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Defense Plan against Loss of Synchronism in Interconnected Power Systems

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Abstract—**This paper presents a new approach for an out-of-step protection system for transmission corridors in interconnected power systems. The novelty of this approach is its interdependence on having a complete observability of the system. A defense plan analyzes voltage phasors measured at different network locations to determine the security state of the transmission corridor. If a disturbed state is detected, the protection system separates the network parts connected by the corridor to avoid synchronous machines falling out of step due to the divagation of the voltage phasors. Exemplary simulations are shown to compare the defense plan with conventional protection systems based on distance protection relays. A presumed interconnection of the UCTE system with the IPS/UPS system is used as simulation scenario.**

Index Terms—**Interconnections, loss-of-synchronism, out-of-step, PMU, protection system, transient stability**

I. INTRODUCTION

THE protection schemes of interconnected power systems are usually based on distance protection relays installed in every substation to protect against faults. Every distance protection relay is typically supplemented by an over current relay as ultimate security instance. Severe system disturbances can cause cascaded tripping of transmission lines often leading to enormous power oscillations that end up in major blackouts caused by synchronous machines falling out of step. The latest examples of this phenomenon are the pan European system disturbance in November 2006 [1], the blackout in Italy in September 2003 [2] and in the blackout in USA/Canada in August 2003 [3], each affecting more than 50 million people. All these disturbances have been caused by the same basic underlying reason: lack of adequate on-line inter-TSO coordination [4].

In such cases a superior protection system is needed to reduce the impact of an initial system disturbance on the entire power system. Transient instability caused by the cascaded development of the transmission line trippings can be avoided by a timely controlled system separation. In the late 1980s an approach for an out-of-step protection system was developed in Japan [5] which observes the phase angle differences between generator groups and separates network areas when severe system disturbances are detected. The accuracy for the comparison of voltage phasors was increased remarkable in the 1990s due to the introduction of Phasor Measurement Units (PMUs) [6]. Following this development, different out-of-step protection systems using PMUs have been proposed. In [7] and [8] the Equal Area Criterion (EAC) is used to protect interconnected power systems against loss of synchronism. This method requires the complete observability of the system status for the reduction of the power system into a two-machine model as basis for the EAC. A recent approach presented in [9] uses the monitored phase angle differences and their first derivatives as input for a prediction system to identify transient instable situations and to form a cut set for the system separation. Again, this requires the complete observability of the power system.

In Section II of this paper a new approach for an out-of-step protection system based on a defense plan observing phase angle differences between network areas and their second derivations is presented. In contrast to approaches know from the literature this defense plan does not require the complete observability of the system status. This is an advantage if the protection system is used between independent control areas in interconnected power systems.

In recent years a harmonization of standards between the UCTE system and the IPS/UPS system has been aspired [10]. As a consequence, studies were carried out analyzing the possibilities of a synchronous interconnection between the two systems. Results of these studies show that a superior protection system against severe events would be necessary in case of a synchronous interconnection [11]. In section III of this paper a simplified model based on public available data of a presumed interconnection between the UCTE system and the IPS/UPS system is presented. This model is used to generate scenarios of severe system disturbances at the interconnection between the two systems. Simulation results will be presented in section IV illustrating the dynamic behavior of the proposed protection system at two different fault scenarios. Comparisons to a classical protection by distance protection relays will be carried out. Section V will discuss the possibility of using the proposed protection system at UCTE-internal corridors. Finally, section VI will give a summary and conclusions.

II. DEFENSE PLAN

Figure 1 shows a block diagram presenting the principle operation mode of the defense plan against loss of synchronism. This defense plan forms the core of the protection system presented in this paper.

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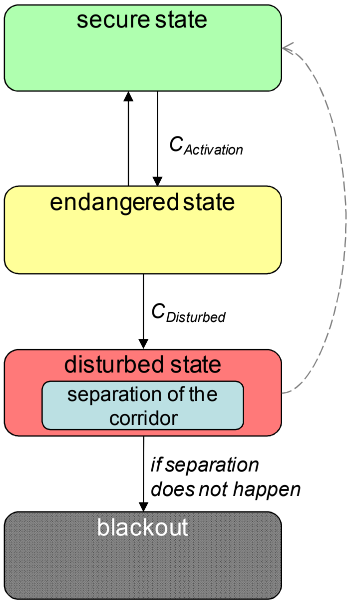

Fig. 1: Block diagram of the defense plan to protect transmission corridors against transient instability

This defense plan distinguishes between four different system states. To determine the state of a transmission corridor, PMUs monitor the phase angle difference $\Delta\delta(t)$ between the two areas that are connected by the regarded transmission corridor. During steady state operation the system stays in the secure state. The defense plan recognizes a fault and changes from secure to endangered state if the phase angle difference exceeds a limiting value for small signal stability of $\Delta\delta_{limit}$.

$$C_{Activation} = (|\Delta\delta(t)| > \Delta\delta_{limit}) \tag{1}$$

In electrical power systems transient instability appears if a transmission corridor is highly stressed and a short circuit nearby causes an acceleration of the phase angle difference across the corridor which is not reversible after clearing of the fault. To distinguish between stable and instable situations while the defense plan is in the endangered state, it is necessary to observe the second derivation of the phase angle difference expressing whether the phase angles at the two observed network locations accelerate or decelerate relative to one another. If the phase angle difference decelerates after fault clearing, the two systems will remain in transient stability. Vice versa an acceleration of the phase angle difference after fault clearing indicates a soon following loss of synchronism between the two systems. The major difficulty for the implementation of this criterion in the defense plan is to determine the time at which the fault has been cleared only by use of discrete measurement values of the PMUs. During the development of the defense plan it has turned out that a criterion observing the latest three measurement values of the PMUs according to (2) (in case of a positive phase angle difference) can distinguish very well between stable and instable situations. A disturbed situation is detected in constraint C_+ if the second derivation is higher or equal then a lower boundary $dd\Delta\delta_{min}$ for at least three consecutive time steps $T_{StepSize}$ each of them in the range of some ten milliseconds. The corresponding constraint C_- for the opposite power flow direction is set up analogical (3).

$$\begin{aligned} C_+ = {} & (\Delta\delta(t) > 0) \wedge \left(\frac{d^2\Delta\delta(t)}{dt^2} \geq dd\Delta\delta_{min}\right) \wedge \\ & \left(\frac{d^2\Delta\delta(t-T_{StepSize})}{dt^2} \geq dd\Delta\delta_{min}\right) \wedge \\ & \left(\frac{d^2\Delta\delta(t-2\cdot T_{StepSize})}{dt^2} \geq dd\Delta\delta_{min}\right) \end{aligned} \tag{2}$$

$$\begin{aligned} C_- = {} & (\Delta\delta(t) < 0) \wedge \left(\frac{d^2\Delta\delta(t)}{dt^2} \leq dd\Delta\delta_{min}\right) \wedge \\ & \left(\frac{d^2\Delta\delta(t-T_{StepSize})}{dt^2} \leq dd\Delta\delta_{min}\right) \wedge \\ & \left(\frac{d^2\Delta\delta(t-2\cdot T_{StepSize})}{dt^2} \leq dd\Delta\delta_{min}\right) \end{aligned} \tag{3}$$

To detect instable cases in which the phase angle difference is neither accelerating nor decelerating in theory the lower boundary should be $dd\Delta\delta_{min}=0$, but in practice this value will be different from zero to avoid mistakes caused by noise in the measured signal. The defense plan recognizes a soon following situation of transient instability and changes to the disturbed state if (4) is fulfilled.

$$C_{Disturbed} = \left(C_{Activation} \wedge (C_+ \vee C_-)\right) \tag{4}$$

In the disturbed state the two areas of the corridor get separated immediately to avoid the two power systems slipping against each other in order to enable the system to change back to the secure state. Otherwise the power systems will suffer a blackout caused by tripping of generation units due to intense power oscillations and voltage drops.

III. SIMULATION MODEL

To analyze stability and to validate the presented defense plan it is necessary to design an adequate simulation model. For this purpose a synchronous transmission corridor between the European UCTE system and the Russian IPS/UPS system was assumed. A reduced dynamic model of this interconnection was set up on the basis of public available data. The level of detail of this model has to fulfill a compromise between high precision to consider realistic dynamics on the one hand and manageable scale on the other hand. The focus of the defense plan presented in this paper is mainly on the interactions at the interface between two power systems. For this reason it is adequate to concentrate on the interface region instead of modeling the power systems in their complete dimensions. Thus, the model covers the following countries forming the interface region:

- Poland (UCTE)
- Czech Republic (UCTE)
- Slovakia (UCTE)
- Hungary (UCTE)
- Ukraine (IPS)

In reality Romania also belongs to the interface region but it is neglected in this model as no public available data could be obtained for the allocation of generation and load in this region. As Romania is not located in the center of the interface area, its importance for the interface region is not as high as the other countries. Therefore the detailing of the model is sufficient for a realistic test scenario for stability analysis. Figure 2 shows the central area of the modeled interface region in which the border between the two systems is highlighted by a dashed line. In this illustration the location of the PMUs for the observation of the phase angle difference is marked by oval circles and the flashes indicate the location of two different fault scenarios. Simulation results of both fault scenarios will be presented in section IV.

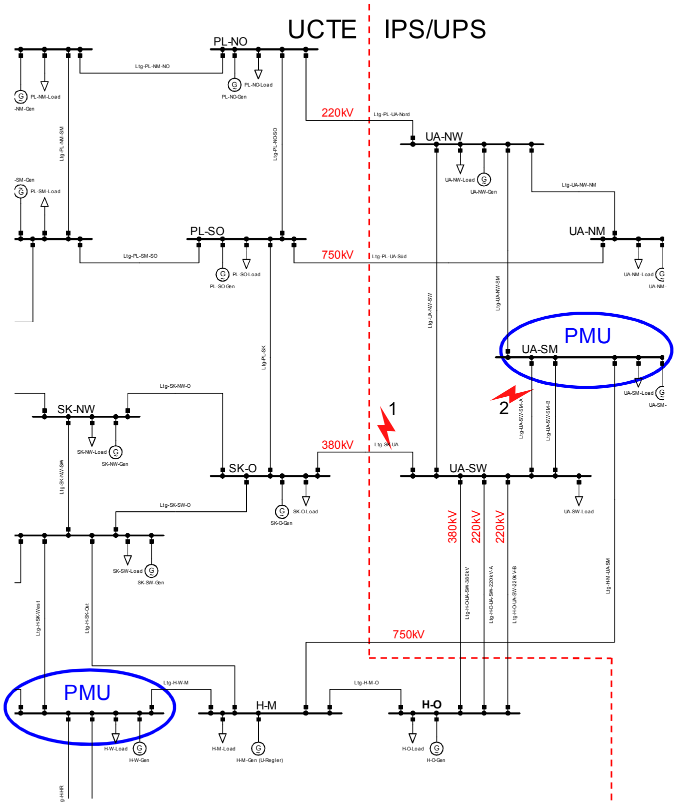

Fig. 2: Central area of the interface region showing fault positions and locations of PMUs

Based on the UCTE map [12] every state in the interface region (the UCTE map also covers the Ukraine) is concentrated to a few numbers of important nodes, each replacing an area with a high density of substations. The entire system is modeled by 31 nodes. Every node is equipped with a load and a generation cluster representing the total load and generation of the replaced area. All transmission lines inside a replaced area are neglected. The amount of load and generation of each node cluster inside the UCTE area is obtained from the winter peak situation in Zhou/Bialek's model [13]. The total load of the Ukraine $P_{Load,UA}$ is estimated by reducing the maximum load $P_{LoadMax,UA}$ according to the ratio between modeled $P_{Load,UCTE}$ and the maximum load $P_{LoadMax,UCTE}$ of the UCTE power system obtained by statistics [14][15][16]:

$$P_{Load,UA} = P_{LoadMax,UA} \cdot \frac{P_{Load,UCTE}}{P_{LoadMax,UCTE}} \tag{5}$$

In the base case the total generation of the Ukraine is equal to the total load. The allocation of load and generation in the Ukraine is estimated according to the number of power plants and load nodes in each modeled node cluster. To produce transit scenarios between the IPS/UPS system and the UCTE system the amount of generation can be relocated between the two systems.

The generation clusters in every modeled node are set up as a number of parallel connected synchronous machines with a nominal apparent power of 600 MVA each. All generators are equipped with voltage control and primary control. All network parts adjacent to the interface region are modeled by Thevenin equivalents to represent the remaining UCTE and IPS/UPS system respectively. The generation or load of these external network parts is adjusted according to the transits into the interface region obtained from the winter peak situation in Zhou/Bialek's model.

The length, voltage level and number of transmission lines between the modeled nodes are estimated according to the UCTE map. All transmission lines are converted to a uniform voltage level of 380 kV and transformers are neglected. It is assumed that the specific reactance and the nominal current of the transmission lines are modeled with common values according to Table I [17][18]. Line resistances and line capacitances are neglected. Several parallel lines are merged to one single line with the equivalent reactance (except interconnecting lines and lines where faults are simulated).

TABLE I
MODELING OF NON INTERCONNECTING TRANSMISSION LINES

Voltage level	Conductor	Nominal current	Specific reactance
220 kV	2x240/40 Al/St	1290 A	0.30 Ω/km
330 kV	4x240/40 Al/St	2580 A	0.26 Ω/km
380 kV	4x240/40 Al/St	2580 A	0.26 Ω/km
750 kV	4x560/50 Al/St	4160 A	0.28 Ω/km

Interconnecting transmission lines between the UCTE system and the IPS/UPS system have to be modeled very carefully. They have lower nominal currents than the other transmission lines. Thus they are modeled with individual values given in Table II estimated according to real data [19]. Tripping currents are assumed to be 140% of the nominal currents.

TABLE II
ASSUMED NOMINAL CURRENTS AND TRIPPING CURRENTS OF INTERCONNECTING TRANSMISSION LINES BETWEEN UCTE AND IPS/UPS

Voltage level	Nominal current	Tripping current
220 kV	1000 A	1400 A
380 kV	1700 A	2380 A
750 kV	2000 A	2800 A

IV. DYNAMIC SIMULATIONS

In this section simulation results illustrating the dynamic behavior of the protection system during two different severe system disturbances are presented. Blackout scenarios are usually induced by a sequence of unforeseen events. To get into a severe situation both interconnecting 750-kV-lines are switched off before the initialization of the simulation and a transit of 3000 MW is flowing from the IPS/UPS system towards the UCTE system. These initial conditions are the same for all simulations presented in this paper. This situation violates (n-1)-security and most of the interconnecting lines are highly stressed in terms of thermal capacity.

A. Fault scenario 1: Fault on an interconnecting line

In fault scenario one a fault occurs on the interconnecting 380-kV-line between the nodes SK-O and UA-SW (see figure 2). The fault happens at simulation time *t=1s* in the following figures. The line gets tripped 150 ms later to clear the fault and further 500 ms later it is switched on again by automatic reclosing. The fault current relights and further 150 ms later the line gets finally tripped.

Figure 3 shows the consequences of fault scenario one if the interface region is only protected by conventional distance protection relays including an over current tripping function. From top to bottom the four charts in this figure present the following variables:

1. The phase angle difference $\Delta\delta$.
2. The switching status of the remaining interconnecting lines.
3. The cumulated active power injection P_{Gen} at the nodes H-W and H-O
4. The amplitude of the voltage V at the nodes H-W and H-O.

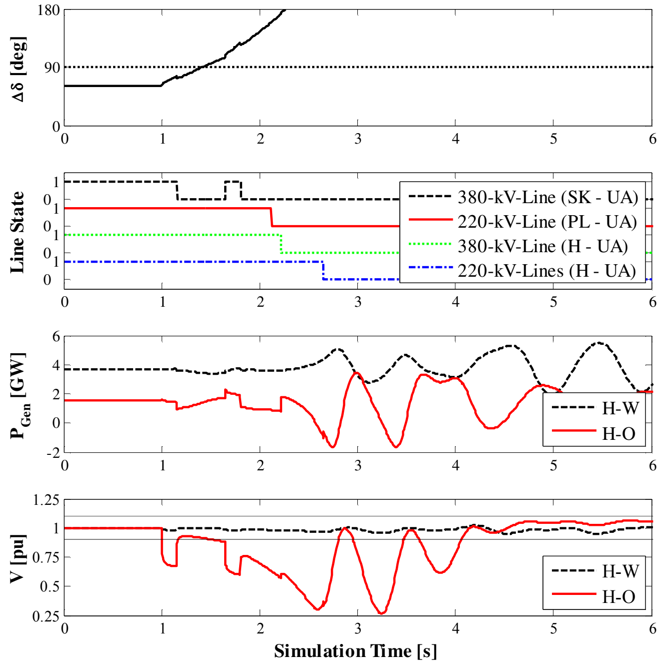

Fig. 3: System parameters during a fault on an interconnecting line without using the defense plan

The over current protection of every single line causes a cascaded tripping of the remaining interconnecting transmission lines leading to a divagation of the voltage phasors between the two systems. The generated power at the highly affected node H-O located in the UCTE-area close to the interconnection, starts to oscillate intensively. Even more important for the overall stability of the power system is the voltage level at the generating nodes. As a consequence of the phase angle divagation serious voltage dips occur at node H-O oscillating for several seconds. The intensive voltage drop at this node will be fatal for the system as it will force local power plants to disconnect from the grid and a blackout situation gets very likely. This tripping of about 1700 MVA would lead to an even higher stressing of the affected region and might likely result in a blackout caused by a cascaded tripping of further power plants and a lack of reactive power injection.

Figure 4 shows the same fault scenario with the interface region being additionally protected by the defense plan. From top to bottom the four charts in this figure present the following variables:

1. The phase angle difference $\Delta\delta$.
2. The system state of the defense plan.
3. The cumulated active power injection P_{Gen} at the nodes H-W and H-O
4. The amplitude of the voltage V at the nodes H-W and H-O.

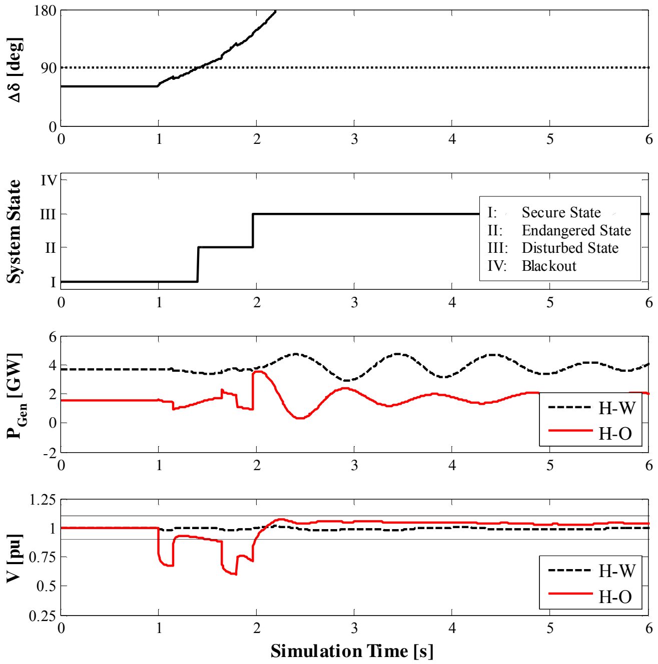

Fig. 4: System parameters during a fault on an interconnecting line by using the defense plan

The system state changes to the endangered state according to the defense plan when the phase angle difference exceeds 85°. About half a second later the defense plan recognizes that the two systems will not return back to a secure operation point and changes to the disturbed state. Immediately all remaining interconnecting lines get tripped automatically, which happens earlier than without the defense plan as shown before. The effect on the active power generation of the power plants in the UCTE-area is significantly lower than without the protection system. Especially the serious voltage drop in the node H-O is reduced intensively. The voltage returns into the allowed voltage band immediately after the corridor gets opened and the intensive voltage oscillations are prohibited.

B. Fault scenario 2: Fault on a transmission line within the IPS/UPS system

In fault scenario two a fault occurs on one system of the transmission line between the nodes UA-SW and UA-SM (see figure 2). The fault happens at simulation time *t=1s* in the following figures. The faulty line gets tripped 150 ms later by the distance protection relay to clear the fault and further 500 ms later it is switched on again by automatic reclosing. The fault current does not relight and the transmission line stays in operation.

Figure 5 shows the consequences of fault scenario two if the interface region is only protected by conventional distance protection relays including an over current function. The structure of this figure is similar to figure 3. The fault causes a divagation of the voltage phasors between the two power systems leading to a cascaded tripping of the remaining interconnecting transmission lines by the over current function of the distance protection relays. Although the fault happens inside the IPS/UPS system it causes severe power oscillations inside the UCTE system after the uncontrolled system separation. Again the intensive voltage drop at node H-O will be fatal for the system as it will force local power plants to disconnect from the grid and a blackout situation gets very likely.

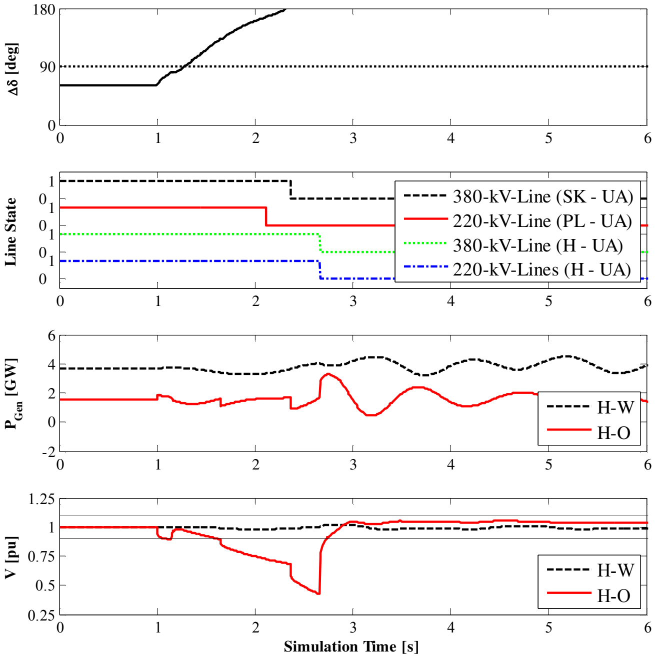

Fig. 5: System parameters during a fault on a transmission line inside the IPS/UPS system without using the defense plan

Figure 6 shows the same fault scenario with the interface region being additionally protected by the defense plan. The structure of this figure is similar to figure 4. At the time when the phase angle difference exceeds 85° the defense plan changes to the endangered state and about 250 milliseconds later it changes to the disturbed state. All interconnecting lines get tripped at once by the protection system. The comparison of the power generation at exemplary nodes inside the interface region indicates that the excited oscillations are lower when the separation of the interconnected corridor happens controlled and in advance. The serious voltage drop at the node H-O does not happen and the tripping of the power plants at that node is prevented by the defense plan. A blackout is not likely to happen.

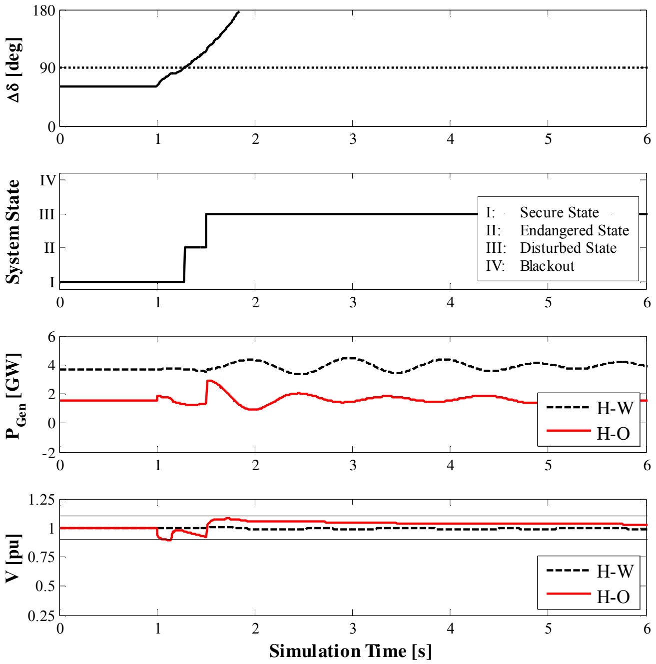

Fig. 6: System parameters during a fault on a transmission line inside the IPS/UPS system by using the defense plan

V. POTENTIAL FOR THE DEFENSE PLAN AT INTERNAL CORRIDORS IN THE UCTE NETWORK

In principle the defense plan is also useful to protect other corridors than the presented interconnection between IPS/UPS and UCTE. This section discusses the applicability of the defense plan at internal corridors inside the UCTE system. In this context it can be distinguished between two different kinds of corridors to be protected.

On the one hand there are narrow corridors which form the only connection between two parts of the network like the connection of Italy, the connection of the Iberian Peninsula or the connection of western Denmark. These examples are marked with character A in the map illustrating the UCTE area in figure 7. In such corridors the systems have a predefined cut set at which the transmission lines can be tripped by the defense plan in situations of severe system disturbances. For the implementation of the defense plan at a certain corridor the corresponding parameters $\Delta\delta_{limit}$ and $dd\Delta\delta_{min}$ have to be determined. Typically these corridors are highly loaded bottlenecks. After the separation of a regarded corridor the transit flow gets interrupted, yielding a surplus of generation on one side and a lack of generation on the other side of the corridor. These deficits have to be balanced by primary control. In the first synchronous zone of the UCTE the maximum power deviation to be handled by primary control is 3000 MW [20]. To guaranty frequency stability in the remaining UCTE network after a separation of the regarded corridor the transit power during steady state operation has to be limited according to the primary control reserve.

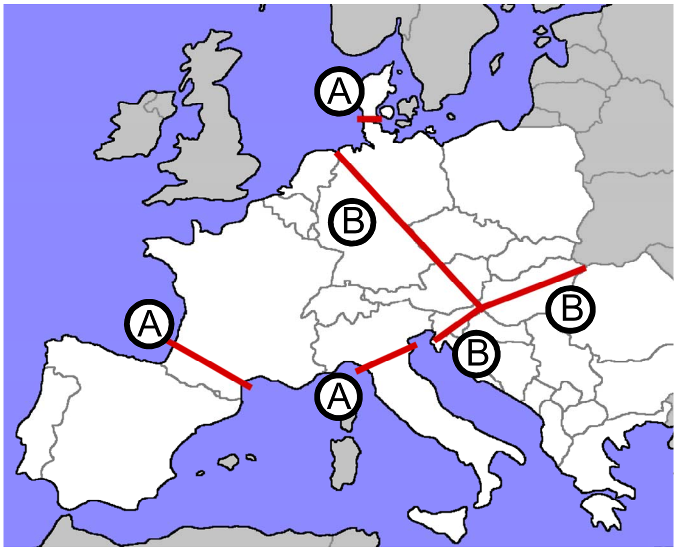

Fig. 7: Map of the UCTE area showing different corridors which could be protected by a defense plan

On the other hand there are wide area corridors across the meshed network which can be difficult to recognize during undisturbed operation, but typically can form a cut set after severe system disturbances. Such corridors emerged across the UCTE at the system disturbance in November 2006, marked in figure 7 with character B. Another example for such a corridor is the interconnection between the old UCTE members and the new members from the eastern part of Europe added since the 1990s. This corridor is placed in the center of today's UCTE network but only consists of a few interconnecting transmission lines. The exact cut set of wide area corridors is not predefined and varies depending on the load flow situation. For the application of the defense plan at such corridors without a predefined cut set, further research is needed.

VI. CONCLUSIONS

It was shown that the defense plan proposed in this paper can avoid loss of synchronism in cases of severe system disturbances by controlled separation of transmission corridors. The input values for the defense plan are the voltage phasors on both sides of the transmission corridor. Further observation of the power system is not necessary. This is an important advantage if the protected transmission corridor is not completely observable.

For future research, simulations of the defense plan at internal fault scenarios within the UCTE system should be carried out. Thereby, the dependency of the defense plan parameters on the protected corridor should be analyzed.

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VIII. BIOGRAPHIES

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