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## **Review of grid control in interconnected systems**

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**Abstract:** The control of power networks with very high penetration of renewable energy sources is difficult. This is due to the very large number generators with stochastic inputs and the limited commercial interest that generators have in the operation of the network within a de-regulated environment. However, there are many useful parallels with large de-regulated transmission networks (although at a different scale) and small autonomous power systems (e.g. on oilrigs and ships). By this, the main objective of task 1.1 is to investigate on the one hand the available and primarily used techniques for controlling interconnected power systems (e.g. UCTE-system) and on the other hand for controlling small autonomous power systems.

In this report Uni Kassel introduced the basics and the structure of the european interconnected systems as well as the control measures (primary -, secondary - regulation) for frequency and voltage in the european interconnected systems (GB, NORDEL, UCTE).

U N I K A S S E L  
V E R S I T Ä T



# ***DISPOWER***

*Distributed Generation with high penetration of renewable energy sources*

Contract ENK5-CT2001-00522

## ***Report on Grid Control in interconnected systems***

Contribution to Deliverable / Task Report 1.1

*Review of Available Techniques for Controlling Grids*

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## 1. Introduction and physical coherences

In this report, the state of the art in the field of management and control of conventional electric power supply systems will be described. The main focus of the report will be on the public electricity supply, i.e. the structure, the operation and the characteristics of electrical power supply networks.

Due to the important technical-economical advantages, the three-phase alternating current technology became generally accepted and a world-wide standard for the electrical power supply in the course of the last 100 years.

Nowadays, direct current systems are used only in special cases, e.g. at the high voltage direct current transmission (HVDC), into tramways and railways, in motor vehicles as well as into electrical system of small expansion in the power range up to 1 kW. Therefore, direct current systems of any type are not regarded in this report.

In the following section the substantial characteristics and physical background of the three-phase alternating current technology should be represented briefly.

The three-phase alternating current systems can be generated e.g. by three-phase induction machines (synchronous or induction generators) or 3-phase power electronic inverters. In the ideal case, such a three-phase system consists of three sinusoidal alternating voltages, respectively shifted temporally by  $2\pi/3$ , (and if necessary currents) of uniform frequency and same amplitude. Thus, the phasors of the three concatenated alternating voltages between the three conductors L1, L2 and L3 form in the ideal case of symmetrical generation an equilateral triangle with e.g. 400 V rms, the three voltages between the conductors and the neutral conductor N are smaller around the factor  $\sqrt{3}$  ( $400 \text{ V}/\sqrt{3} = 230 \text{ V}$ ) in each case.

The following two characteristics (values) are essentially used for the identification of three-phase systems:

- \* frequency and
- \* rms-value of the grid voltage

### 1.1 Frequency regulation

The starting point for the following views for frequency regulation in an electrical power supply system in the island or interconnected operation is the mechanical motion equation of an individual rotating system. There the following relation applies:

$$M_B = M_A - M_L = \theta \frac{d\omega}{dt} = 2\pi\theta \frac{dn}{dt} \quad (2.1)$$

with the factors

$M_B$  = acceleration torque,

$M_A$  = driving torque

$M_L$  = load torque

$\theta$  = mass moment of inertia

$\omega$  = mech. angular frequency

$n$  = mech. rotation speed

According to equation (2.1), a rotating system has a constant speed in case of a balanced condition when the balance between driving and load torque is equated ( $M_B = 0$ ). If the driving moment  $M_A$  is larger than the load moment  $M_L$ , i.e.. the acceleration moment  $M_B$  is positive, then the system will be accelerated. Thereby, its speed will rise until the balance of the moment is re-established. However, if the load moment  $M_L$  is larger than the driving moment  $M_A$ , the system is slowed down whereby its speed is reduced.

These physical relationships apply to all rotating systems, independently of the type of the work- and load machine. With the employment of electrical machines as motors, the electrical moment of the electrical machines is used as the driving moment. Using electrical generators, the produced electrical moment represents the load moment. On the basis of an individual rotating system, equation (2.1) can be applied also to a three-phase alternating current supply system, which represents a very complex mechanical-electrical system.

In conventional three-phase alternating power supply systems, exclusively direct grid-coupled synchronous machines are used for electricity generation as well as for grid formation.

Due to their type of construction, such synchronous machines show a rigid coupling between the mechanical speed  $n_s$  (synchronous speed), the electrical grid frequency  $f_{grid}$  and the number of pole pairs  $p'$ :

$$n_s = \frac{f_{Netz}}{p'} \quad (2.2)$$

However, by induction machines, a softer coupling results by the slip due to it's load dependency, according to equation (2.3):

$$n = n_s (1 - s) = \frac{f_{Netz}}{p'} (1 - s) \quad (2.3)$$

In steady state operation, every arbitrarily expanded three-phase alternating current supply system has the same frequency anywhere. Therefore, according to equation (2.2), all synchronous machines, which operate directly at this grid, in each case run with the synchronous speed  $n_s$ , due to the rigid coupling from mechanical speed and electrical frequency, unless they are operated within the natural stability limits (i.e. with a load angle  $< 90^\circ$ ). This synchronism is a basic characteristic of synchronous machines, which can be kept up also without regulation through the exchange of so-called synchronous moments in case of small disturbances. For this purpose, all synchronous machines must possess a positive synchronising torque  $M_s$  and satisfy the following condition:

$$M_s = \frac{\partial M_{El}}{\partial \vartheta} = \frac{\partial}{\partial \vartheta} \left( \frac{\sqrt{3}U_s U_p}{\omega X_D} \sin \vartheta_0 \right) = \frac{\sqrt{3}U_s U_p}{\omega X_D} \cos \vartheta_0 > 0 \quad (2.4)$$

For a safe and – beyond that – an economically optimised operation of an electrical power supply system and its power stations, it does not only make sense, even it is absolutely necessary to support the tendency of the synchronous machines to maintain the synchronism resp. the synchronous speed by the employment of a regulation.

Similar to the mechanical motion equation (2.1) a direct relationship between the frequency and the active power balance can be determined regarding to arbitrarily expanded three-phase current supply systems.

If the active power need of the consumers exceeds the active power momentarily generated in the power stations, the frequency in the entire power supply system falls and thus, the generator speed drops.

Regarding to the frequency regulation of the grid, it is necessary to adapt the active power generation in the power stations to the active power need of the consumers all the time. Due to the direct dependency between active power balance and frequency, it offers itself to use it as the controlled variable for the speed - active power regulation of the power stations. Due to the fact, that the frequency information is available everywhere in the grid, there is no need for an extremely complex and expensive communication and data transmission in order to co-ordinate measures for the frequency active power regulation.

Thereby, at first the active power deficit is referred from the rotation energy of all machines running at the grid.

Thus in a rotating power system it is not possible that the frequency changes abrupt due to the enormous total moment of inertia of the rotating machines also during a suddenly load step, but first it will drop, resp. rise evenly. However in electrical power supply systems, which are fed exclusively or predominantly by static supply units (systems with power-electronic converters) the frequency can be changed very fast, i.e. within the millisecond range in principle. This can lead to problems, because thereby frequency-sensitive consumers can be disturbed, damaged or destroyed. Due to their moments of inertia and the thereby stored rotation energy, rotating supply units and loads contribute to a brief frequency regulation.

## **1.2 Voltage regulation**

The supply voltage at any point of the grid depends above all on the reactive power balance, the grid structure, the capacity of the feed-in units, the load flow as well as the length and dimensioning of the cables. In order to ensure an acceptable voltage profile in the whole power supply system, it is advisable to compensate the reactive power need of the grid components and the consumers as near as possible by single compensation units or additionally through synchronous generators running in phase-shift-operation. In contrast to the central co-ordinated frequency-active power regulation the voltage regulation takes place decentralised.

Rotating supply units with electrically excited synchronous generators enables the supply of regulated reactive power. With these generators the reactive power (inductive or capacitive), necessary for the compensation, can be changed by the synchronous internal voltage and the excitation current. Also static supply units with self-commutated inverters offer such control possibilities. In contrast to it, conventional, directly grid-coupled induction machines or grid-commutated inverters need inductive reactive power from the grid. Their need of reactive power depends on the operating condition and can be changed only by additional devices (e.g. capacities). Therefore, the above-mentioned supply units with adjustable reactive power feed-in can be used very much better for voltage regulation than the latter.

## **2. Formation and structure of public electricity supply grids**

On the basis of a short outline of the historical development and fundamental considerations for the electricity generation, transmission and distribution, the main focus in this section deals with the structure and the current reached state of the art in the area of the public electricity supply.

### **2.1 Historical trend**

The beginnings of the public electricity supply hand back about 100 to 120 years. After in the 18. and in the first half of the 19. Century the crucial theoretical bases of electrical engineering (Faraday, Maxwell, Ohm, etc..) were educed, constructing to it groundbreaking electrical

developments were derived up to working maturity in the course of the next decades (dynamo of Siemens 1866, lamp of Edison 1878). Starting from the year 1880 the demand for electricity increased enormously in particular for lighting purposes, released by the successful spreading of the lamp, in Germany and also in the other industrial nations. Thereby, primarily in the cities, at first small regional direct current power supply systems with very low voltages and transmission rates within the kW range were established. Compared with our current standard of the electricity supply, the supply situation in these island grids, which can be marked by the following characteristics, was extremely unsatisfactory:

- \* poor voltage quality,
- \* low supply reliability,
- \* homogeneous consumption structure,
- \* high degree of simultaneity,
- \* slight number of utilisation hours and
- \* high costs.

The above-mentioned technical-economical deficiencies by the electricity supply, the far rising demand and the increased regional expansion of the island systems as well as the possibility to use energy sources which are bounded to a location (water power, brown coal sources etc.) for the electricity generation or to build-up power stations outside of the main load areas, almost inevitably resulted to an interconnection of the separate, local island grids to a larger regional and national system.

Thereby, a transition took place from the direct- to the alternating- and finally to the three-phase current technology. The world-wide break-through for the successful spreading of this type of current crucially affected by the large success of the world-wide first three-phase current distant transmission in the year 1891 at the international electrical exhibition in Frankfurt. Here, a three-phase AC-power of 100 kW with 15 kV was transferred over a distance of 175 km. The induction machine developed by Dolivo-Dobrowolsky in the year 1889, as well as the already longer admitted principle of the rotating field were important milestones for the fact that the three-phase AC-current technology became generally accepted as standard for the electricity supply.

## 2.2 Fundamental considerations for electricity supply

The outstanding technical-economical advantages of the three-phase alternating current technology in particular by a symmetrical structure and operation of the grid as well as its components, like

- \* Possibility of transforming (adjustment of the grid voltage at generator-, consumer devices and transmission rate),
- \* Galvanic separation of the different grid levels (disturbance delimitation),
- \* Temporally constant power flow,
- \* Loss of the neutral line (saving in material)
- \* Natural current zero crossovers (suitable points for switching) as well as
- \* Natural synchronous running of all synchronous generators (exchange of synchronous moments)

have advanced the interconnection of the island grids as well as the further rapid development of the public electricity supply.

Due to the particularly high importance of a safe and low-priced electricity supply for the economic development of a country as well as its technical characteristics like the storage

problem and the conduction-boundary, already in 1936 in Germany with the power industry law (EnWG) a legal basis for the public supply of electricity as well as the two other conduction-bound energies gas and long-distance heating was created, mainly unchanged up to a few years ago. The EnWG obligates all supply utilities to fulfil their legally prescribed order for supplying with consideration of the opposed targets

- \* safety,
- \* reliability of the supply as well as
- \* cost-efficiency of the electricity.

Besides this, nowadays the conscious, careful handling of environment and resources has also a high relevance. Up to the middle of the 70's the power consumption rose around 5 to 7 % per year on average, which corresponds to a duplication in 10 to 15 years. Due to strong efforts regarding the rational utilisation of energy, protection of primary energy resources and the change of the industrial structure, the current growth rate sank ever further and lies nowadays near 1 %/a. In the year 2000 the power consumption of the public utilities in Germany was about 523 TWh. The maximum load of the year 2000, which arose on 14 November, amounted to 76,800 MW; the installed maximum power of the public power stations rose to 106,200 MW up to the year 2000.

In order to be able to cover the enormous, continuously growing load demand it was technically and economically necessary to develop and use larger power station units. With those, besides the respectable improvements of efficiency, noticeable cost reductions could be achieved.

For the distant transmission of large power ratings over distances from a few kilometres to several hundred kilometres, by technical and economic reasons very high voltages are necessary.

The fundamental advantages of grid or interconnected operation are obviously already by combining two power stations of different types - in the ideal case one power station, whose power output is adjustable without a delay, as well as one second power station which can be started in a few minutes (e.g. a storage power station) - and several consumers, whose power consumption differs temporally. Thereby, the following positive interconnection effects are a result:

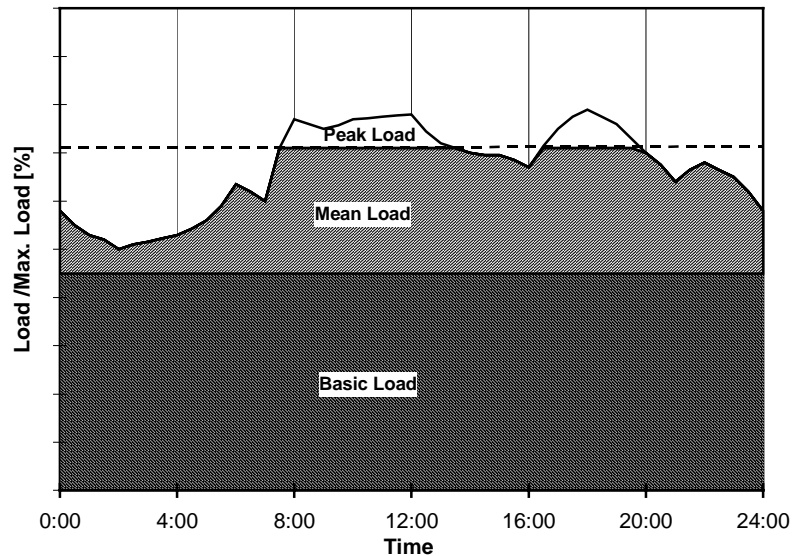
***Equalisation of Power Generation.*** Due to the fact, that electricity is not storable in an industrial scale, it must be produced for the moment it is needed. By the interconnection operation of the power stations it is possible to use in each case the power stations for power generation which are able to provide the daily and seasonally varying electrical power demand according to figure 2.1 with the lowest costs.

Doing so, primarily power stations with very low operating costs come to application to cover the over the whole day almost independent base load. Usually these base-load power stations are operated almost continuously with full load and so they reach 6000 to 7000 full load hours per year. Above all, run river-, brown coal- and nuclear power stations are used as base-load power stations in Germany. The power demand, which changes only insignificant during one period of one day up to several months, is called mean load. This power demand is covered by mean-load power stations. They possess higher generation costs than the base-load power stations and reach annually 3000 to 5000 full load hours.

Compared with the base-load power stations the mean-load power stations must cope a frequent load change, e.g. with daily turn-on and driving-off procedures, without any problems. In Germany, preferably hard coal power stations took over this mean-load range. Those, beyond that, daily only during short time intervals up to several hours needed maximum electrical

power is generated by peak-load power stations. Due to the constantly changing *peak load*, they must possess high power gradients as well as short start-up times. The power stations used in this range exhibit the comparatively highest operating cost. Their full load hour number usually remains under 1000 h/a. Covering the peak-load, mainly gas turbines-, storage- and pumped-storage power stations are used in Germany.

**Equalisation of Load.** It occurs only very rarely that the majority of the consumers refer their maximum power from the grid at the same time. Rather it comes to an equalisation of load, locally by different consumer structures and -habits (industry and/or household customers) as well as regional differences in settling (densely populated areas, rural regions).



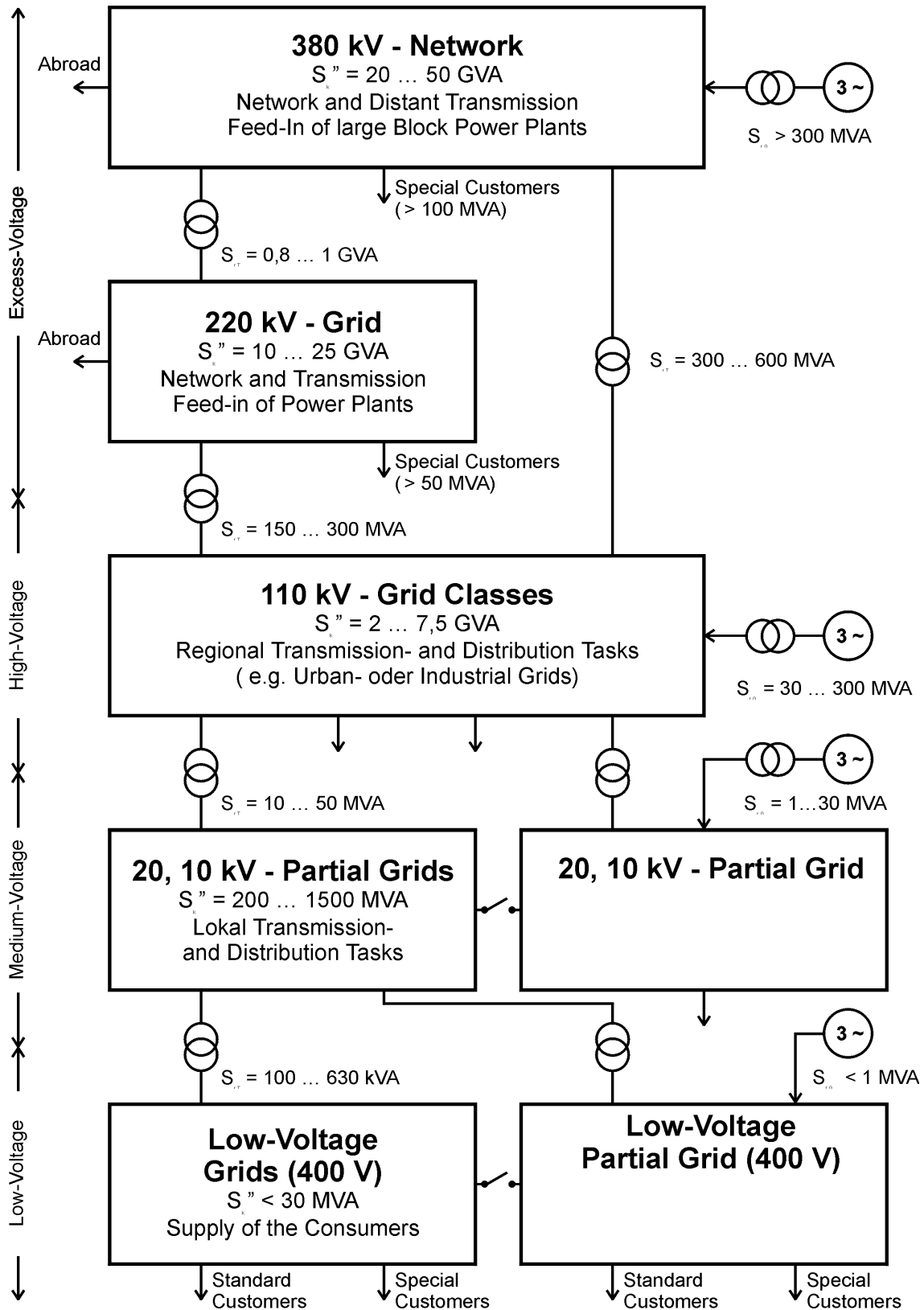
**Figure 2.1** Typical trend of the grid load over one day

**Equalisation of Disturbances.** All operative system components of the electricity supply grid (power stations, lines, switchgears, transformers, etc.) are available in extreme situations i.e. in case of disturbance or loss of individual operating resources as reserve. By the common reserve position and thus mutual assistant possibility, the redundancy in large interconnected systems can be kept substantially lower than in island systems. Thereby, the efficiency of the power supply is substantially improved.

### 2.3 Structure of the public energy supply

Lines, switchgears and transformers are the substantial components of electrical power supply grids. They connect the power stations resp. the feed-in systems with the consumer devices and form the system of the public electricity supply together with the grids. Thereby, the transfer of energy from the power station to the consumer performs over several transforming coupled grids of different voltage levels, depending upon the transmission distance, power station achievement and reference power consumption of the consumers.

Figure 2.2 gives an overview of the technical structure of the public electricity supply in Germany, the main functions of the individual voltage levels as well as typical power data of the grids, feed-in systems and substantial components.



**Figure 2.2** Technical structure of the public energy supply in Germany [1]

Just like in Germany, in the range of the public electricity supply a structure with 4 voltage levels was formed in all industrialised countries.

**Extra-High-voltage level.** Together with their predecessor 220 kV, the 380 kV voltage level possesses a central role for the interconnection of the electricity supply grids within international and national range as well as for the distant transmission of large power rates. Further, usually large power stations are attached, with a rated power approximately starting from 300 MVA, to the two extra-high voltage levels specified above. In very rare cases customers are supplied directly from the extra-high voltage levels. This is economically and technically reasonable only for special industrial customer with a power demand starting from 100 MVA.

**High-voltage level.** Above all, the 110 kV high-voltage level is used for regional transmission- and distribution functions in interconnected operation. Thereby, the transmission distances reach from 10 to 50 km. However, particularly in large cities or congested urban areas this grid level takes over predominantly the primary distribution, i.e. large industrial companies (with 10 to 50 MVA load) or transformer stations to the medium-voltage level are supplied directly from this grid level via short distances (up to several kilometres). In addition smaller power stations with power rates up to 200 MVA feed into this voltage level. In order to limit the short-circuit power, the 110 kV high-voltage level is divided into galvanic isolated grid areas, which differ in its structure and expansion very strongly, depending on the individual supply tasks and areas.

**Medium-voltage level.** Primarily, the medium-voltage levels with 10 kV, 20 kV and 30 kV are responsible for the local transmission and secondary distribution, i.e. the supply of the low-voltage grid stations and the supply of medium-voltage consumers. Thereby, in sparsely populated areas the preferably used rated voltage is 20 kV. However, in urban regions with high load density and normally smaller station distances, the rated voltage 10 kV is used. Due to the technically necessary limitation of the short-circuit current, the medium-voltage grid segments are supplied usually only by one transformer (10 – 63 MVA) from the superior grid and thus they are operating galvanic isolated from each other. Additionally, the predominant majority of the decentralised power stations, e.g. small hydroelectric power plants, combined heat and power units, wind energy plants or even whole wind parks, with output powers of 1 MVA up to 30 MVA, feed into the medium-voltage grids.

**Low-voltage level.** Nearly without exception, the public low-voltage systems in Germany are operating with 400 V. They are the lowest link in the chain of the generation, transmission and distribution of electricity and thereby, they take over the supply of the numerically largest consumer group of the tariff-consumers and special tariff-customers. Low-voltage systems are usually implemented as four-wire grids (L1, L2, L3, PEN).

### **3. Interconnected Systems**

#### **3.1 Active Power Balance and Grid Frequency**

Up to now, economically it does not make sense to store electricity, e.g. in batteries or capacitors, within an industrial scale. Thus, in electrical power supply systems, the active and reactive power used by the consumers have to be provided by the power plants of the grid at any time.

As described already before, an imbalance between generation and consumption of active power will lead to a dropping or rising of grid frequency, possibly into inadmissible ranges.

In order to be able to compensate significant power deficits, which result e.g. from an load increase, the breakdown of small generation units or large power stations as well as from the loss of power imports, within an appropriate period, the utilities are obligated to have sufficiently power reserves in store.

Many, in particular electronic consumer devices have very high requirements to the constancy of the frequency. For this reason generally the tolerance range of the grid frequency is held very small. According to DIN EN 50160 [6], the 10 s mean value of the frequency does not exceed or under-run the nominal value of 50 Hz about 1% with a probability per year of 99% in the interconnected power system. According to the UCTE the deviation between the synchronous time  $t_s$  and the astronomical time additionally must remain smaller than 30 seconds. This is described by the following equation:

$$\Delta t = t - t_s = t - \frac{1}{f_n} \int f(t) dt \leq \pm 30s \quad (2.6)$$

In order to keep this condition, a equalisation of the synchronous time is made within the UCTE power system by variation of the frequency setpoint value in the tolerance range from 49.99 to 50.01 Hz. This frequency value is given central for the entire UCTE power system area by the dispatcher in Laufenburg/Switzerland. Table 3.1 gives an overview of the UCTE definition of the grid operation condition in dependence of the frequency deviation as well as their impact on grid operation.

$ \Delta f_{\text{Grid}} $	Grid operation condition	Impact on grid
$\leq 50$ mHz	Normal	No
$> 50$ mHz and $\leq 150$ mHz	Impaired	No major risks
$> 150$ mHz	Severely impaired	Significant risk of malfunctions

**Table 3.1** Grid operation condition in dependence of the frequency deviation

In order to operate against a propagation of a disturbance in the UCTE power system, caused by significant frequency decreases which cannot be intercepted by the grid control and in order to prevent the danger of a complete breakdown of the entire interconnected power system, the UCTE recommends the following five-step plan to its members for a frequency-dependent load shedding:

$f_{\text{Grid}}$	Measure
$< 49,8$ Hz	Alerting of personnel, Activating of all power station reserves not mobilised yet
$< 49,0$ Hz	Instantaneous load shedding of 10% - 15% of the grid load
$< 48,7$ Hz	Instantaneous load shedding of additional 10% - 15% of the grid load
$< 48,4$ Hz	Instantaneous load shedding of additional 15% - 20% of the grid load
$< 47,5$ Hz	Separation of the power stations from the grid

**Table 3.2** Five-step plan of the UCTE for load shedding

Regarding the power assurance, 3 time intervals are differentiated:

Time interval 1 begins at the point of time of the load step and persists only a few seconds (3 - 4 s). As already described in section 1, due to the load increase, at first the frequency will decrease and the mech. speed of all generators and other rotating systems running at the grid will be reduced. Since in this time interval the power stations cannot contribute to the compensation of the power deficiency, due to the time constants of the turbine regulations, a part of the missing active power is compensated by the released rotation-energy of the decelerated generators and the rotating loads as well as by the frequency dependency of the loads (self regulating effect).

Time interval 2 (primary regulation) starts after a few seconds, when in the primary regulating power stations due to the regulation of the turbine governors the driving power of the generators has been increased and thus the power balance has been equalised until the frequency decrease is stopped. For such a kind of regulation proportional controllers are used in island grids for frequency regulation. The primary regulation in interconnected power systems is based on the frequency-active power regulation. Due to the proportional behaviour of the governors, a permanent offset is remaining, i.e. the frequency will be stabilised to a value unequally the setpoint value. In interconnected power system, all partners must take part according to their production rate  $C_i$  solidly for the primary regulation.

Time interval 3 (secondary regulation), which can last up to 15 minutes, follows approx. 20 to 30 s after the occurrence of the disturbance subsequent to the primary regulation. With the secondary regulation the remaining offset of the primary regulation is eliminated and the frequency is raised to their setpoint value. Thus, the secondary regulation must possess an integral behaviour. According to the costs-by-cause principle, in the context of the secondary regulation, the active power deficit should equalised exclusively by the disturbed regulation area (e.g. a supply area), so that, concerning the interconnected operation, the power transfer with the network partners will be lead back to its original values by nominal frequency.

Rotating and static supply units, with which power output can be adapted in few seconds according to the active power need, can participate in the primary and secondary regulation and thus they contribute to the power assurance. Since renewable power units (WEA, PV) are subjected to the stochastic fluctuations of the natural power supply in their power output behaviour, they are only conditionally suitable for power assurance, contrary to fossil-fuelled generation plants or storage power stations.

### 3.1.1 Primary Control and Frequency Value of large conventional power plants

In order to achieve a defined power output of the power stations, which take part at the primary regulation, the turbine power of these power stations and thus, the active power output of their generators are modified according to a frequency-dependent static characteristic. As described already before, since a remaining offset is tolerated by the primary regulation, so-called proportional(P)-controllers are deployed in these generating plants. The following equation describes these controller behaviour:

$$\Delta P_{Prim} = P(f_{Grid}) - P_{50} = \lambda_T (f_{Grid} - f_n) = \lambda_T \Delta f_{Grid} \quad (2.7)$$

with

$f_n$ [Hz]	nominal value of the frequency = 50 Hz,
$P_{50}$ [MW]	power at 50 Hz grid frequency,
$\Delta P_{Prim}$ [MW]	power difference,
$\Delta f_{Grid}$ [Hz]	frequency deviation and
$\lambda_T$ [MW/Hz]	power frequency characteristic of the turbine

The static-factor  $\beta$ , a dimensionless characteristic value for the quotient from frequency deviation  $\Delta f_{Grid}$  and power difference  $\Delta P_{Prim}$  is build with the standardisation of the frequency deviation on its nominal value and the power difference on the power value  $P_{50}$  by this frequency. According to this, the following equation can be defined for  $\beta$ :

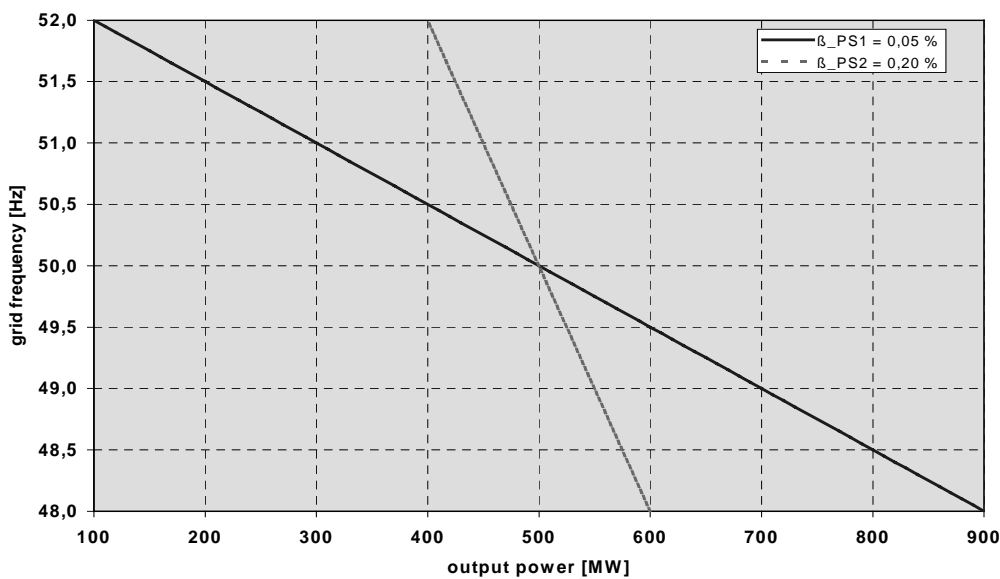
$$\beta = \frac{\Delta f_{Grid}}{f_n} \Bigg/ \frac{\Delta P_{Prim}}{P_{50}} = \frac{\Delta f_{Grid}}{f_n} \cdot \frac{P_{50}}{\Delta P_{Prim}} \quad (2.8)$$

From the equations (2.7) and (2.8) one can get the relationship between the power frequency characteristic and the static-factor  $\beta$ :

$$\beta = \frac{1}{\lambda} \frac{P_{50}}{f_n} \quad (2.9)$$

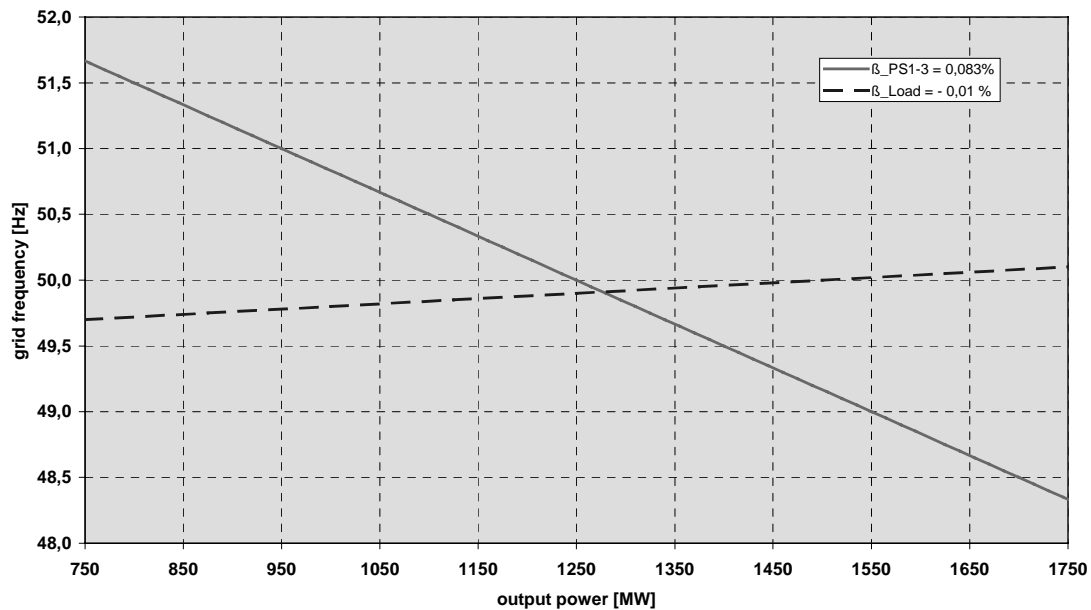
Thus the static-characteristic of a power station or a grid can be described with the following equation:

$$P(f_{Grid}) = P_{50} - \Delta P_{Prim} = P_{50} - \lambda \cdot \frac{\Delta f_{Grid}}{f_n} \cdot P_{50} = P_{50} - \frac{1}{\beta} \cdot \frac{\Delta f_{Grid}}{f_n} \cdot P_{50} \quad (2.10)$$



**Figure 2.3** Exemplary static-characteristics of two power stations each with 500 MW output power at 50 Hz

Figure 2.3 shows exemplary the static-characteristics of two power stations each with 500 MW output power at 50 Hz grid frequency. Power station 1 (PS1) possesses a static-factor of 0,05%, the power station 2 (PS2) however has a static of 0,2%. Both characteristics have a negative gradient, i.e. with decreasing grid frequency the power outputs of the two power stations must increase and with raising frequency they can be throttled again. Beyond that, it becomes clear that the power gradient becomes smaller with an increasing static-factor.



**Figure 2.4** Grid-static and load characteristic of a supply system

The generation characteristic of the whole grid (so-called grid static) results by the superposition of the static characteristics of all power stations of the supply system. This grid static runs much flatter than the static's of each individual power station due to the power contributions of many power stations. The flatter the static's characteristic of a power station is, the more deeply this system is involved in the primary regulation.

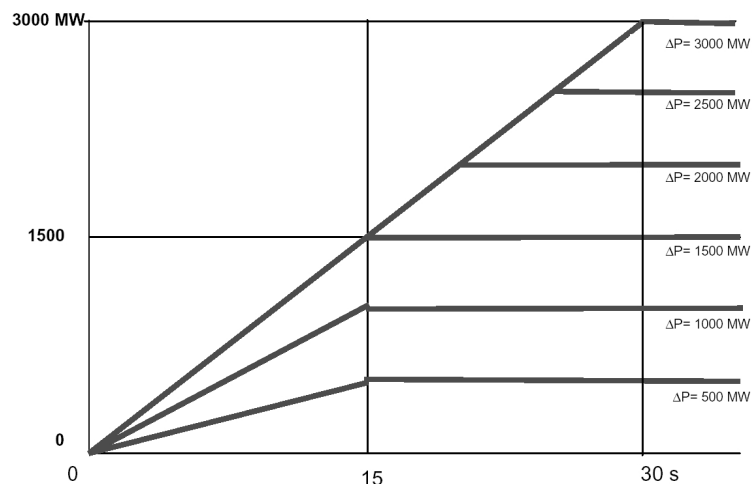
The power demand of all loads in the system in dependence of the frequency leads to the so-called load characteristic. The intercept point of the grid-static with the load characteristic leads to a possible steady state operating condition of the supply system.

The UCTE has made the following presumptions regarding the primary regulation in the Central European interconnected power system and constructing on it the minimum requirements for the participating utilities are specified:

The whole system of the UCTE system possesses a peak load of 300 GW and an low-load of 150 GW. An instantaneous deviation of 1% of the maximum load (=3000 MW) is assumed as a reference incident.

In case of an power deficit in the amount of the reference incident, the frequency must not fall below an instantaneous value of 49.2 Hz, the quasi-stable frequency deviation must be less than 180 mHz. The turbine speed governors must possess a measuring sensitivity lower than 10 mHz. The overall grid frequency characteristic  $\lambda_{00}$  for the system is set at 18000 MW/Hz.

The primary control reserve for each area of the UCTE system, calculated in proportion to the contribution coefficient  $C_i$  for that area (generation of the area / total generation), must therefore be capable of full deployment in response to a disturbance of less than 1500 MW and within a time period of 15 s complete and for disturbances ranging from 1500 MW to 3000 MW within additional 15 s in a linear way.

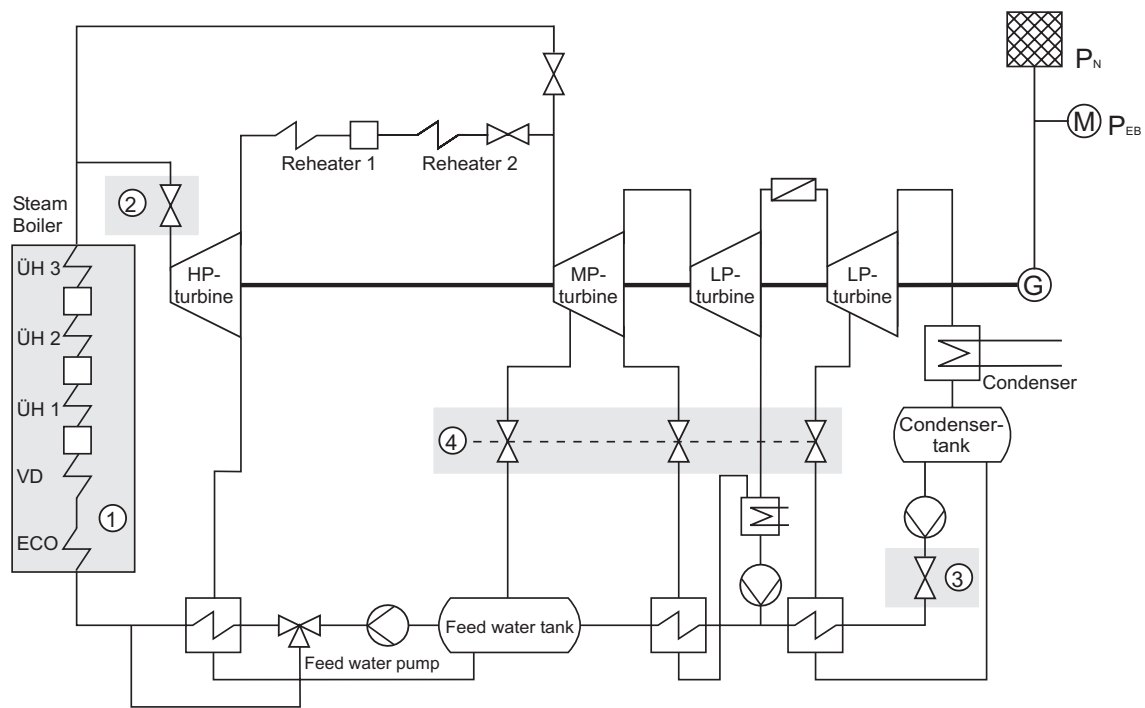


**Figure 2.5** UCTE-demands for the temporal activating of the primary control reserve [7 and 8]

### 3.1.2 Measures for the Primary Control by the Power Stations

Essentially three operation modes are used for the power adjustment of steam power plants in (part load-) operation:

- \* Sliding-pressure operation
- \* Fixed-pressure operation
- \* modified sliding-pressure operation



**Figure 2.6** Block diagram of a thermal power station (Source: M. Rothert)

In the **pure sliding-pressure** operation the demanded power is controlled exclusively via the firing power of the steam boiler (1). Here, the steam pressure in the boilers, the live steam pipeline and the steam turbine is always adjusted according to the physical relationships. The turbine inlet valve remains permanently opened.

However, in the **fixed-pressure operation** the power of the steam turbine is adjusted by change of the turbine inlet valves (2), so-called throttling. Thus, the steam mass flow through the turbine is changed, however, the steam pressure before the turbine is kept constant on its nominal value.

The combination of the two operation modes described before is called **modified sliding-pressure operation**. The turbine output is regulated within the range of the rated output as well as in the lower partial load range ( $< 0,40 P_n$ , dependent on the minimum pressure of the turbine) by throttling of the turbine inlet valves (fixed-pressure operation). However, in the upper partial load range, e.g. between 95% and 40% of the rated output, the operation mode changed to sliding pressure operation. [12]

The operation modes of the steam turbines, described before, differ substantially according to their response time to load changes and regarding the attainable load gradients. Due to the thermal inertia of the steam boiler and the associated large response time, the pure sliding pressure operation is hardly used in practice. However, the advantage of the sliding pressure operation is the possibility to provide increasing power over a longer period. Nevertheless, in the fixed pressure operation the live steam, lining up in the steam cycle, can, opening of the throttled turbine inlet valve immediately, directly flow into the turbine and leads to a very fast power increase in the HP-part. The dynamic of this procedure essentially depends on the manipulating time of the turbine inlet valve as well as the time constants of the HP-turbine. Power enhancements of e.g. 5% within a few seconds can be obtain with this operation mode, above all limited by material stress in the HP-part [13].

In order to be able to perpetuate the desired output power increase during a period from several minutes, due to the limited storage capability of the steam cycle, it is additionally necessary to increase also the firing power (combined sliding-pressure operation). Further, it must be noted that the throttling leads to higher losses and thus to an increased fuel requirement due to the smaller efficiency in partial load operation [13].

Power stations with gas turbines as well as combined gas and steam turbines(GUD)-plants can provide substantial power reserves within seconds and also for arbitrarily long periods.

With these plants even the world-wide highest requirements for frequency stabilisation can be fulfilled, such plants are very well qualified for active power frequency regulation (primary-, secondary regulation) in interconnected systems and particularly in island grids. According to [13], gas turbines should be driven in a large working area with constant exhaust gas temperature, whereby an optimised burn process with minimised stress of the equipment components (gas turbine, steam turbine, waste heat boiler) is reached. Thus, in practice the load change gradient of the gas turbine is limited primarily by the dynamics of the exhaust gas temperature regulation.

The load change capability of GUD-power stations is determined particularly by the gas turbine within the first minute. According to [14], a power enhancement up to 10% within 10 s can be reached with gas turbines or GUD-power stations in the standard version. Plants with high-speed guide vane pitch adjustment devices or by active inclusion of the steam turbine (combined sliding-pressure operation) exhibit still higher load alteration rates, for example a GUD plant in England obtain a power enhancement of 20% within 10 s [14].

### 3.1.3 Secondary Control of Frequency and Power Exchanges

As already presented in section 3.2, in the framework of the so-called secondary regulation the deviation between actual frequency and its setpoint value become balanced. The secondary regulation should start after 30 s and must be terminated at the latest 15 min after the load step. The secondary regulation may become active temporally only after the primary regulation in order to prevent the danger from automatic control loop oscillations, which otherwise insists with the simultaneous interference of several automatic controllers on a common controlled system.

Due to the short start-up times and high power gradients for the secondary regulation, above all gas turbine and GUD-plants as well as hydro-electric power plants (build as storage or pumped-storage power station) are used.

According to the costs-by-cause principle, in the context of the secondary regulation, only the power stations of the regulation zone are used, in which the failure respectively the load step arose. Thus, it is to be achieved that the delivered power rates with the neighbouring regulation zones as well as the power output of all power stations, which took part at the primary regulation, go back to the original value again (contractually specified or according to the operational planning scheduled).

In order to recognise in which regulation zone the failure resp. the load step arose, the mixed signal  $\Delta f \cdot \Delta P_{\bar{U}}$  is used, thereby it also serves as a criterion for the participation of a regulation zone at the secondary regulation. This signal is formed from the product of frequency deviation  $\Delta f$  and the difference of power exchange  $\Delta P_{\bar{U}}$ . For example if the grid frequency of a regulation zone decreases due to a load increase ( $\Delta f < 0$ ), then the missing power is supplied from the other regulation zones, i.e. the difference of power export from the connected regulation zone  $\Delta P_{\bar{U}}$  is negative, for all other regulation zones  $\Delta P_{\bar{U}}$  is positive, since there the power export increases there accordingly. From this follows, that those power stations of the regulation zone must take part in the secondary regulation, with which the mixed signal  $\Delta f \cdot \Delta P_{\bar{U}}$  is positive.

In order to be able to compensate a lasting offset, the secondary regulation must show an integral behaviour. According to [7 and 8] the following formula applies to the secondary or power regulator of the regulation zone i:

$$\Delta P_{di} = -\beta_i \cdot G_i - \frac{1}{T_{ri}} \int G_i dt \quad (2.10)$$

with 
$$G_i = \Delta P_i + K_{ri} \cdot \Delta f \quad (2.11)$$

The used symbols have the following meaning:

$\Delta P_{di}$ [MW]	actuating signal of the grid regulator, which acts on the power stations in the regulation zone, which take part at the secondary regulation
$\beta_i$	proportional constant of the grid regulator of the regulation zone i,
$T_{ri}$ [s]	integration time constant of the grid regulator of the regulation zone i,
$G_i$ [MW]	total offset of the regulation zone i,
$\Delta P_i$ [MW]	tolerance between the power exchange of the regulation zone i and the assessed value,
$K_{ri}$ [MW/Hz]	constant adjustable to the grid regulator of the regulation zone i,
$\Delta f$ [Hz]	actual frequency tolerance from the setpoint value

Concerning to the UCTE-demands [7 and 8], the following values shall be assessed for the above mentioned regulation parameters:

- \* The power exchange rate is to be acquired with a measuring cycle from 0,1 to 2 s in the future. Thereby, the failure should not exceed a maximum value of 1,5%.
- \* The parameters of the power regulator  $i$  and  $T_{ri}$  are to be adjusted in such a way that the dynamic behaviour of the power regulator  $i$  agrees with the machines which take part at the secondary regulation. The value range for the gain  $\beta_i$  becomes generally between 0 and 0.5, the value range for the average time constant between 50 and 200 s.
- \* The regulator constant  $K_{ri}$  is to agree exactly with the power factor  $\lambda_i$  of the regulation zone  $i$  and therefore it has to be adjusted annually again, according to the production portion  $C_i$  as well as the power factor  $\lambda_{u0}$  of the overall system. Further the following condition is to apply:

$$K_{ru} = \sum_{i=1}^N K_{ri} = 1,1 \cdot \lambda_{u0} \quad (2.12)$$

### 3.2 Reactive Power Control and Voltage Stability

A condition for a stable and reliable electricity supply and thus for the faultless function of the components connected to a power supply system is that on the one hand the operating voltage and on the other hand the frequency changes only slightly, within fixed operation ranges. Therefore, the transmission system operator is responsible that the grid voltage at any node in its supply area does not exceed the limit values fixed in the standards [6].

According to DIN EN 50160:1999 [6] it is requested that in the medium- (1 kV to 35 kV) and low-voltage range (< 1 kV) 95% of the 10-min average values of the supply voltage for each week interval deviate maximally + 10% or - 10% from the rated voltage. Additionally, it is defined for the low-voltage level that all 10-min average values must lie within the tolerance range from 85% to 110% of the rated voltage.

As already described in section 1, the supply voltage at any node depends particularly on the supplying structure as well as the load flow and the reactive power balance.

In contrast to the central co-ordinated frequency-active power regulation the voltage regulation takes place decentralised. In order to ensure an acceptable voltage profile in the whole power supply system, it is necessary to compensate the reactive power need of the grid components and the consumers as near as possible to their origin. In practice, various concepts and devices are used for voltage stabilisation:

- \* Feed-in of reactive power into the high voltage level by large (hydro) power plants, in which their synchronous generators are running in phase-shift-operation.
- \* Transformers, which are used for the supply of MV-grid segments are often equipped with tap changers. With the tap changing control of such transformers, the grid voltage of the low-voltage terminal can be stabilised on a setpoint value.
- \* By small compensation units with capacitor banks, which are directly allocated to one single consumer device.
- \* Flexible AC Transmission Systems (FACTS) are innovative devices with power electronic conversion systems. They offer various possibilities to improve the performance of HV power transmission systems, like voltage stabilisation, improvement of power quality etc. [17]
- \* A so called Grid Control Unit (GCU), offers advantages for voltage stabilisation particularly in grid regions with large renewable power plants, like windfarms. The GCU adapts the operational behaviour of renewable and other small decentralised power systems to conventional power plants, by active modification of the reactive and partly active power feed in. [2]

Rotating supply units with electrically excited synchronous generators enables the supply of regulated reactive power. With these generators the reactive power (inductive or capacitive), necessary for the compensation, can be changed by the synchronous internal voltage and the excitation current. Also static supply units with self-commutated inverters offer such control possibilities. In contrast to it, conventional, directly grid-coupled induction machines or grid-commutated inverters need inductive reactive power from the grid. Their need of reactive power depends on the operating condition and can be changed only by additional devices (e.g. capacities). Therefore, the above-mentioned supply units with adjustable reactive power feed-in can be used very much better for voltage regulation than the latter.

## 4. Annexes

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## 4.2 Nomenclature

FACTS	Flexible Alternating Current Transmission System
GCU	Grid Control Unit
GUD	Gas- und Dampf- (Combined cycle gas and steam-)
HVDC	High Voltage Direct Current
HP	High Pressure
Hz	Unit for Frequency
kV	kiloVolt – Unit for Voltage
LP	Low Pressure
MP	Medium Pressure
MVA	MegaVoltAmpere – Unit for Apparent Power
MVA <sub>r</sub>	MegaVoltAmpere reactive – Unit for Reactive Power
MW	MegaWatt – Unit for Active Power
UCTE	Union for the Co-ordination of Transmission of Electricity