OPERATION AND CONTROL STRATEGIES FOR NETWORKS WITH A HIGH DEGREE OF RENEWABLE GENERATION

Zbigniew A. Styczynski, Krzysztof Rudion; Peter B. Eriksen, Antje G. Orths;
Thomas Schäfer; Walter Sattinger; Luis Rouco; Arun Phadke
Otto-von-Guericke-University Magdeburg, Germany; Energinet.dk, Denmark;
Vattenfall-ET, Germany; Swissgrid, Switzerland; Universidad Pontificia Comillas Madrid, Spain; VirginiaTech, USA
sty@ovgu.de

Abstract – New challenges to the power system have been evoked by the worldwide shortage of primary energy sources and have resulted especially in a high penetration of renewable energy generation in the system. However, the high reliability of customer supply must be maintained in the future while the structure and the tasks of the power networks will change. The way to the future power system is long and expensive and must be undertaken in a few steps with regard to safety and security of supply. So new strategies for network operation and control have to be successively developed and applied in an intelligent manner taking into account the future challenges. Much new research should be done on this field.

The theoretical background, realisation possibilities, current international practice and future requirements and possible solutions for the operation and control of the networks with a high degree of renewable generation is shown and discussed in this survey paper.

Keywords: Power system, operation, control, renewable generation, future power system.

1 INTRODUCTION

Electrical energy is one of the most important energy forms in the modern world, and the main task of the electric power system is to ensure a safe and reliable power supply to the consumers. For this reason the power system has to operate under normal conditions without operational constraints, e.g. bottlenecks or voltage drops. Due to critical contingencies, the system can switch to an emergency state in which not all conditions of normal operation are fulfilled. Therefore, power system operation has to be continuously monitored and analysed in order to avoid non-desirable operational states. This task is very complex since many factors influence power system operation.

The reality of a shortage of primary energy resources is increasingly gaining public awareness. Both the social acceptance and growing energy demand have led to the increasing penetration of renewable generation. Thus, future secure operation of power systems must take into account:

- changes in the grid structure,
- stochastic character of demand,
- stochastic and intermittent character of renewable energy generation, e.g. wind,
- non-desirable events such as disconnections of large wind power generating units partly due to strong wind.

Power system operation requires sufficient data acquisition for system-state estimation. Data acquisition is provided by a SCADA system. It includes information about the voltage and power in selected power system nodes as well as information about the grid structure. Moreover, detailed information such as tap changer positions or controlled capacitor bank values can be obtained from additional measurements. All of these above-mentioned measures are generally necessary to make the power network observable.

The data provided by a SCADA system do not allow full observability of the power system in the case of very high penetration of renewables due to the generally stochastic character of energy generation and due to the localisation of most renewables in the distribution system. The number and concentration of renewable generation units is increasing rapidly and must be considered in relation to control and operation at the distribution (local) level and at the transmission (global) level.

In countries like Germany, Spain or Denmark “local” generation is significant and amounts to up to 100% depending on weather conditions [1]. How does one operate such a “new” power system? How is it possible to observe and control it? Are the currently acquired data in the SCADA system sufficient for the observability at the distribution level? What is the theoretical background for this? How can the future requirements be met by the technical and standardised solutions? Are the technical solutions good enough to guarantee the fulfilling of market requirements? These are the questions that will be answered in this survey paper.

2 THEORETICAL BACKGROUND

2.1 General Power System Control

The power system is one of the most complicated technical systems developed. For example, the UCTE power system has more than 200,000 km of transmission lines, provides electrical energy to more than 450 million people, includes more than 1,000 big generators equipped with millions of local control systems and provides electrical energy synchronous with the frequency of 50 ±0.02 Hz under normal conditions. This system is very reliable, which is indicated by a very short average interruption duration (e.g. Germany 20 min/a, France 51 min/a, Spain 118 min/a) [2]. In order to reliably operate the power system, it is necessary to observe some general rules. The first rule is that balance between demand and generation should be provided continuously. Both load and generation could be controlled for the stabilisation of the system, but in practice only a part of the concentrated generation (regulating power plants) is currently used for this purpose. The settings of the control system provide stable operation of the current power system in the event of load changes or unexpected faults in the system (e.g. emergency disconnection of the power system). The structured primary, secondary and tertiary power reserve corresponds well with the expected statistical power disturbances, e.g. faults, load changes, outages. Due to the expansion of the power system some additional functions were implemented in the control system, such as the inter-area oscillation damping system. The stability of the system can be threatened if there is an imbalance between generation and demand. If the system operates close to the stability limit and cannot be balanced because of bottlenecks, generator limits, etc. it can lead to system collapse.

In Figure 1 the operational space for an autonomous power system in which the power balance is provided internally is presented schematically. The stability margin is represented as the distance between the external and internal shells. However, the power system is constantly undergoing development, which can be observed in the increase of the system size on the one hand, and in the interconnection of neighbouring power systems on the other. This leads to a new situation as presented in Figure 2. In this case the stability of each individual power system is additionally influenced by the interconnected neighbour.

The rapidly increasing amount of dispersed generation of a stochastic nature in the power system, such as wind turbines and PV, introduces an additional factor influencing the overall system stability as shown in Figure 3. If the changes in the load balance ΔP_A and ΔP_B in the traditional system can be coordinated between the interconnected subsystems in a way that the stochastic deviations from the schedule are compensated, the distributed generation ΔP_{WT} or ΔP_{PV} would decrease the stability margin and, in critical cases, bring the system to an unstable state, disconnect subsystems or cause a blackout.

Most of the dispersed generation units are connected to the distribution system, which, in general, is not considered in a detailed manner during the system analysis.

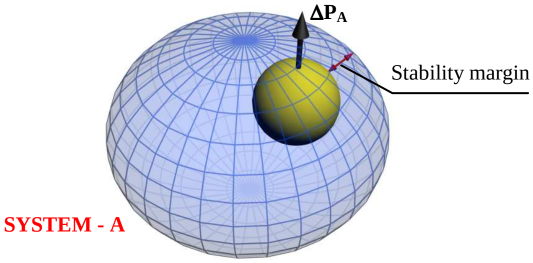

Figure 1: Traditional autonomous power system.

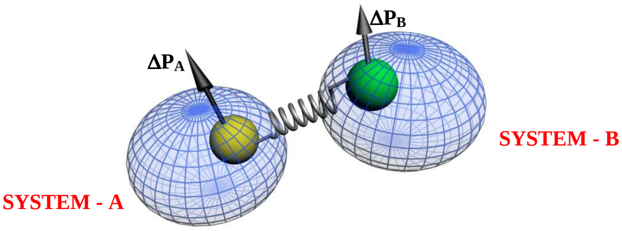

Figure 2: Interconnected power system.

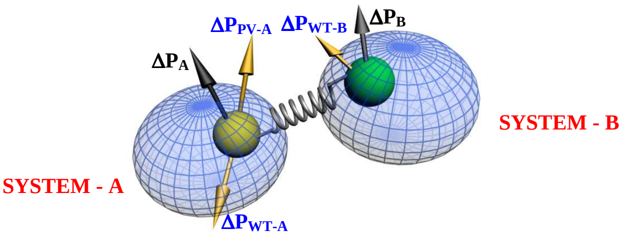

Figure 3: Interconnected power system with stochastic generation.

It is common practice to represent parts of the distribution system as lumped loads or lumped generators, respectively, connected directly or by a step-up transformer to the transmission system. Since most of the dispersed generators are placed in the distribution system, its simplified representation during the analysis can lead to loss of significant information about the overall system state because most of the stochastic-based deviations and inaccuracies appear at the distribution level. Moreover, the operation of the overall power system is coordinated centrally at the transmission level. However, the control process cannot be performed optimally due to the lack of information about conditions on the distribution level.

This new situation significantly lowers both the observability of the power system and the controllability, especially when taking the distribution systems into account. This, in turn, influences the stability of the power system. An appropriate controller is therefore necessary in order to stabilise power system operation. The general structure of such a controller is shown in Figure 4.

In the traditional control system, the power system state was identified by the frequency signal. The perturbation signal “*e*” is dependent on statistical issues such as changes of weather or system component outages, and is generally eliminated when its influence at the measured signal “*y*” is observed. The “*e*” signal is not directly used for tuning the system stabiliser [4]. Instead, sometimes only a very fast signal, such as the inter-area oscillations, is used for tuning the control signal. If the perturbation has a stochastic character, is fast (e.g. $dP/dt > 4$ GW/h) and its value is significant in comparison to the system state value, this value must be directly delivered to the feedback system for predictability of the system reaction in order to guarantee full observability. It is necessary to know the transmittance of the signal to this control space, which is not trivial for stochastic values.

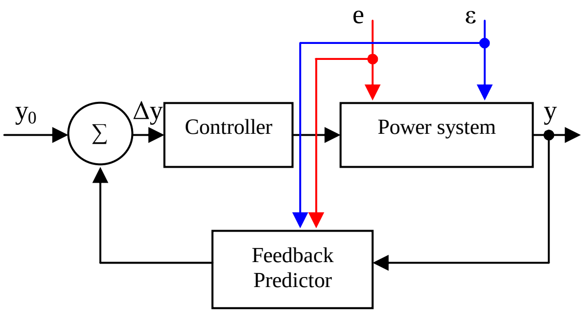

Figure 4: General structure of the power system controller. Additional options indicated by the colours red and blue.

If the controlled system is coupled with another autonomous system, the changes in it influence the control stability (see also Fig. 2) and, finally, if the changes in the coupled system are significant and not measured the control system can become unstable (Fig. 3). The method to stabilise the interconnected systems in this situation is to deliver the information from the connected system directly to the controller, signal ε.

2.2 Operability during Stochastic Disturbances in an Interconnected Power System

An optimal control strategy for power system operation is based on measurements, which are an important element of the power system state observation. In order to guarantee stable power system operation, full observability is required, which is defined by the existence of sufficient information (measured values such as voltages, power flows or node power) at the time of t_0 to predict the state of the system in the next time step without knowledge of the information before t_0 [3].

As already discussed, stochastic generation, which has been an uncontrolled part of the power system up to now, is becoming more and more important. So the signal “ε” can no longer be considered passive. Instead, it becomes active and is generally stochastic, which requires new and more complicated methods for system control.

The control of a stochastic system requires some additional and fast measurements from the power system. In some cases the model-based control approach, which relies on prediction control, is the right solution to obtain a controller with fast response.

The key to stable power system operation is sufficient observability, which allows assessment of the current state of the system, and sufficient controllability, which allows the influence of the state of the system in the required manner.

Taking into account the new situation in the power system concerning new forms of dispersed generation often placed at the distribution level, there are several technically possible measures that can be applied to improve both the observability and controllability of this subsystem. However, there are also corresponding countermeasures, which make this difficult or even impossible. These aspects are summarised in Table 1.

System	Measures & Goals	Barriers
Distribution	Network Security Management (NSM)	Renewable Energies Act (REA)
Distribution	Demand Side Management (DSM)	Missing incentives and regulatory framework
Distribution	Generation Management (GM)	Missing communication infrastructure
Transmission	Better information exchange of load and generation situations in own system (TSO)	Unbundling of the sectors: generation, transmission, distribution
Transmission	Better information exchange of load and generation situations at neighbouring TSOs	Competition concerning energy trading

Table 1: Measures and goals as well as corresponding barriers concerning improvement of power system observability and controllability.

An appropriate model is required in order to analyse the system behaviour and check if it is stable or will retain stability following some disturbances [4]. In the state space representation, the power system can be generally described by Eq. (1) using the matrix notation.

Where x – is the state vector, u – is the vector of input and t – is time. In general, the derivative of the state vector is time-independent in the explicit manner and the introduced equation can therefore be simplified accordingly.

$$\dot{\mathbf{x}} = f(\mathbf{x},\mathbf{u},t) \tag{1}$$

On the one hand, the output of the system model can depend on the state variables, and on the other, it can depend on the input variables and is described by Eq. (2).

$$\mathbf{y} = g(\mathbf{x},\mathbf{u}) \tag{2}$$

If all derivatives of the state vector are equal to zero, which corresponds to the condition defined by Eq. (3), the system is in the steady state and all variables are constant.

$$f(\mathbf{x_0}) = 0 \tag{3}$$

In many cases the analysis of the power system behaviour can be performed using a linearised system model, which can be created from Eq. (1) through the expansion into the Taylor series taking into account only the linear elements. The resulting linearised system model is given by Eq. (4) and Eq. (5).

$$\Delta\dot{\mathbf{x}} = \mathbf{A}\,\Delta\mathbf{x} + \mathbf{B}\,\Delta\mathbf{u} \tag{4}$$

$$\Delta\mathbf{y} = \mathbf{C}\,\Delta\mathbf{x} + \mathbf{D}\,\Delta\mathbf{u} \tag{5}$$

In this representation, the matrix A – is the state matrix defined with partial derivatives of the system equation with respect to individual states; B – is the input matrix defined with partial derivatives of the system equation with respect to individual system inputs; C – is the matrix defined with partial derivatives of the output equation with respect to individual states; and D – is the feedforward matrix defined with partial derivatives of the output equation with respect to individual inputs. The system matrix – A can then be used to calculate the eigenvalues of the power system considered, which are then used to assess its stability, as discussed in [3]. Furthermore, by applying the sensitivity analysis it is possible to find out which elements of the system matrix influence each individual mode the most, and in this way identify the potential instability sources in the analysed system.

In a power system with significant wind energy penetration of a strong stochastic character, the system matrix also exhibits change as a result of the fluctuation of the working point of the electrical system. It contributes to the frequent shifting of modes into the unsafe system operating area as shown in Figure 5.

$$\Delta\dot{z} = \left(\Lambda + \Delta\Lambda_{wind}\right)\Delta z \qquad (6)$$

The phenomena of mode changes can be explained by means of Eq. (6). Due to modal transformation, the system dynamic is described by the new variable *z*, the calculations of which are a result of the parameter of the diagonal matrix - Λ. Because of the changes of the network operating point, the modal transformation generates new modes which can differ significantly from the old ones. This can modify the system dynamic completely. Therefore, in order to achieve the desired system performance taking into account dynamic system behaviour, the continuous estimation of the power system quantities and their application into the control feedback should be carried out (Figure 4).

Using the general model of the power system control, significant changes can be observed when uncontrollable generation increases. Figure 5 illustrates such a situation. In a test system [3] uncontrollable wind generation using current sources has been modelled. In this case the stability margin is decreased.

This quite logical approach shows that in addition to applying the quasi-online calculation of the power system modes to design or changes in controller parameter (Figure 4), including the method of predicting non-controllable generation, it can also determine the margin of the safe operating network area.

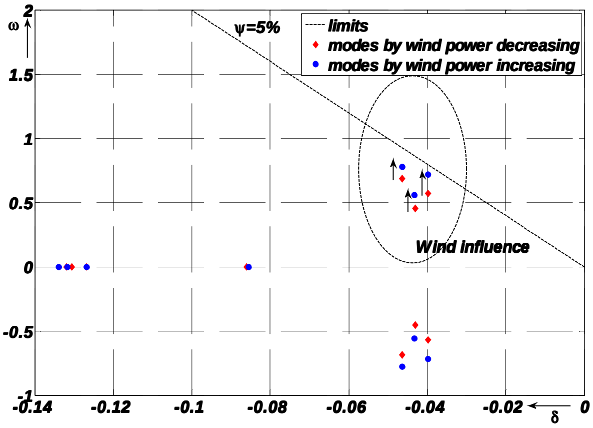

Figure 5: Changes of eigenvalues in the power system if wind generation increases from 5% to 40% of local generation.

If the uncontrolled generation is increased only by a short time (as a result of wind forecasting) it could allow the power system modes to move on above the limit of 5% of the damping ratio, see Figure 5. Theoretically, this moving on should contribute to the controller parameter changes that rapidly modify system behaviour. This could be very dangerous for the system. However, predicting the decrease of the uncontrollable generation could allow the system to smoothly return to the safe operating area without changing the controller parameter.

This simplified investigation shows that the integration of stochastic generation into the model is necessary. It is possible by extending input data or by introducing a second input stream which can influence the state matrix parameters when there are stochastic values. This quite complex approach requires a lot of investigations and is generally bypassed by static rules in the system such as DMS or EMS systems working locally. Generally, from a theoretical point of view, new advanced control methods are necessary to operate the power system in a stable way. In particular, full observability of the system has to be guaranteed. This occurs if the redundancy requirements concerning the measurement number are fulfilled. According to [5] the number of measurements has to be equal to twice the number of unknowns in the system model. Moreover, 75% of measurements should be the line power flows, 20% the nodal powers and 5% the voltage magnitudes.

At present, the market requirements, regulatory rules and technical solutions are not harmonised and thus do not guarantee stable power system operation in each case.

3 COMMON PRACTICE IN SYSTEM OPERATION AND CONTROL

3.1 General Information

The above-mentioned problems are identified by TSOs, and various common praxis rules are defined to ensure stable power system operation. These rules generally have an organising character, such as specific operational modes (e.g. FRT) and do not have any influence on the signals of the power system controllers. In general, following the unbundling, the TSOs do not have enough information from DSOs, and neither TSOs nor DSOs can control the IPPs. According to the Renewable Energy Act (in Germany) (REA), the IPPs such as wind or PV, are not involved in the market procedure. Moreover, restricted observability of the power system has resulted as a consequence of the market confidentiality. Generally the critical ΔP or also the dP/dt are not known and the observation of this value is only limited to one TSO. Figure shows the difference between the scheduled and the real load flow in Europe on 4 November 2006 at 10:18 pm. The differences were immense, especially in the Vattenfall region of Central-Germany. For example, the scheduled/physical exchange with Poland differed between an import of -500 MW and an export of +730 MW. The reason for this difference was the market requirements in connection with the realisation of the scheduled generation by the power station. The TSO cannot influence those strategies because of the regulatory law. This unexpected difference takes part a few minutes before the disturbance in Europe occurs. The UCTE system was divided into three parts with different frequencies.

3.2 Central Approach – TSO Level

Today the TSOs are obliged to guarantee reliable and stable operation of the power system. On the one hand, the main task of the system operator is to control the frequency, and on the other to control the voltage level in the grid. Since the frequency depends on the balance of active power, the operation schedule for the overall power system is prepared for each successive day. Generally, the goal of the scheduling is to estimate the most likely load profile during the next day, which has a stochastic but quite well predictable character, and which has to be optimally covered by the available generators.

However, this process became more complex since the number of dispersed generators interconnected to the distribution grid increased significantly. Most of the DGs such as wind and PV, have a stochastic and intermittent character that depends on the weather conditions. As a result, the prepared schedule for the next day does not always match the real conditions and has to be corrected. For this purpose the TSOs have different kinds of reserve power at their disposal that are used to continuously keep the balance between generation and load. Moreover, in order to improve the situation tools for predicting wind power generation have been developed [6]. But the accuracy of the forecasts is limited and decreases if the time horizon is longer.

Currently, the normalised root mean square error of the day-ahead forecast equals 5.7%. In order to minimise this error and, at the same time, minimise the required reserve, short-term forecasts during the day are continuously performed and the schedule is modified accordingly.

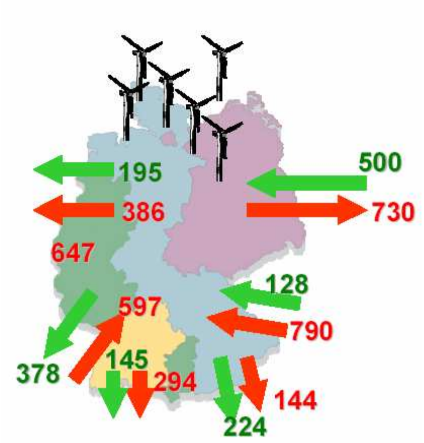

Figure 6: Scheduled and measured load flow on 4 November 2006 in the UCTE power system. Selected part: Germany [UCTE Report].

Apart from keeping the generation and load in balance in order to guarantee an appropriate frequency, the TSO also has to control the voltage level in the transmission system in order to keep it within an allowable range. For this purpose the TSO has to have sufficient reactive power resources at its disposal.

3.3 Local Approach – Distribution Level

The situation at the distribution level is quite different from the transmission level. Since most of the dispersed generators are connected to the distribution grid, appropriate interconnection requirements have been developed [7]. These technical rules should coordinate the operation of the DG units and their interaction with the rest of the power system through the definition of allowable operational modes and ranges. But such an operation approach for the dispersed generators is far from the operation approach based on the active participation in the control of the power system, as is the case with conventional power plants. Moreover, according to the primary revision of the Renewable Energy Act (REA) in Germany, the DGs are allowed to produce the maximum power that is currently available from the prime mover. This approach can have a negative influence on the system stability in some situations, e.g. at low load and high wind speed. Therefore, the new revision of REA was introduced, which allows the DSO to decrease the output power from the chosen dispersed generators if the system stability is threatened. Network security management (NSM) tools have been developed for this purpose and introduced to the DSO control rooms [8]. However, this solution can be applied only in emergency situations and is not a sufficient, active control approach for the future operation of the power system with an even higher number of DGs. In past years the system operators have introduced new extended interconnection rules for DGs, especially for wind turbines, which should support the stability of the system [9]. According to these rules the wind turbines are obliged to support the grid voltage and to ride through the fault without disconnection from the grid. However, concerning the provision of ancillary services, the DSOs are not generally involved.

4 FUTURE APPROACHES FOR POWER SYSTEM OPERATION

4.1 New Operational Schemes

New operational schemes are necessary in order to improve the situation of the global stability of the power system. The main issue here is the transfer of the well-proven operational approaches and mechanisms from the transmission level to the distribution level. The focus is on the local delivery of ancillary services already in the distribution grids. Currently, most system services are provided only at the transmission level as shown in Figure 7. In the distribution grids, only measures such as transformer tap control and device monitoring and control are possible to some extent, whereas the other measures are unavailable. This should change and already in the near future the possibility of scheduling, reactive power control and provision of minute reserve will be the standard at the distribution level.

Furthermore, in the long term the other system services should also be available in the distribution grids as shown in Figure 7.

In order to be able to realise the new operational schemes at the distribution level, the observability and controllability have to be improved significantly. The key to this task is the sufficiently developed communication technology based on an appropriate and uniform communication standard [10]. Furthermore, a significant improvement of the system observability can be obtained by the use of the time-synchronised phasor measurement units (PMU) [11]. Some interesting approaches regarding application of these technologies to the distribution systems are discussed in [12][13].

In order to coordinate the operation of a large number of spatially dispersed generation units in an optimal way, and in order to award them the properties comparable to the big conventional generation units, the DGs have to be organised in the virtual power plants. Currently, there are some virtual power plants in operation in Germany [14]. However, missing incentives as well as a lack of legislative and technical frameworks defining and regulating the operation according to the new approaches hamper the development significantly. Additionally, the fear of the investors that an operation scheme, other than the one according to the Renewable Energy Act, will have a negative effect on the resulting profit and will be a further factor that slows down this process.

To overcome the above-mentioned barriers, the research platform Smart Grids has been established in the European Union. The concept of this platform is to have an intelligent grid in the future where the operation of the power system will be shared between large power plants and actively controlled dispersed generation units as shown in Figure 8.

4.2 *Dynamic Security Assessment*

Currently, the power system operates close to its limits due to the new situation, which makes the loss of load more probable. In order to maintain the high level of reliability, the current network operation strategies have to be changed towards new, innovative strategies.These new strategies should take into account the security evaluation of the actual network state. The usual methodology of security assessment systems has a stationary character and is performed offline. Such an approach is, however, no longer sufficient for systems with a large number of dispersed generation units with an intermittent character. Therefore, there is a need for dynamic security assessment (DSA) systems, which consider the additional aspects, e.g. the influence of controllers on the security and stability of the power system (see Figure 9). This evaluation is done on the basis of the calculated security margins for different contingencies.

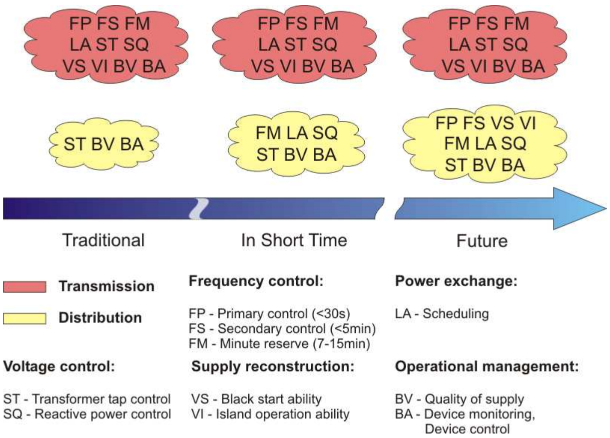

Figure 7: Development of system services delivery [EU].

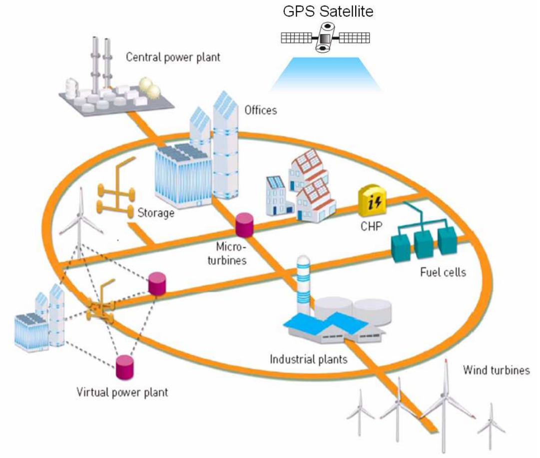

Figure 8: Concept of Smart Grid.

The margins would now allow for operating the network and never exceed a certain probability of loss of load. The main tasks of such a DSA system are:

- monitoring,
- margin calculation,
- visualisation.

Again as with the virtual power plant, the communication is an important aspect of monitoring power systems. A high degree of observability is essential for a fast state estimation as well as appropriate reaction to security problems [15]. New, fast algorithms have to be developed in order to process as many contingencies as possible. Therefore, the margin calculation algorithms themselves have to be improved, and the selection and ranking of the contingencies have to be evaluated [12]. The third important aspect is the visualisation of the calculations in order to help the staff in the control room during the decision process. They usually do not have much time to take decisions, but the information that is important is becoming more and more complex as the number of control elements rises (DGs, FACTS, SVC, etc.). Hence, an innovative visualization scheme is needed that can use all senses of the control room personnel in order to manage the information flow from the technical equipment to the people in charge (Figure 10).

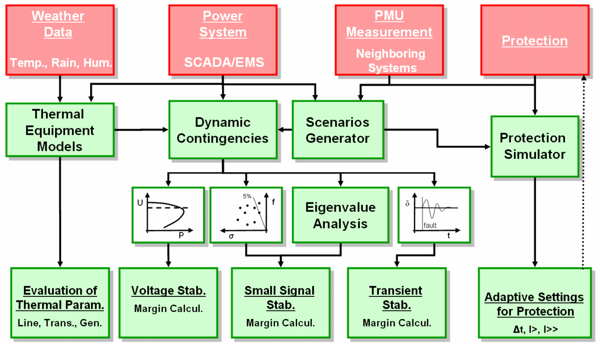

Figure 9: General structure of a DSA system.

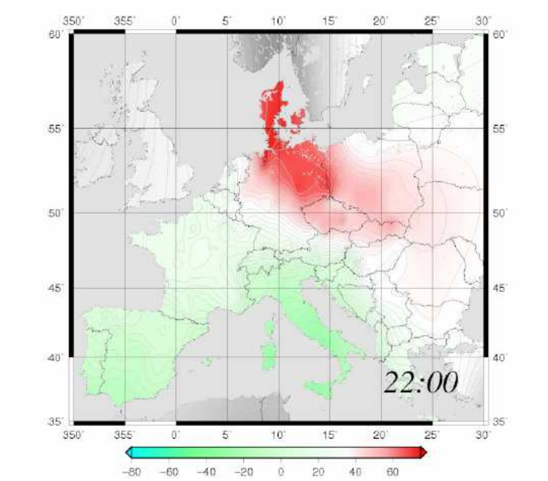

Figure 10: Possible visualisation of system condition with synchronous measuring. Here, only post mortem analyses of November 4, shown in Figure 6 [UCTE Report].

5 SUMMARY AND FURTHER RESEARCH

The complexity of the power system is very high. The added high penetration of stochastic generation from renewable sources like wind energy or PV, which cannot be precisely predicted, makes control and operation of the power system more complicated than before. The additional, not controllable changes in generation increase the number of errors in the controlled signals (e.g. voltage or frequency), thus the system stability margin becomes smaller, and the dynamics of the control systems and controlled object might not be enough to dampen the resulting oscillations which can lead to unstable operation (e.g. Europe on 4 November, 2006). More blackouts are also the result of this new situation.

Some of these disturbances come from the distribution system and can be dampened locally by different measures, such as better balancing of local load-generation schedules, or local voltage control if necessary, which is also done by NSM systems. The aggregated disturbances at the TSO level should be more predictable with the introduction of global system observability. This is possible using synchronous measurements. The necessary interpretation of the result of these measurements and the implementation of the resulting signals in the predictive control systems could help to operate and control the future power system. A more level based operation plan is necessary to ensure safe and reliable power system operation.

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