Dynamic model based complex checking of out-of-step protections

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***Abstract*--In the recent period, with power systems operating closer to stability limit due to market liberalization and cross-border trade increase, and at the increasing "demand" related to blackout lessons, more and more protection manufacturer firms include functions of protection against "asynchronous operation " (out-of-step functions) in the protection numerical terminals for transmission lines.**

This paper presents a possible variant for the complex checking of the settings, logic and selectivity of pole-slip/ out- of-step protection functions implemented at two transmission system levels, that is at generator terminals (24kV) and on the transmission lines (400kV) connected to the bus bars receiving the generators output.

***Index Terms*--asynchronous operation, out-of-step/pole-slip protection, protection settings.**

I. Introduction

In today's electrical power systems, the choosing, coordination and checking of settings and action logic for classical/numerical protection systems is a current expert activity, which takes place according to known procedures. In the "classical" sense, the role of protection systems was also "classical", that is to detect, evaluate and command the clearing/separation of faults (short-circuits) by tripping of the breaker(s) adjacent to the fault. In this "classical" conception, the protection systems did not have the role to detect abnormal and/or dangerous regimes such as:

- loss of angle stability, leading to active and reactive power oscillations (swings), asynchronous operation,
- loss of voltage stability leading to zonal voltage collapse etc.
- severe imbalance between generation and consumption leading to severe frequency disturbance; the imbalance is caused in most cases by cascade tripping of major elements in the transmission network, that is the simultaneous/ cascade tripping of a significant number of large power units, highly loaded transmission lines, large transformer units etc.

Even if such abnormal operation regimes were analyzed (more or less, depending on available models and calculation capability), the conclusions were usually limited to operational recommendations for prevention of such situations, and/or in some cases the realization of some simple local automata with limited action (except the UFALS).

At present the electrical power systems operation is characterized by:

- the strongly meshed interconnected operation within very large systems (UCTE for instance), with large power flows in some sections (cuts) and possible flow reversals in these sections, depending on specific variable operation of some generation capacities (hydro units, storage-pumping hydro units, wind turbines), load characteristics, deregulated electricity market conditions etc.;
- the fast evolution, the advanced integration of numerical control and protection systems and the modeling in these systems of sophisticated monitoring, detection, evaluation and action functions, for the elimination of faults (short-circuits) and unstable and/or dangerous regimes;
- the large scale secure use of dedicated transmissions;
- the use of high performance hardware and software and of evolved system models, making possible in-depth dedicated analyses in multiple variants, both for steady-state and for dynamic regimes;
- increased requests for transfer capacity between different zones from the deregulated electricity market, simultaneously with also increased requirements regarding the operation security of the interconnected power systems as a whole (contrary requirements);

The facts mentioned above and other considerations, mostly related to security, impose the progress from the limited analyses followed by preventive measures, planning and dispatch control of system operation, towards the corresponding implementation in the numerical control-protection systems of monitoring parameters, risk level estimation criteria, action parameters, and finally to real-time automatic hierarchic decision making regarding actions.

The target is the real-time automatic control/correction/ /interruption of dangerous operation regimes in power systems or parts of power systems, be it "asynchronous operation interruption", "voltage collapse limitation", "frequency disturbance limitation", etc.

Severely disturbed and/or dangerous regimes not corrected by automatic actions, efficiently and in appropriate time (as fast as possible), can lead to blackouts affecting large areas or even the whole power system. Consequently these automatic actions are part of the "Defense plan of the electrical power system against major disturbances".

The arguments above and unfortunately the lessons of the last years blackouts justify the affirmation that in the present electrical power systems the "solely by operator" control of operation regimes (even assisted by an expert system), although correct and efficient in normal and/or slightly/moderately disturbed operation regimes, is neither correct nor efficient in severity disturbed regimes prelude to blackout.

The only possible conclusion is the need to implement rapidly the automatic control of severely disturbed regimes, at least in critical (sensitive) sections of the transmission network. The aim of this paper is to convince experts and decision factors that this is not only necessary and efficient from the point of view of power system operation security, but also

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feasible.

Out-of-step protections/protection functions were used until now almost exclusively as specific pole-slip protections, dedicated for large generators, mainly for generator security. In this situation choosing settings and action logic was relatively simple. The dedicated equipments were included in the generator protections set in the classical technology, and in the numerical technology the respective functions were included in a first stage only in generator protection terminals.

In the recent period, under the influence of the arguments presented in part 1,and at the increasing "demand" related, I repeat, to blackout lessons, more and more protection manufacturer firms include more or less evolved functions of protection against "asynchronous operation " (out-of-step functions) in the control-protection numerical terminals for transmission lines.

This paper presents a possible variant for the complex checking, on the dynamic model of the power system, of the settings, logic and selectivity of pole-slip/out-of-step protection functions implemented at two transmission system levels, that is at generator terminals (24kV) and on the transmission lines (400kV) connected to the bus bars receiving the generators output.

II. Technical Backgriund

A. Calculation Conditions

Figure 1 illustrates the study system zone.

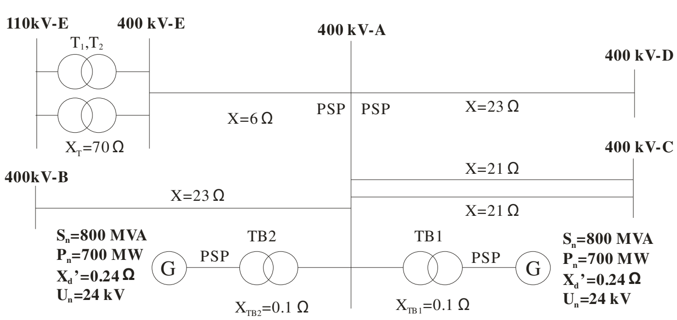

Fig. 1. A simplified network diagram of the relevant area (without the single-phase substations diagrams) and the main parameters of the elements.

Note: The 400 kV SSs A, B, C, D, E and the 110 kV SS E are connected to the rest of the power system.

In Figure 1 the following notations have been used:

- X_T is the transformer reactance at 400 kV;
- X_{TB1} and X_{TB2} are the block transformer reactance at 24 kV;
- X_d' is the non-saturated transient reactance;
- S_n is the generator apparent power;
- P_n is the generator active power.
- Only main parameters used for PSP settings were indicated in the figure.
- PSP - Pole Slip Protection / protection function;

B. Calculation Variants

TABLE I

Mathematically possible	Technically possible
Fault clearing time Matrix: t_A=60 ms t_B=60 ms, 210, 460 t_A=210 ms t_B=60 ms, 210, 460 t_A=460 ms t_B=60 ms, 210, 460 9 variants **Fault location and type** net three phase short-circuit (without automatic reclosure) on 400kV-OHL A-B short-circuit at point K_1 short-circuit at point K_2 2 variants	• t_A=60 ms, t_B=60 ms; correct action of protections, teleprotections and circuit breakers; • t_A=60 ms, t_B=210 ms; refusal of 400 kV CB-B; • t_A=210 ms, t_B=60 ms; refusal of 400 kV CB-A • t_A=60 ms, t_B=460 ms; unavailable TP on 400 kV OHL A-B • t_A=460 ms, t_B=60 ms; unavailable TP on 400 kV OHL A-B • t_A=460 ms, t_B=210 ms/t_A=210 ms, t_B=460 ms; unavailable TP on 400kV OHL A-B simultaneously with refusal of 400kV CB-B/CB-A*
Network Topology complete (before tripping of 400 kV OHL A-B) 400kV OHL A-C 1 unavailable 400kV OHL A-C 1 &2 simultaneously unavailable 3 variants	* simultaneously refusal of 400kV CB-A, CB-B (in 2 different substations) was not considered TP: teleprotection
Mathematically possible calculation variants 54	**Technically possible calculation variants 30**

C. Dynamic Simulations

Dynamic simulations were done for all possible variants.

The branch on which short-circuits were simulated, the fault clearing times and the dynamic simulations analyzed after eliminating first, the ones technically impossible, and second, the obviously stable ones, are presented in Fig. 2 and Table 2 respectively.

The identification of dynamically stable/unstable regimes was done based on the evolution of the analyzed generators internal angles $\delta = \delta(t)$. Finally the 8 simulations indicated in Table II were selected as suspicious of presenting asynchronous operation.

TABLE II

Short circuit in K_2			Short circuit in K_1		
Dynamic simulation	Fault clearing time CB-A 400kV t[ms]	Fault clearing time CB-B 400kV t[ms]	Dynamic simulation	Fault clearing time CB-A 400kV t[ms]	Fault clearing time CB-B 400kV t[ms]
ccn5c	210 ms	60 ms	ccn13c	460 ms	60 ms
ccn7	210 ms	460 ms	ccn17	460 ms	210 ms
ccn7b	210 ms	460 ms	ccn17b	460 ms	210 ms
ccn7c	210 ms	460 ms	ccn17c	460 ms	210 ms

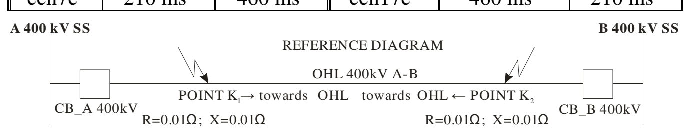

Fig. 2. Dynamic simulations:

ccn(xx): Complete topology; tripping of 400 kV OHL A - B

ccn(xx)b: Unavailable 400 kV OHL A - C 1; tripping of 400kV OHL A-B

ccn(xx)c: Simultaneously unavailable 400 kV OHLs A-C 1, 2; tripping of 400kV OHL A-B

Note: 1. In the simulations 7, 7b, 17, 17b there is no asynchronous operation .

2. In the simulations 5c, 7c, 13c, 17c the asynchronous operation manifests.

Figures 6, 7, 8, 9 include, for each selected dynamic simulation and each out-of-step function analyzed - G1, G2 (the same) and 400kV OHLs A-D, A-E:

- the impedance hodograph $Z=f(R,X,t)$
- the impedance hodograph and the superimposed action characteristic of the out-of –step protection in the Z plane (zoom on the area of interest).

The graphics in these Figures show suggestively that:

- In the dynamic simulations ccn5c and ccn7c, Fig.6, and the dynamic simulations ccn13c and ccn17c, Fig.7, an asynchronous operation appears, which is eliminated by the respective functions of 400kV OHL A-D PSP (1st zone, 1st half-cycle, t=2.1 sec.) and 400kV OHL A-E PSP (2nd zone, 1st full cycle, t=2.7 sec.); line PSPs action is correct and selective (towards the action of generator PSPs).
- In the dynamic simulations ccn7 and ccn7b, Fig.8, and the dynamic simulations ccn17 and ccn17b, Fig.9, the asynchronous operation does not appear, and no PSP has action conditions, which is correct from the point of view of the dynamic regime.

D. Considerations on the out-of-step functions in the protection terminals

The pole-slip functions in the protection terminals of generators G 1 and 2 (marked with PSP in Figure 1.) are specific to terminals ABB – REG 216, and settings were chosen according to manufacturer firm recommendations.

The out-of-step functions in the protection terminals of 400kV OHLs A-D, A-E (marked with PSP in Figure 1) are specific to terminals ABB – REL 531, and settings were chosen according to manufacturer firm recommendations.

The action characteristics in the Z plane (R, jX) and the number of "cycles" set for tripping in the "second zone" of the out-of-step protection functions are presented in Figure 3, Figure 4, Figure 5.

- the outer dark blue line represents the detection of asynchronous operation of G1,2 PSPs and 400kV OHLS A-D and A-E PSPs, respectively;
- the inner magenta line represents the detection of asynchronous operation, of 400kV OHLS A-D and A-E PSPs;
- the yellow line represents on which the disconnection is commanded, on the sides inclined at line angle;
- the turquoise lines represents the limit of the 1st zone (the zone in which the disconnection is ordered in the 1st half-cycle – for G1,2 PSPs, the zone delimited by the line and the blue polygon outline, towards negative X, and for 400kV OHL A-D,A-E PSPs, the zone delimited by lines and the inner polygon magenta outline) from the 2nd zone (the zone in which the disconnection is ordered with cycle counting – for G1,2 PSPs, the zone delimited by the line and the blue polygon outline, towards positive X, and for 400kV OHL A-D,A-E PSPs, the zone outside the lines and the inner polygon magenta outline, towards positive and negative X).

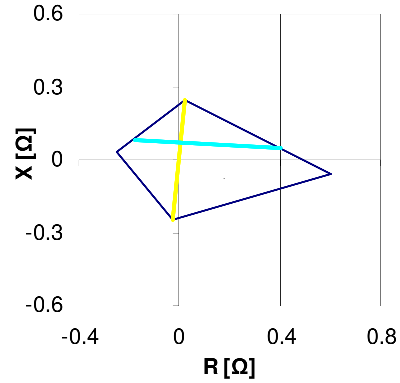

Fig. 3. The action characteristic of G1,2 PSPs (REG 216)

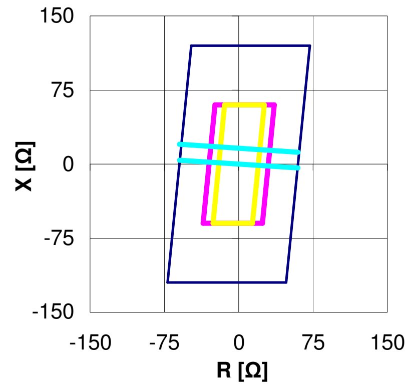

Fig. 4. The action characteristic of 400kV OHL A-D PSP (REL 531)

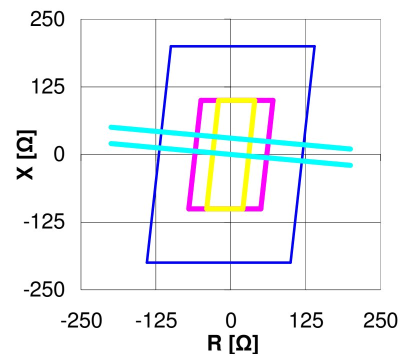

Fig. 5. The action characteristic of 400kV OHL A-E PSP (REL 531)

E. Considerations on dynamic modeling

Dynamic simulations were performed on the model of the Romanian power system operating interconnected with the UCTE network (with the transmission network in neighbor and near power systems preserved and network equivalents for more distant network areas).

Generator units in the Romanian power systems and nearby systems were modeled by representing the generator, turbine, excitation and turbine control systems, with real settings; the models are detailed and give a satisfactory representation of equipments for evaluation of dynamic behavior at power plant, area and system level.

Dynamic simulations were done with the software Eurostag 4.4 [4].

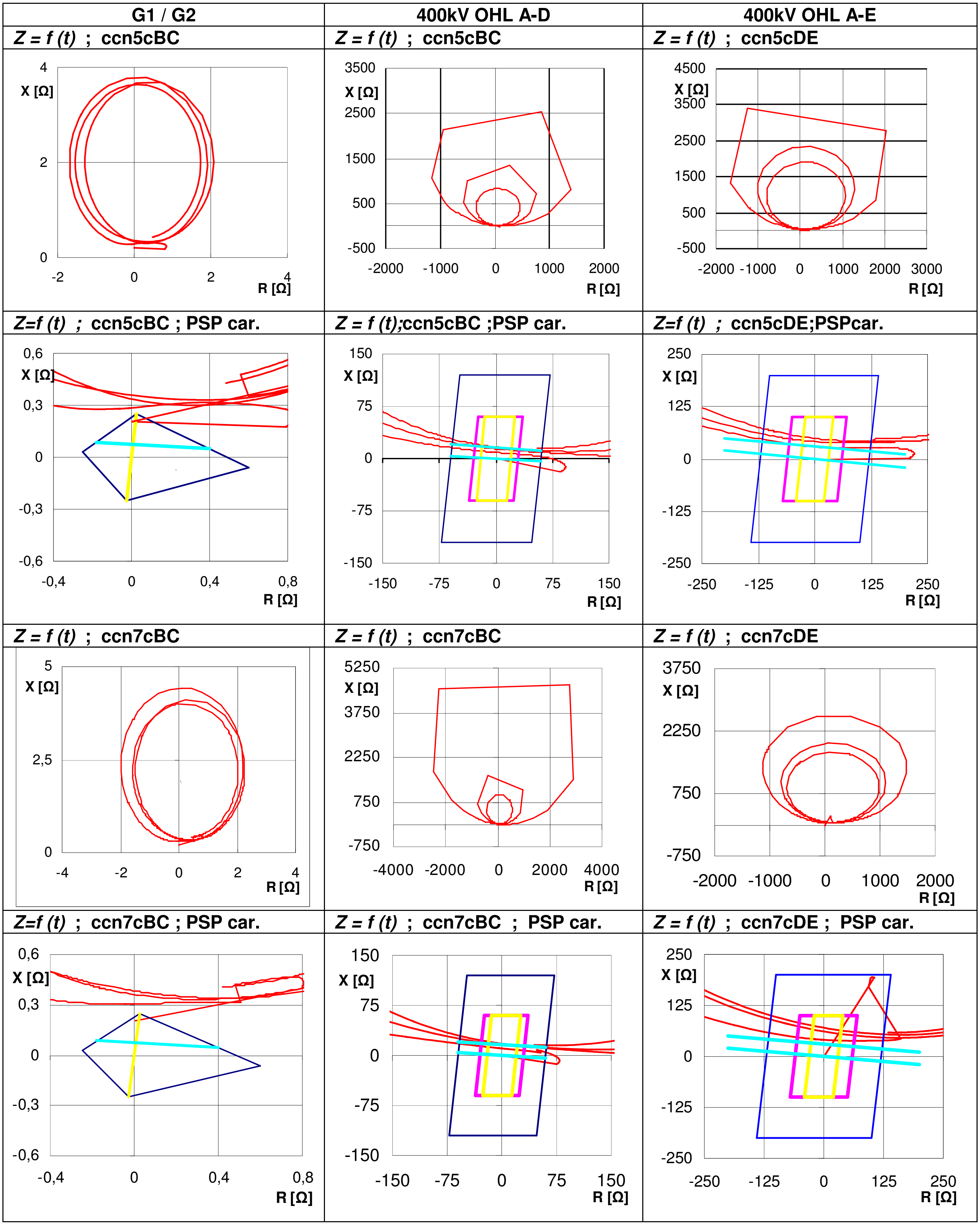

Fig. 6. Graphics for simulations ccn5c & ccn7c

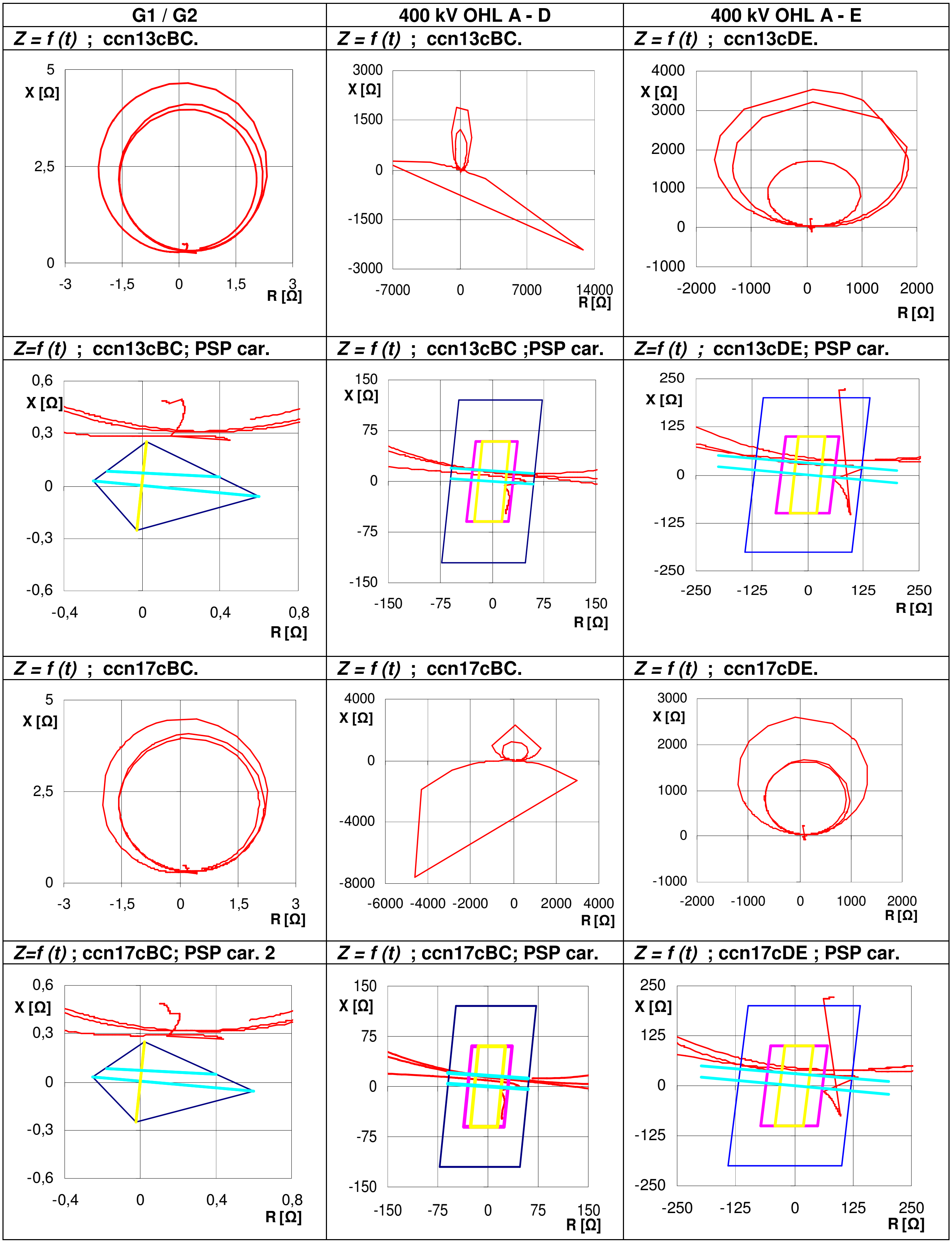

Fig. 7. Graphics for simulations ccn13c & ccn17c

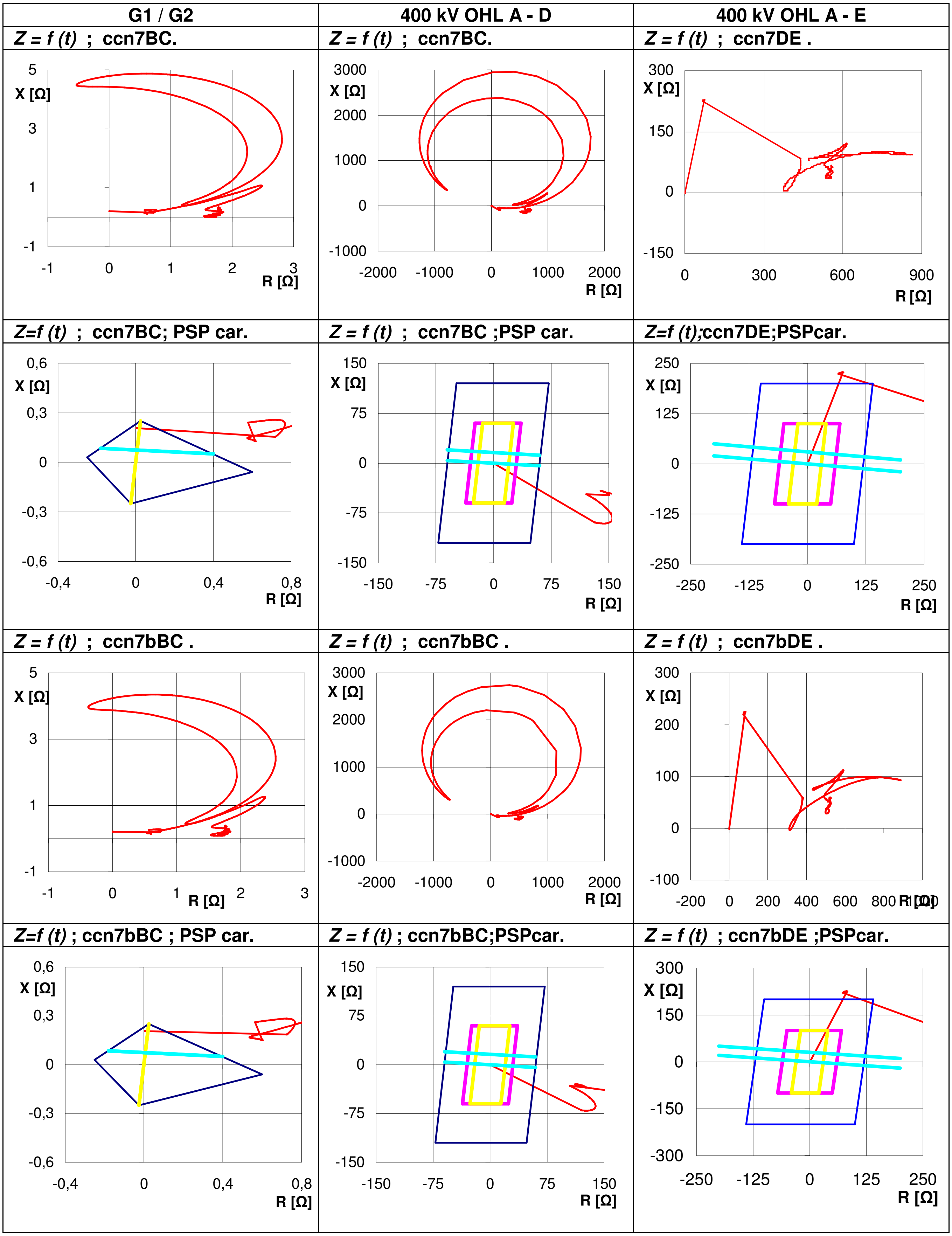

Fig. 8. Graphics for simulations ccn7 & ccn7b

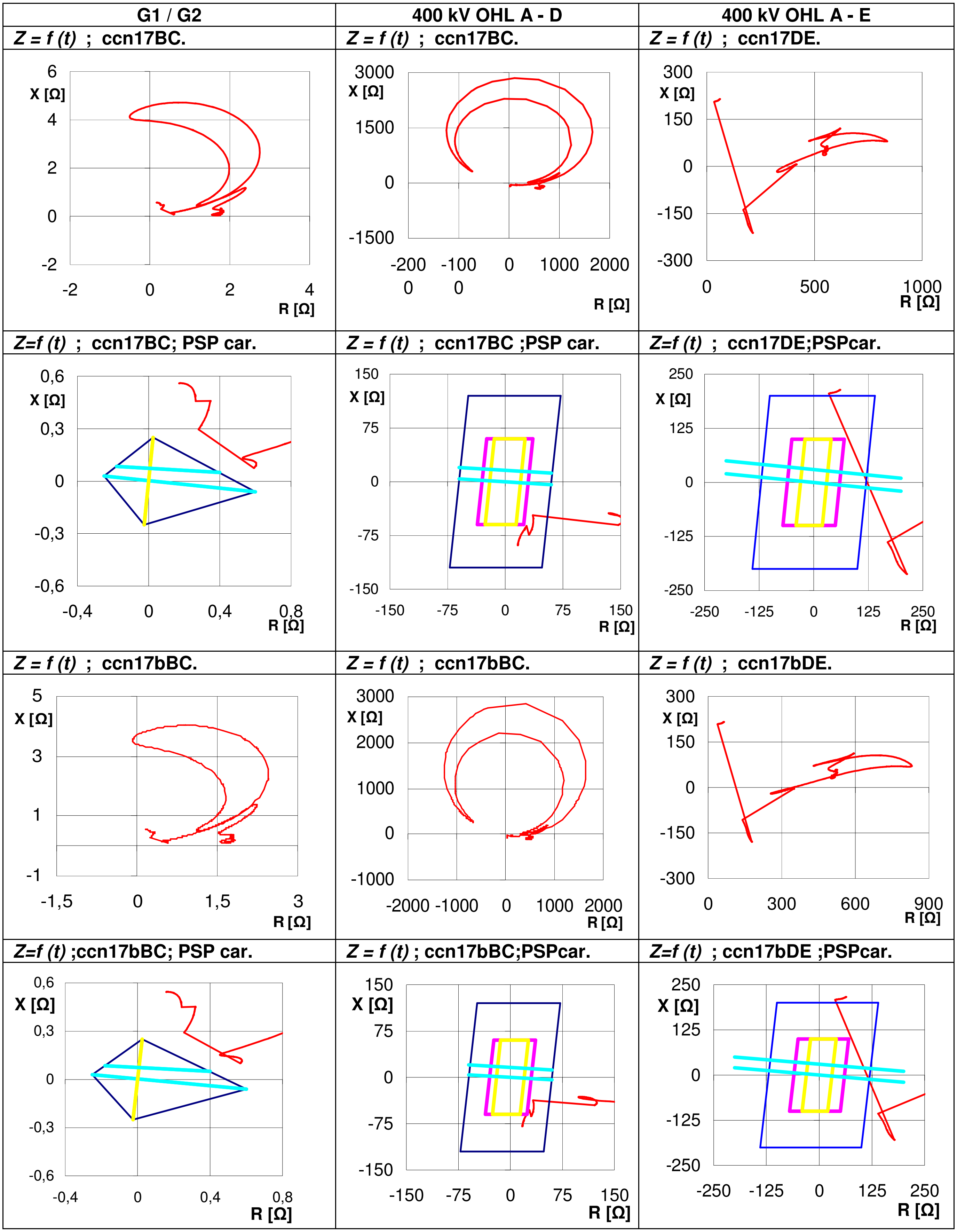

Fig. 9. Graphics for simulations ccn17 & ccn17b

III. Results and Comments

Taking into consideration the most restrictive conditions for short-circuit in points K_1 and K_2 in the analyzed variants:

1. The tripping of breakers 400kV CB-A and 400kV CB-B at t≤210ms, in any combination (normal operation of CB-A and CB-B, of protections and teleprotections – t_A=t_B=60ms), in complete topology and in any of the topologies with unavailabilities analyzed, or the refusal of one of 400kV CB-A , 400kV CB-B with normal operation of protections and teleprotections (t_A=60ms, t_B=210ms or t_A=210ms, t_B=60ms, in complete topology and in any of the topologies with unavailabilities analyzed), do not determine generator transient stability problems or risks for PSP action.

There is one exception: The calculation variant ccn5c (refusal of 400kV CB-A, t_A=210ms, only in the topology with double unavailability n-2, even if 400kV CB-B disconnects correctly at t_B=60ms). The variant was further analyzed (according to the table).

2. The tripping of breakers 400kV CB-A and 400kV CB-B at t=210ms and t-460ms in any combination (breaker refusal – t=210ms, simultaneously with tripping in 2nd stage at the other end – unavailable TP), or the refusal of 400kV CB-A after action of line protection in SS A in 2nd stage, leads to dangerous regimes at stability limit or to transient instability of generators both in complete topology and in any topology with unavailabilities analyzed.

There is one exception: The calculation variant ccn13c with tripping of 400kV CB-A at t=460ms, in topology with double unavailability, leads to transient instability regardless of the tripping time of 400kV CB-B (including 60ms).The variant was further analyzed (according to the table).

3. Protection or teleprotection unavailability can be, in some situations, worse than a breaker refusal.

In the study case the 400kV substation A and all adjacent lines are equipped with two independent protection and teleprotection systems which reserve each other 100% (both protection and teleprotection systems have a "base" function ("main"), identical settings and similar performances).

IV. Conclusions

1. For the analyzed example the simultaneous unavailability of two elements will not be accepted in planning / programming.

2. Full redundancy should be insured for protections and teleprotections as a guarantee for operation security and stability.

V. References

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VI. Biographies

Doru Mircea Paunescu Technical project manager, Romanian Power Grid Company –Transelectrica, Bucharest - Romania. Diplomat engineer from 1967 when graduating from the Technical University of Cluj – Electrical Department. Between 1967 and 1970 activated as an engineer in the Ministry of Energy - Bucharest T&D Branch. Between 1970 and 1974 activated as an Expert engineer in the Bucharest Area Dispatch Center. Between 1974 and 1982 activated as an Expert engineer in the Ministry of Energy. Between 1982 and 1990 activated as Head of the Protection and Automation in the Dispatch Center for the Interconnected East – European Electrical Power Systems in Prague (Czechoslovak Republic). Between 1990 and 2000 activated as Head of Protection & Automation Department in National Dispatch Center. Between 2000 and 2008 activated as Chief Inspector of System Safety in the Romanian National Power Grid Company - "Transelectrica" S.A.

Rodica Balaurescu Chief of diagram planning office, Romanian Power Grid Company–Transelectrica, Bucharest – Romania. Diplomat engineer from 1978 when graduating from University "POLITEHNICA" of Bucharest – Electric Power Systems Department. She activated since graduation as an engineer at the National Dispatch Center , in the Operational Planning Department. In 1991 she obtained the PhD title from the Bucharest Technical University.

Hans-Erik Olovsson Global Solution Manager, ABB Power Systems, T&D Substations.
Master of Science (Electrical Engineering) from Chalmers University of Technology in 1979. Have since graduation been working for ASEA/ABB in different positions. From 1979 to 1986 working with relay protection application and technical project management for transmission projects worldwide. 1986 appointed Manager for Electrical Co-ordination and Protection Office. 1990 appointed Senior Specialist, Substation Electrical Coordination and Protection. 1996 appointed Senior Specialist, High Voltage Systems. 2002 appointed Manager technical marketing of substation business. 2004 appointed Company Senior Specialist, High Voltage System and System Engineering. 2006 appointed Global Solution Manager, T&D Substations.