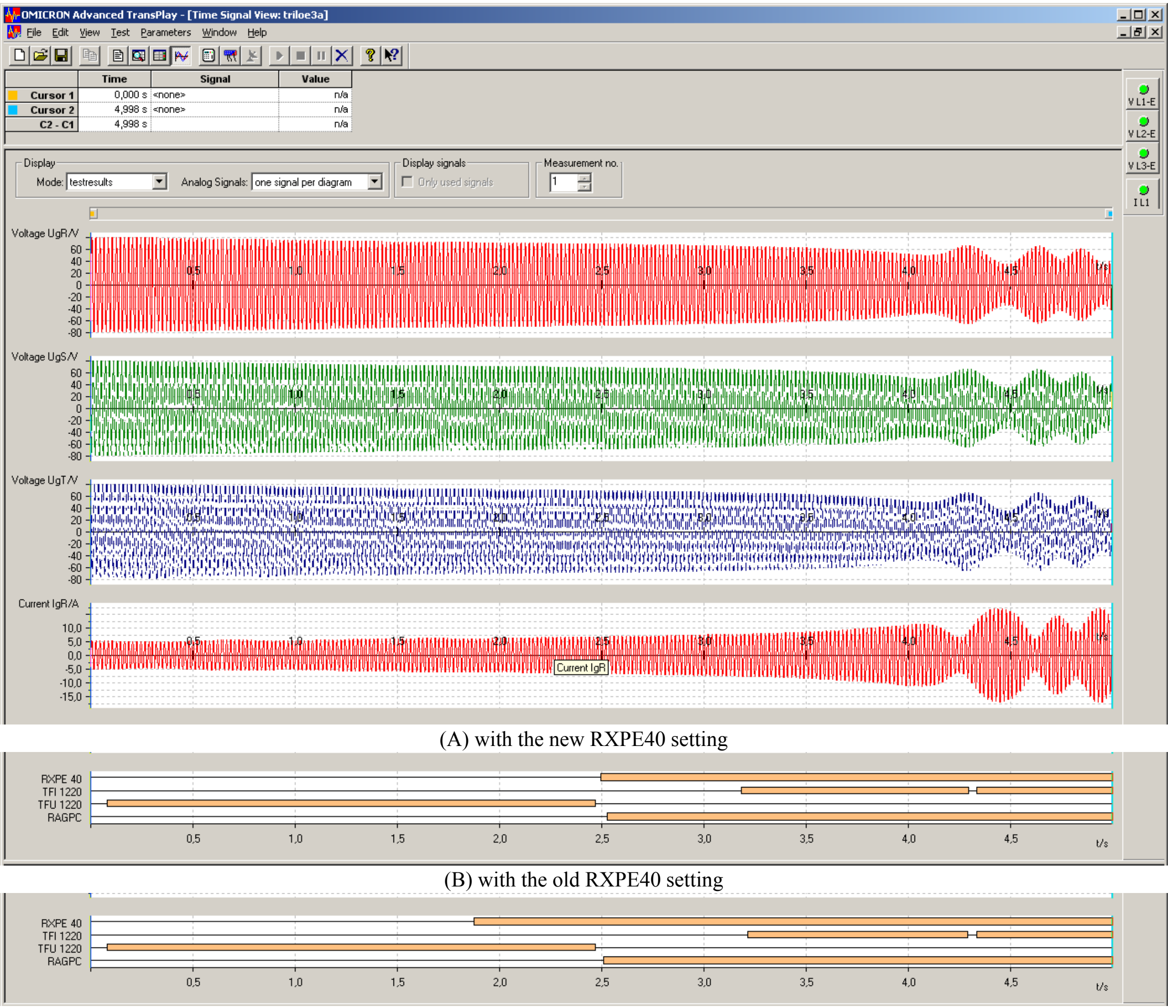

Fig. 7. An example of transient replay sequence: RAGPC response to simulated generator currents and voltages for the case of loss of excitation (Efd=0) with the generator initially producing 300 MW, +37 MVAr, with old and new setting of the directional current relay RXPE40

On basis of the performed tests (Table 1) it can be concluded that the LOE protection will operate properly in case of loss of excitation. It would not operate in case of close faults if they are cleared by line protections operating in the 1^{st} zone (i.e., within total time up to 150 ms) but will trip the machine if a fault persists and the unit loses synchronism.

Finally, two points of the directional relay characteristic (with reduced setting equal to the old setting of I_S) were recorded with the generator operating connected to the system (Fig. 6). Trip signal from the LOE protection was blocked and the generator driven into underexcitation region until the directional relay RXPE40 picked up. This primary check confirmed that the operating characteristic of the LOE protection is correct.

V. Conclusion

Use of modern equipment with transient replay capability greatly enhances relay protection performance testing, particularly in case of complex protection schemes. This is demonstrated here on an example of testing an existing loss-of-excitation protection of a large turbogenerator. Great value of the new method is the possibility to repeat tests with various scenarios and different settings which enables fine tuning of protection.

The protection has been thoroughly tested, both in a classic way and with injection of simulated generator current and voltages, and its correct operation and selectivity in various scenarios has been verified. The newly proposed setting of the directional relay avoids interference of the protection with the underexcitation limiter, thus enabling full use of the generator capability in the underexcited region.

Introducing test procedures that rely on simulated signal calls for greater accuracy of power system and equipment modelling. Judicios reduction of the modelled system to a manageable size will often be necessary but should be done very carefully.

Protection devices need not to be modelled in such simulation analyses that are aimed at transient replay testing but it is sometimes desirable to have such models included in simulation. In this work it was done for purpose of prediction of the protection behaviour with the new setting and to compare the model with the real protection operation. We found the results acceptable. More accurate modelling would be achieved e.g. by representing hysteresis effects of protection relays, realistic models of instrument transformers etc.

VI. References

[1] ASEA Directional relay type RXPE 4 Catalogue RK 51-10 E, Edition 2 January 1976.

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VII. Biographies

Darko Nemec was born in 1961 in Zagreb, Croatia. He received his B.S. and M.S. degrees from Faculty of Electrical Engineering, University of Zagreb, in 1983 and 2000 respectively. From 1983 to 1991, he was employed with Končar Electrotechnical Institute where he was working in the field of power system modelling, analysis and testing. Since 1991 he has been employed with Energy Institute Zagreb. His main area of interest is modelling and analysis of power system dynamics and control.

Milan Stojsavljević was born in 1946 at Velika Popina, Croatia. He received his B.S. and M.S. degrees from Faculty of Electrical Engineering, University of Zagreb, in 1969 and 1980 respectively. In 1969 he was employed with Electrotechnical Institute "Rade Končar" in Control Systems Division. He participated in numerous projects in the field of power system stability and control, e.g. dynamic stability enhancement of power system of former Yugoslavia in parallel operation with UCPTE (1973). From 1984 to 1991, he was the manager of Power plants and systems division. Since 1991 he is with Energy Institute Zagreb. Currently, he is head of the Department for analysis of electric power plants and systems. He was a member of the CIGRE Task Force 38.01.09: Requirement and Performance of Excitation Systems.

Hrvoje Bulat was born in 1973 in Split, Croatia. He received his B.S. degree from Faculty of Electrical Engineering Split in 1998. Since 1999 he has been with HEP (Croatian Electricity Utility) as a relay protection engineer at the Relay Protection Department of Zagreb Transmission Region. He is currently working on his M.S. thesis

Čelio Klapčić was born in 1958 in Rijeka, Croatia. He graduated from Technical Faculty of Rijeka, Electrical Engineering Department, in 1986. Since 1981 he has been employed with Croatian Electricty Utility (HEP). Currently, he is head of the electrical maintenance department at TPP Rijeka.