Implementation of a dynamic grid training simulator

Model-development, compilation and training design

Philipp Hinkel
University of Kaiserslautern
Chair for Energy Systems and Energy Management
Kaiserslautern, Germany
hinkel@eit.uni-kl.de

Davood Raoof-Sheibani
University of Kaiserslautern
Chair for Energy Systems and Energy Management
Kaiserslautern, Germany
sheibani@eit.uni-kl.de

Abstract—**In today's modern society, a secure and reliable supply of electrical energy is indispensable. That task, which is becoming more complex in the context of an increasing share of renewable energies in a liberalized energy market, is achieved by grid operation management in control centers. This paper presents a training concept, which provides the basic qualifications for grid operation management. Therefore, a grid model is implemented and fitted to the training requirements, using the grid description language GDL of the training simulator DUtrain PSH. The load flow of the grid model in PSH is verified. Deviations compared to offline simulation are observed in the contingency analysis. The developed simulator training will be used as part of the forthcoming lecture "Netzplanung und Netzführung II". Here, the students gather practical experience concerning grid operation management by completing realistic training scenarios in a control center replica.**

Keywords-grid operation management; renewable energy; simulator training

I. INTRODUCTION

The supply of the population with electricity is one of the basics for everyday life in a modern society. Thereby, the end consumers rely on a continuous power supply. This secure and reliable supply of electricity is achieved by monitoring and remote controlling of the grid at any time by grid operators in control centers. Deviations from the normal grid operation or failure of equipment often occur in which cases corrective actions have to be taken. Due to this fact, grid operation management is a challenging task that requires lots of practice and experience.

The grid operation management is becoming increasingly complex in consideration of the adopted energy concept "Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Stromversorgung" by the German Federal Government in September 2010 [1]. The objectives are a massive reduction of greenhouse gas emissions and the development of renewable energy sources to a share of 35 % of the gross electricity consumption in 2020 and up to 80 % in 2050. Concurrently, the policy statement „Der Weg zur Energie der Zukunft", in response to the nuclear reactor disaster in Fukushima, regulates the abandonment of nuclear energy by 2022 [2]. As a result, the proportion of power plants that produce electricity as required reduces. Rather, the proportion of volatile supply rises by renewable energies. The increasing complexity in the power grid enhances the demands on the grid control management. Therefore, it is imperative that the responsible personnel in a control center is subjected to a thorough education and training. Here, the universities have the responsibility to ensure a solid basic education of students and an academic qualification of their employees.

In order to continue granting a secure and reliable supply of electricity, taking into account the growing share of renewable energy, the chair for Energy Systems and Energy Management (ES+EM) of the University of Kaiserslautern researches in cooperation with the DUtrain GmbH on dynamic models of renewable generation units. On the part of DUtrain, a real-time dynamic training simulator for grid operation management is provided as a part of this collaboration. To accomplish a contemporary education of students and to establish practical relevance beyond theory, the training simulator will also be used in academic teaching.

This paper presents a simulator training concept which will be used in the forthcoming lecture "Netzplanung und Netzführung II" and is first offered in winter semester 2014/2015 for master students majoring in electrical engineering. Focusing on the grid operation management in a virtual control center, students can practice and understand the complex tasks of grid operation during the simulator training. The basis for the training simulator is a grid model introduced by the chair for ES+EM. This model includes the typical voltage levels and grid configurations in Germany as well as conventional power plants and renewable generation units.

The paper is organized as follows. First, training simulators as an appropriate training tool for grid operators are identified in section II. After the classification of different types of training simulators, the DUtrain real-time dynamic simulator is embedded in this context. Section III presents the implementation process of the grid model into the training simulator. Afterwards, the grid model and the grid data language with its properties is introduced. This knowledge allows the description of the grid to an executable target grid inside the simulator. Furthermore, the grid model is adapted to the amended didactic requirements. Thereafter, the grid model is verified in several steps in chapter IV. A training concept and detailed training scenarios with their respective objectives and tasks are developed in chapter V.

II. TRAINING SIMULATORS

A. *Necessity of training simulators*

The grid operation management in a liberalized energy market with a growing share of renewable energies will become more challenging and increasingly requires decisions and interventions in the grid operation. The supply-side positioning of the renewable generation results in a modified transmission task from the wind-rich Northern Germany to the economically strong Southern Germany with high loads. At the same time, due to the liberalization, there are large-scale current transits through energy trading. This overall trend means that grid operators need to intervene more frequently and perform redispatch measures to maintain system stability. These redispatch measures increased from 1,589 hours in 2010 to 7,966 hours in 2013 [3].

In particular, the grid operation management is under high stress in fault situations, since an interruption of the electricity supply has enormous social and economic impact. In addition to the normal grid operation, especially the control of alert and emergency grid conditions is of importance. In such critical situations, measure to prevent further spreading of the fault and the fault avoidance must be taken as soon as possible to achieve a secure grid state. While failures of individual equipment occur frequently enough allowing the staff to receive routine in their daily work, strongly disturbed conditions and the blackout instead are extremely rare. Hence, these crucial grid states are a great experience deficit of the staff. To compensate their lack of experience, the use of training simulators is a possibility to prepare the employees.

The training of control center personnel is intended in the TransmissionCode 2007, as well as in the Network Code in Operational Security of ENTSO-E. Here, in section 3.3.14.5 respectively chapter six the training and certification is of primary importance [4],[5].

B. *Classification of training simulators*

Training simulators are different from other simulation systems due to the fact, that all processes are performed parallel and in real time. In addition, it outputs the results to interfaces for real operation and allows to operate the simulated process via these same human-machine interfaces. The training simulator for grid operation is a replication of a control room with simulation programs running in the background. Generally, they can be distinguished into attached, semi-attached and stand-alone simulators [6].

Attached training simulators use part of the hardware and software of the control room, while semi-attached simulators use only the software components with separate hardware. For this reason, the data coding of the grid can be greatly reduced. Training simulators as part of control centers are state of the art, but cannot represent dynamic phenomena. Of course, the application of the simulator is restricted to this very control center.

Stand-alone systems instead operate independently from each control center. Any grid model can be described whereby the number of users and its profitability can be increased. Thus, it is possible to train the cooperation between transmission system operators (TSOs), distribution system operators (DSOs) and power plant operators (PPs) as it is particularly necessary in crucial grid conditions and during grid restoration. Also future grid expansions can be trained. However, for stand-alone simulators all data of the power system components have to be described in a database.

C. *DUtrain Power System Handler*

The DUtrain Power System Handler (PSH) is a stand-alone training simulator for electric power systems. To alleviate the data problem, an efficient data-collecting and -handling system named Grid Data Language (GDL) has been developed with an automated design of the operational surfaces. The simulator enables the parallel and hierarchical connection of neighboring grids and beyond the separated output of the simulation results on several virtual control rooms. This allows to train the cooperation between TSOs, DSOs and PPs. Basis of the PSH is a dynamic long-performance with a full Newton-Raphson iteration every 10s and a medium-term performance with a resolution of 100ms is used for the frequency model. The PSH also features a load model, limit check, synchronizing equipment, network-protection, power-plant-protection and contingency analysis. Please see Fig. 1 for the four trainee places of the PSH at the chair of ES+EM. For surveillance of the students and to intervene in the simulator training by switching sequences, there is a trainer working place installed in the back of the trainees.

Figure 1. Setup of PSH at the chair for ES+EM

III. IMPLEMENTATION OF THE GRID MODEL

A. *Selection and presentation of the grid model*

Basis for the simulator training is the grid model developed by the chair for ES+EM. It was chosen for the simulator training because it contains the typical voltage levels and grid topologies of Germany. The grid size is as small as possible for a fast understanding of the grid topology by the students, but also as large as necessary to define various operational scenarios. This grid model allows to assign different responsibilities for the trainees as one TSO, two DSOs and one PP which matches to the number of trainee working places. Further, the grid contains renewable generation units to show the influence of volatile generation on the grid operation management. The model does not include e.g. HVDC-connections, hydro or nuclear power plants and storage facilities due to simplicity reasons which will slightly limit the number of scenarios.

The grid model is shown in Fig. 2 where extra high voltage level (380 kV) is represented in red, high voltage level (110 kV) in blue, medium voltage (20 kV, 10 kV and 6 kV) in green and low voltage (0.4 kV) in purple. The meshed 380 kV voltage level consists of five stations with a connection to two large generators via station A and to two external grids via stations B and C. Each station C and D has a capacitor and inductor to control the bus bar voltages and is coupled with the 110 kV-level. The medium voltage consists of a 20 kV-ring-grid and a 10 kV-ring-grid with neighboring station. Station H15 supplies an induction motor and H16 connects to a low voltage grid with PV units. A wind farm with nine wind turbines is in bottom right-hand corner.

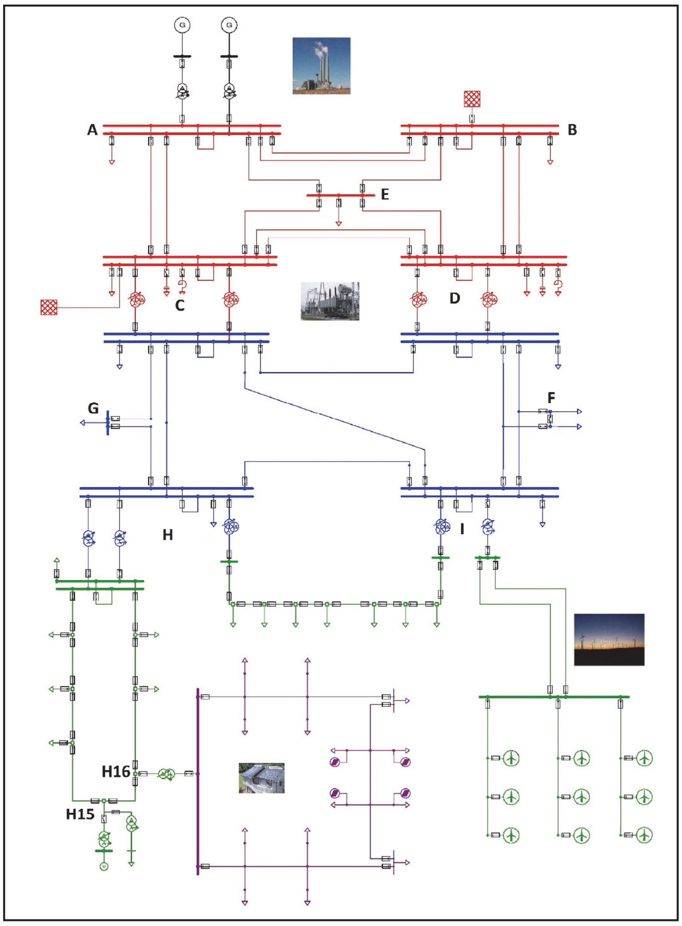

Figure 2. Selected grid model

B. Grid Data Language

PSH requires as input data a GDL formatted grid description. Since PSH has no graphical interface for updating the simulator, the GDL data-system allows an efficient, language-orientated description of electric grids to implement them into PSH. Hereby, the basis of GDL is a hierarchical identification of the equipment. Each grid equipment object, such as bus bars, lines, transformers, loads and generation, has to be uniquely identified by a four-level object descriptor. A fifth level for further specifications is available if necessary. Level four is the "species" and level five the "relative species". To differentiate the levels and to accomplish an unformatted notation, the number of apostrophes indicates the level of the location followed by a square bracket for species and a star for the relative species [7]. Please see the following example: ```Station``VoltageLevel`Feeder[Equipment*controllable].

The source description of a network in principle consists of four files. First, the "dictionary" enumerates every species and relative species which can be used for the grid description, whereas the location is arbitrary. Second, the "attribute source" defines attribute-sequences pertaining every species. Third, the "network-source" using operational terminology describes all operational objects, alarms and measurands. Finally, in the "power-plant source" the generators are entered according to type and parameters.

After a complete chained notation of all objects from the presented grid model in ASCII format, the source description is compiled to a binary GDL process data-base which is pivotal to PSH's software. From here, the automatic set-up of the dynamic model as well as the automatic design of the process surfaces is performed. The automatic design result of Station A with two generators and their main transformers, two bus bars, loads and feeders is shown in Fig. 3.

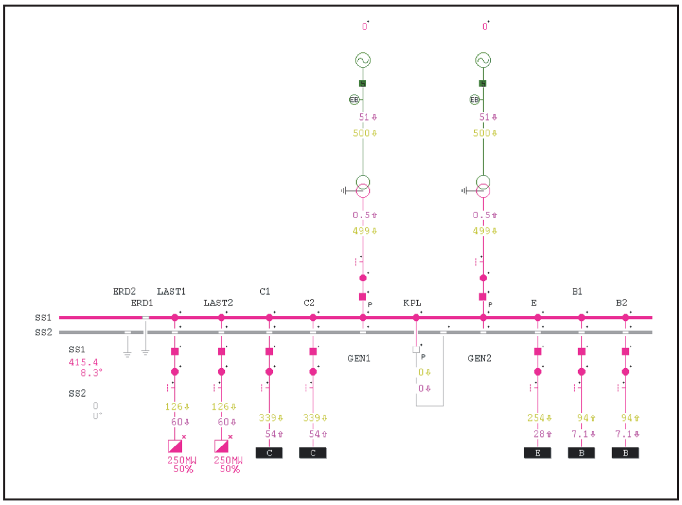

Figure 3. Station A of the grid model

C. Adaption of the grid model

Since the grid model was originally not designed for grid operational training it has to be adapted to the simulator training requirements. Particularly, the influence of volatile generation of renewable energies is too small to show their consequences on grid operation management. Consequently, a large wind farm with an installed capacity of 100MW is added to the grid model to demonstrate high gradients and their influence on the conventional power generation. This new configuration allows to show feedback from 110 kV-level into transmission grid in light load conditions or the effect of forecast errors of renewable generation on the grid frequency and the usage of secondary control power. Furthermore, the training of grid restoration is part of the simulator training, but the grid in its current state has no black start capability. The implementation of a gas turbine solves this deficit. An appropriate location of the gas turbine is station H (110kV) to require a collaboration between TSO and DSO during the grid restoration procedure.

IV. VERIFICATION OF THE GRID MODEL

A. *Verification of the load flow*

After the implementation of the grid model, the load flow of PSH is verified by comparing the load flow results with the grid simulation software PSS®SINCAL. Both simulation programs are provided with the same grid parameters for the verification process. Possible differences are discussed and analyzed.

Both, PSH and PSS®SINCAL, solve the load flow based on Newton-Raphson iteration. While in PSS®SINCAL the accurate value can be set, the PSH chooses its load flow accuracy independently to assure a real-time behavior also in very large grids. PSH specifies its accuracy to 0.1MW and for PSS®SINCAL an accuracy of 0.001MW is achieved.

A sequential verification of the individual equipment in small test grids is chosen to identify basic differences in the load flow. Thereby, the differences can be clearly assigned. Only after a positive verification, the next equipment is verified.

At first, a minimal test grid consisting of one external grid, two loads and a transmission line is compared. Fig. 4 illustrates the load flow results, where the results of are represented in red and of PSH in blue. The result analysis shows that the loads in PSH are not set to 250MW as described in GDL-format, but possess a larger active power component. The reactive power component of the load is slightly different. This deviation is due to DUtrain's load flow calculation method. To allow a further comparison of the load flow, the loads in PSS®SINCAL are adjusted to the ones in PSH. After the modification of the loads, the load flow results are consistent of both simulation softwares.

As a next step, the minimal grid is extended with a transmission line to station D to verify the capacitor and inductor. The capacitor and inductor are turned consecutively and the load flow results are compared. The load results are consistent within the PSH's accuracy and show that the compensation equipment is correctly modeled inside of PSH.

Lastly, the transformer is verified. Therefore, the grid is again extended and the transformer in station D is turned on and is under load on the low voltage side. The power flows of the two simulation softwares match each other within the accuracy limits. Additionally, the bus bar voltages are consistent, but differ greatly on the low voltage side of the transformer. This fact cannot be explained with the accuracy limit of PSH. Since the same transformer parameters are used, the difference in the voltage levels can only be explained by a false transformer model inside PSH. To confirm this assumption, another power flow with a no load condition of the transformer is performed. Without the voltage drop across the transformer's impedance, the bus bar voltages indicate that the transformation ratio in PSH is incorrect. Please see Tab. 1 for the simulation results at station D.

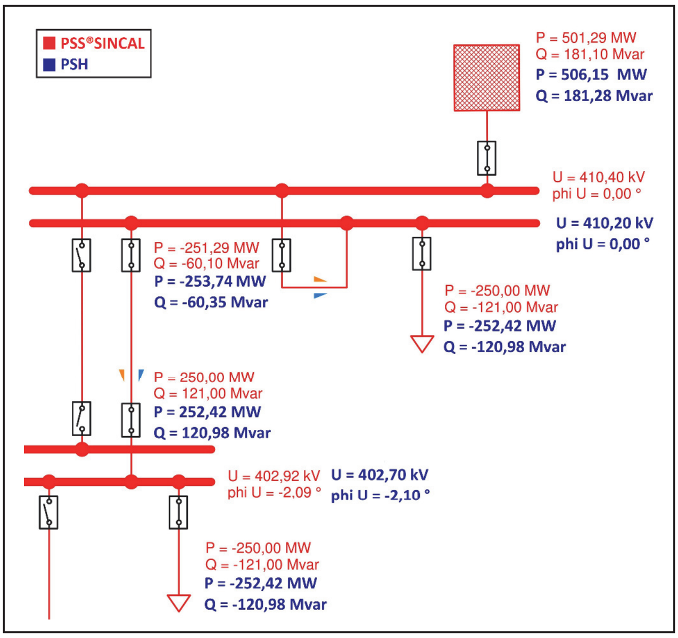

Figure 4. Load flow results of the minimal test grid

TABLE I. LOAD FLOW RESULTS AT STATION D

		PSS®SINCAL	*PSH*
Station D, 380kV	U	386.62kV	386.30kV
	δ	-7.77°	-7.77°
Station D, 110kV	U	115.93kV	111.80kV
	δ	-7.78°	-7.80°

The transformation ratio is calculated in PSH as the quotient of the nominal voltages. This calculation is wrong, because the transformation ratio equals the quotient of the transformer's rated voltages. Since the rated voltages do not match the nominal voltages in general, different voltages occur throughout the whole grid. Especially, the block transformers with a rated voltage of 420kV cause too low voltages. This error can be partially corrected by changing the terminal voltage of the generators, but is still not a satisfactory solution.

B. *Verification of the (n-1)-simulator*

The (n-1)-criterion is an important deterministic planning and operational criterion for grids. PSH has a separate (n-1)-simulator on which a real-time snapshot can be imported. Here, a contingency analysis can be performed. To verify the (n-1)-simulator, the contingency results are reproduced in the normal PSH simulator and compared against each other.

In the following, the failure of a transmission line between the stations D, F and I is considered. This failure results in a supply interruption in station F. The contingency analysis recognizes this failure as not (n-1)-secure. The contingency results in station F are shown in Fig. 5. Here, there is no power flow across the line, but there is still voltage at bus bar “SS2” and “LAST2” is indicated as supplied.

Also other contingency situations show different results as in the normal PSH simulation environment. The reason for the deviations is PSH’s concept of the contingency analysis. To achieve the real-time requirements as well for large grids, a line is not excluded of the load flow calculations, but replaced with a high impedance branch. Thus, unrealistic voltages on unsupplied bus bars can occur. Hence, the (n-1)-simulator provides only an approximate load flow solution and is of limited use for contingency analysis.

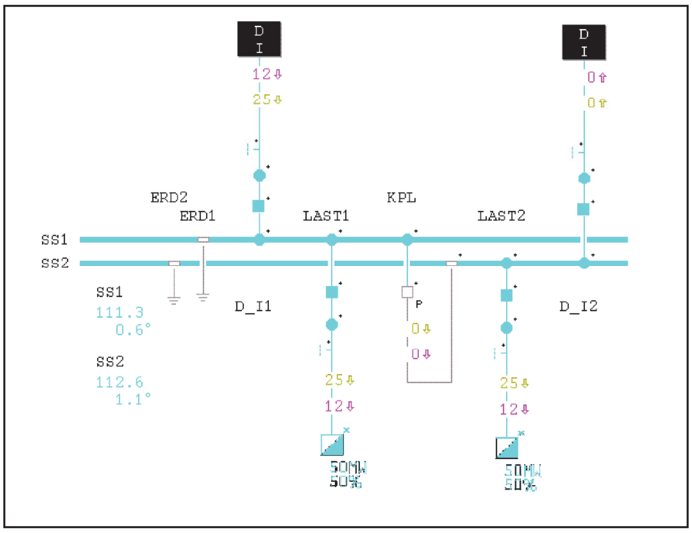

Figure 5. Results of the contingency analysis in station F

V. TRAINING DESIGN

A. *Training concept*

Since PSH is a very extensive software with many interfaces and operating options, it is not possible for the students to solve complex tasks right at the training’s start. In fact, the training provides a transition from a closely guided to a free and independent operation. With a growing knowledge of the simulator handling, the complexity of the tasks rises. This is also reflected in the number of documents. While the students get detailed written tasks at the beginning of the training, later on the students face grid conditions to which they have to respond accordingly and take necessary actions.

PSH offers different opportunities for the simulator training. Two basic operation principles of PSH can be distinguished. On the one hand, an independent simulator can be started on each PC. On the other hand, one simulator is accessed via all PCs. For the training concept, three training types are identified. In the “single company training” company-specific concepts and technical aspects are trained. In the contrary, during a “inter company training” different companies (TSOs, DSOs and PPs) work parallel on one system, focusing on communication and cooperation. The “inter TSO training” practices system management as well as control area exceeding operations. The training types “single company training” and “inter company training” are shown in Fig. 6 in red and blue, respectively [8].

The training type “single company training” allows the students to work on parallel tasks achieving the same knowledge at the end of the training and is the concept of choice. The “inter company training” is used for grid restoration to teach communication procedures. The “inter TSO training” currently cannot be used since only one TSO is represented in the grid model.

B. *Normal grid operation and grid surveillance*

First, the students gather experience in normal grid operation and grid surveillance. This section contains tasks to switching operation, e.g. bus bar changes or switching off lines and transformers. Subsequently, the students practice start-up, synchronization and shut-down of conventional power plants and renewable generation units. At last, voltage and reactive power control respectively transformer tap changer and their influence on the grid operation management will be analyzed by the trainees. The tasks as written worksheets are provided to the students and the trainers will support them whenever desired.

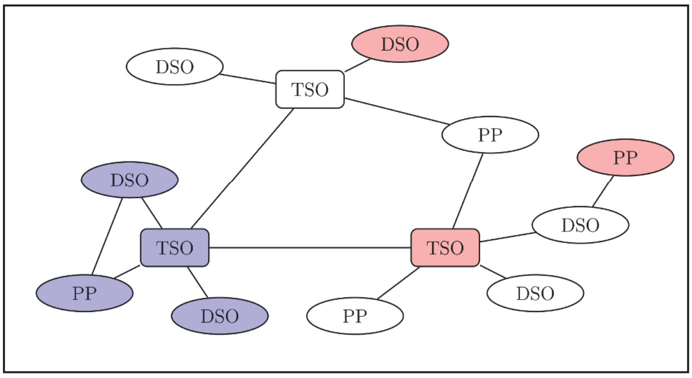

Figure 6. Training types, based on [8]

C. *Load and frequency control*

During this section tasks concerning the control hierarchy of the European interconnected power system are addressed. The emphasis will be on the primary control and the characteristics of its proportional controller as well as the advantages of a large interconnected system. The trainer will input a switching sequence for a gas turbine outage. According to the droop factors, the students should calculate the static frequency deviation. Further, the dynamic frequency deviation and the distance to an automatic load shedding have to be considered. Afterwards, the recovery of the desired grid frequency and the set point exchange power have to be conducted by the students. With this knowledge, the trainees will carry out a schedule management with a perfect forecast and later with forecast errors. In this task, there will be profiles for loads, power stations, renewable generation and exchange power. Herewith, the power station gradients are calculated and the use of secondary control power is minimized.

D. *Operation in disturbed grid conditions*

Constitutive on the previous tasks, the students have gained experience in the simulator handling and in the grid characteristics. Hence, the students now will be “confronted” with various grid conditions as in a real control center. The aim is the control of disturbed grid conditions and to transfer the grid in a secure grid state. For this purpose, the students have to identify which event has changed the grid state to select an appropriate solution to return the grid to a secure grid state. The grid condition has to be checked and verified, if a secure grid condition is achieved. Chosen events by the trainers are short circuits and failure of grid components in different voltage levels. For instance, a one phase fault in the compensated 110 kV-level should be detected by the displacement of the star point and the consecutive switching of transmission lines. A three phase fault in the 20 kV ring grid will cause an interruption of one entire half ring. Here, the students should discover the affected line and conduct a switching of the sectioning point. This section also covers bottlenecks, overloads and voltage range deviations which have to be observed and corrected. Moreover, the (n-1)-criterion has to be guaranteed at all times. At the end of this exercise, the students will perform an inter company training in order to practice communication skills and to be prepared for the upcoming section "grid restoration". A fault on the bus bar in station C in 110 kV-level with additional protection failure of line CD results in a system islanding of TSO and DSO1 respectively DSO2. In stations C and D, a bus bar change should be performed to resupply the loads and to merge the two islands.

E. Grid restoration

The blackout is the worst possible disturbance of an electricity system. It may be unlikely, nevertheless it is a very critical situation in our modern, electricity dependent society. Thus, the grid restoration is the conclusion of the simulator training. The grid restoration is particularly demanding, because only a small mass of inertia of the generators is available and the frequency is very sensitive to load changes.

Since the generators in station A have no black start capability, the grid restoration will be a bottom-up process through a start-up of the gas turbine in station H (110 kV-level). The gas turbine has to be smoothly loaded by medium voltage loads, whereas the electrical output of the gas turbine has to be continuously adjusted to keep the grid frequency close to 50 Hz. Following that, a connection to the generators in station A shall be established. Therefore, line CH, one transformer to the 380 kV-level and line AC will be energized. Thereby, the lines are loaded to reduce high voltages due to the Ferranti effect. Now, the generators in station A can be started up. Hence, the mass of inertia increases and the grid frequency will be less sensitive to load changes. Afterwards all loads shall be resupplied and a secure grid state established. Finally, the interconnection to the external grids will be conducted.

Before the training, the students shall develop a restoration concept similar to the presented one and execute it. If the students cannot recreate the grid, there will be a guided grid restoration by the trainers.

VI. CONCLUSION AND OUTLOOK

In this paper a grid model was implemented into PSH and a didactic training concept for a simulator training of grid operation management was developed.

The presented training concept with its exercises gives a unique opportunity for students to practice and understand the complex tasks of grid operation management.

In future studies, a sample run of the simulator training will be conducted by employees of the chair for ES+EM as trainees. Such a test provides the possibility to monitor the time estimates of the tasks as well as the learning progress to adapt the training concept if necessary.

By using alternative grid models, PSH can be used in research to implement real grids, e.g. the transmission grid of Germany.

REFERENCES

[1] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, "Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung," September 2010.

[2] Bundesregierung, "Eckpunktepapier: Der Weg zur Energie der Zukunft," June 2011.

[3] Bundesnetzagentur und Bundeskartellamt, „Monitoringbericht 2013," June 2014.

[4] VDN, "TransmissionCode 2007: Netz- und Systemregeln der deutschen Übertragungsnetzbetreiber," August 2007.

[5] ENTSO-E, "Network Code on Operational Security," September 2013

[6] A. Litzinger, "Systemintegration, Weiterentwicklung und Anwendung eines Trainingssimulators für die Betriebsführung elektrischer Netze," 1997.

[7] D. Rumpel and J. R. Sun, "Netzleittechnik; Informationstechnik für den Betieb elektrischer Netze," Springer, 1989.

[8] DUtrain GmbH, "Power System Handler – Simulationssystem für die Netzbetriebsführung," 2007.