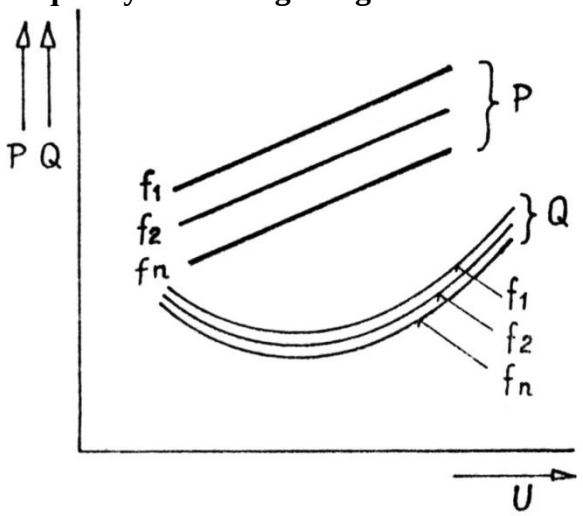
18. Electricity system control

The ES is the connection of parallel power plants, transmission and distribution networks with appliances. The operation is an optimally reliable cost-effective supply of quality electricity. The key parameters are frequency (global parameter) and voltage magnitude (local parameter). Other parameters are the higher harmonic content and any voltage asymmetry.

Frequency and voltage magnitude control



Control is associated with the supply and transmission of active and reactive power in the system.

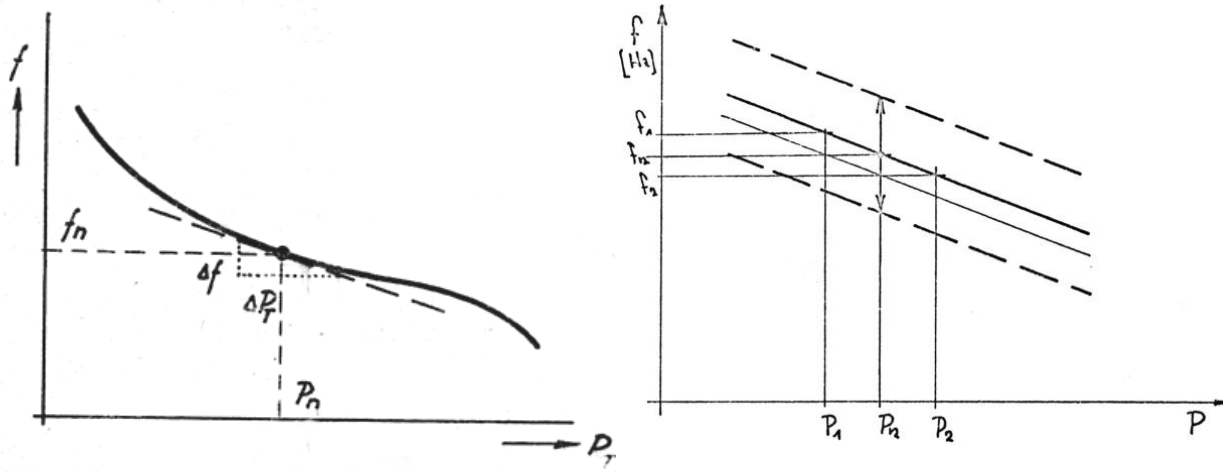
It is clear that the active power is significantly sensitive to changes in frequency and less sensitive to changes in voltage magnitude. For reactive power it is exactly the opposite.

Thus, the influence and linkage of $f \leftrightarrow P$ and $|U| \leftrightarrow Q$ can be analyzed separately.

Frequency and active power control

In an unregulated system, a change in load or source size is associated with a change in frequency according to the characteristics of the loads and sources.

The static characteristics of the sources are determined by the primary speed controllers of the turbines.



The characteristic of the system is then the "sum" of the individual generating units, whose waveform can only be obtained experimentally due to the different relative loads plus the insensitivity and non-linearity of the sub-controllers.
After linearization at the operating point, the power number of the sources can be defined:

$$K_A = -\frac{\Delta P_T}{\Delta f} \quad [MW/Hz]$$

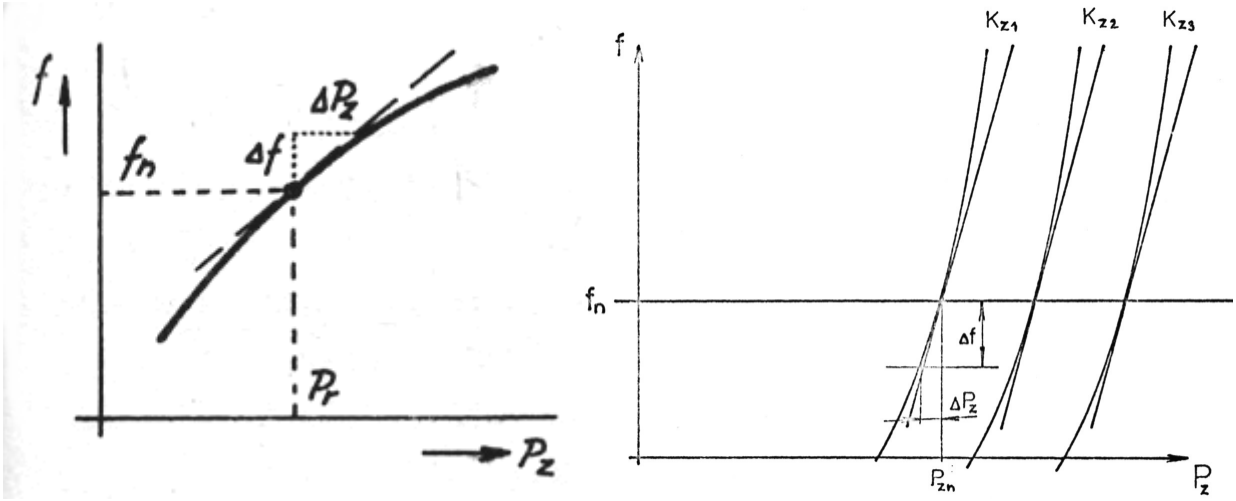
The static coefficient of the sources (static) is then:

$$s_T = \frac{\Delta f[p.j.]}{\Delta p_T[p.j.]} = \frac{\Delta f / f_N}{\Delta P_T / P_{TN}} = \frac{\Delta f}{\Delta P_T} \cdot \frac{P_{TN}}{f_N}$$

The power number in a ratio value:

$$k_A = -\frac{\Delta p_T[p.j.]}{\Delta f[p.j.]} = -\frac{1}{s_T} \qquad K_A = k_A \frac{P_{TN}}{f_N} = -\frac{P_{TN}}{f_N \cdot s_T}$$

Static load characteristics



Again, the resulting load characteristic of the electricity system can be obtained as the "sum" of the sub-characteristics of the individual appliances:

- 20 to 25% heating equipment, lighting - resistive load
- 50 to 70% drives - motor load
- 10 to 12 % - special loads and losses

Similarly to the sources, the power number of the load can be defined again after linearization at the operating point:

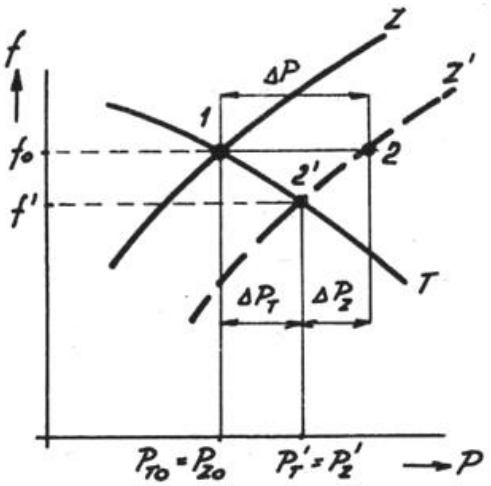
$$K_Z = +\frac{\Delta P_Z}{\Delta f} \quad [MW/Hz] \qquad s_Z = \frac{\Delta f[p.j.]}{\Delta p_Z[p.j.]} = \frac{\Delta f / f_N}{\Delta P_Z / P_{ZN}} = \frac{\Delta f}{\Delta P_Z} \cdot \frac{P_{ZN}}{f_N}$$

$$k_Z = +\frac{\Delta p_Z[p.j.]}{\Delta f[p.j.]} = \frac{1}{s_Z} \qquad K_Z = k_Z \frac{P_{ZN}}{f_N} = \frac{P_{ZN}}{f_N \cdot s_Z}$$

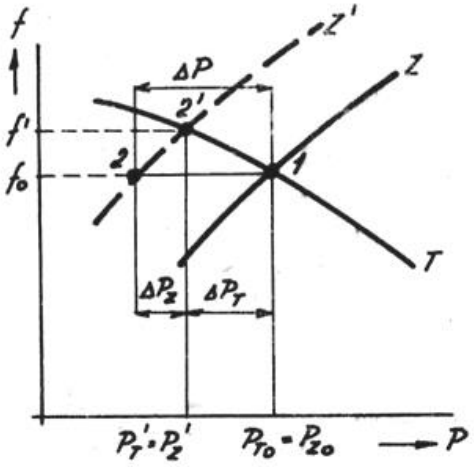
Static characteristics of the electricity system

The operating point is determined by the characteristics of the sources and load and shifts with frequency changes caused by changes in the size of sources and appliances:

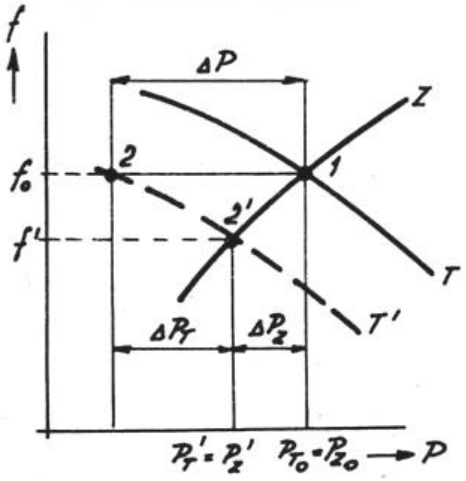
Load increase



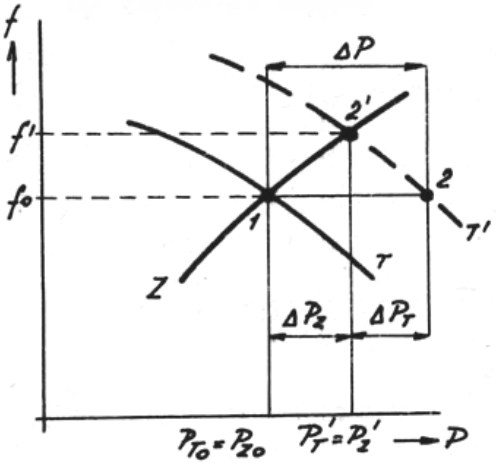
Load drop



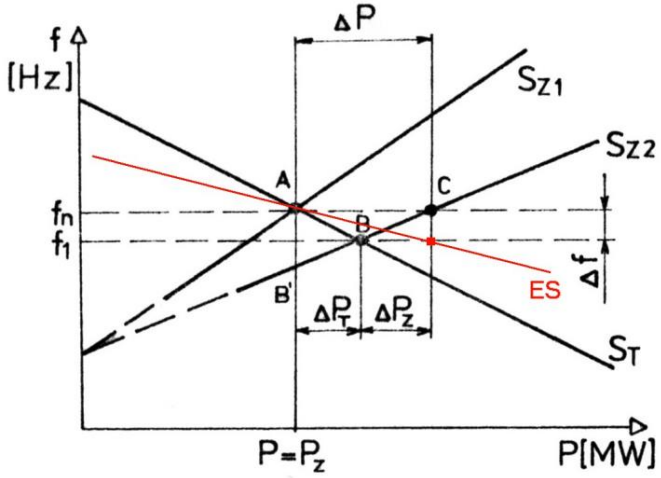
Power failure

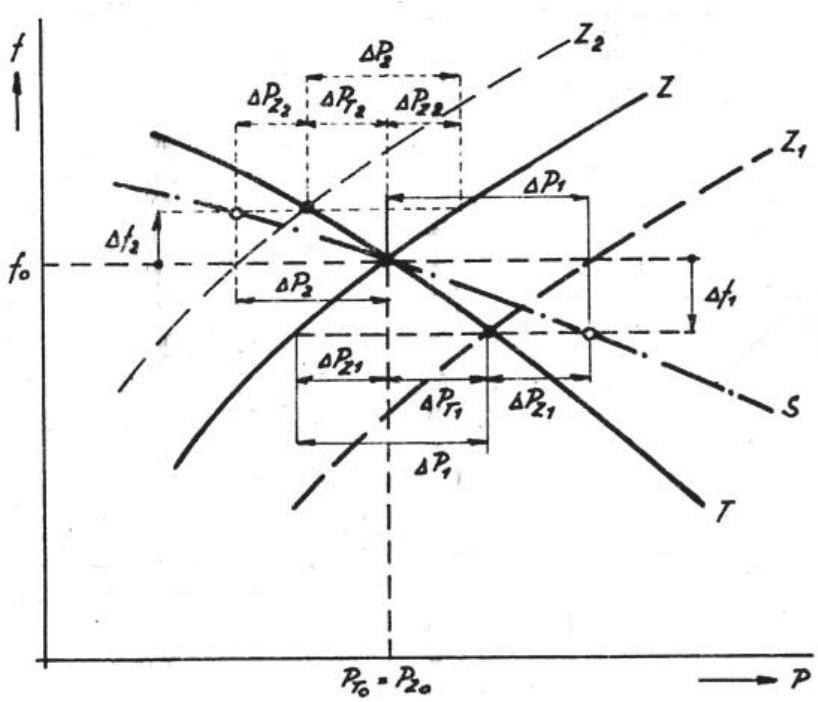


Resource increment



For example, a load increase of ΔP only increases the power of the sources by ΔP_T and the remaining shortfall is covered by reducing the load requirements by ΔP_Z at a reduced frequency. The process is called the self-regulating effect of the power system. The combined characteristic of the system is then:





$$K_{ES} = -\frac{\Delta P}{\Delta f}$$

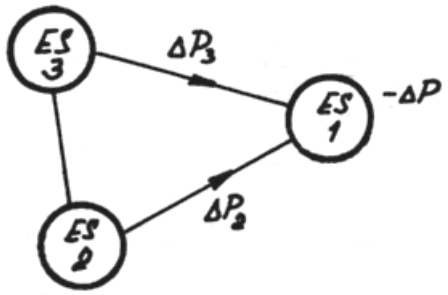
$$|\Delta P| = |\Delta P_T| + |\Delta P_Z| =$$
$$= |-K_T \cdot \Delta f| +$$
$$+ |K_Z \cdot \Delta f| =$$
$$= \Delta f \left(|K_T| + |K_Z| \right)$$

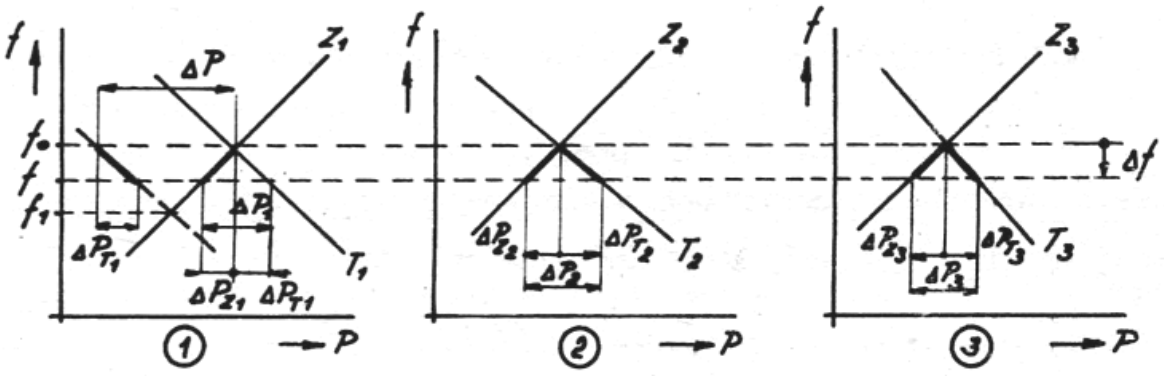
$$K_{ES} = K_T + K_Z$$

Thus, in an unregulated power system, the frequency changes with load: $\Delta f = \frac{\Delta P}{K_{ES}}$

In interconnected, unregulated electricity systems, all systems contribute to make up any power deficit according to their static characteristics. The situation for three interconnected systems, where the source in the first system has failed by ΔP :

$$\Delta P_1 + \Delta P_2 + \Delta P_3 = \Delta P$$



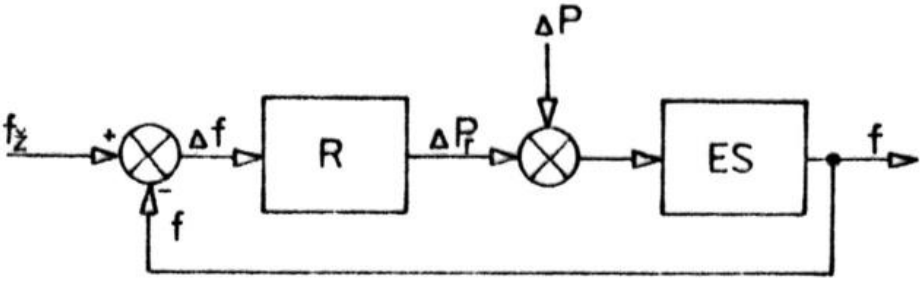


Redundant executions of $\Delta P_2 = \Delta P_{T2} + \Delta P_{Z2}$ and $\Delta P_3 = \Delta P_{T3} + \Delta P_{Z3}$ are passed to the system first. Then $-\left(K_{ES1} \cdot \Delta f + K_{ES2} \cdot \Delta f + K_{ES3} \cdot \Delta f\right) = \Delta P$

$$\Delta f = -\frac{\Delta P}{K_C} \qquad K_C = K_{ES1} + K_{ES2} + K_{ES3}$$

By interconnecting with other systems, the frequency drop in the event of a source failure is reduced.

In regulated power systems, the power shortage or surplus is compensated by the automatic so-called secondary regulation of selected regulating power plants and the system frequency is maintained just as the active power transferred to other systems (balance) by shifting the static characteristics of the primary regulator:



Regulation must distribute the load among resources while maintaining the balance and respecting the regulatory capacity of the resources. The algorithm is usually based on the proportional or integration principle.

The static characteristics method determines for each source: $\Delta P_{Ri} = -K_{Ri} \cdot \Delta f$, where

$$\Delta f = f_{\check{Z}} - f \qquad \text{a} \qquad \Delta P_{Ri} = P_{Ri} - P_{R\check{Z}i}$$

The controller will change the desired power value until: $\Delta f + \frac{1}{K_{Ri}} \Delta P_{Ri} = 0$ or

$\Delta f + S_{Ri} \cdot \Delta P_{Ri} = 0$. The power distribution is then in the ratio:

$$P_{R1} : P_{R2} : \ldots : P_{Rn} = \frac{1}{S_{R1}} : \frac{1}{S_{R2}} : \ldots : \frac{1}{S_{Rn}}$$

This means that the power distribution is fixed (determined by the static settings of the sources) and depends only on the frequency, which is favourably simple without the need for information links between the sources. The disadvantage is that the frequency variation is not completely removed and the possible economy of operation is not respected. The static coefficient is selected for power plants:

- Basic power plants - 4 to 6%
- Regulatory power plants - 0.5 to 1.5%

The method of apparently static characteristics introduces information about the deviation of the source from its share of the total output of the control sources:

$$\Delta f + S_{R1}\left(P_{R1} - \alpha_1 \sum_{k=1}^{n} P_{Rk} \right) = 0$$

…

$$\Delta f + S_{Ri}\left(P_{Ri} - \alpha_i \sum_{k=1}^{n} P_{Rk} \right) = 0$$

…

$$\Delta f + S_{Rn}\left(P_{Rn} - \alpha_n \sum_{k=1}^{n} P_{Rk} \right) = 0$$

The sum of the outputs of all regulatory sources:

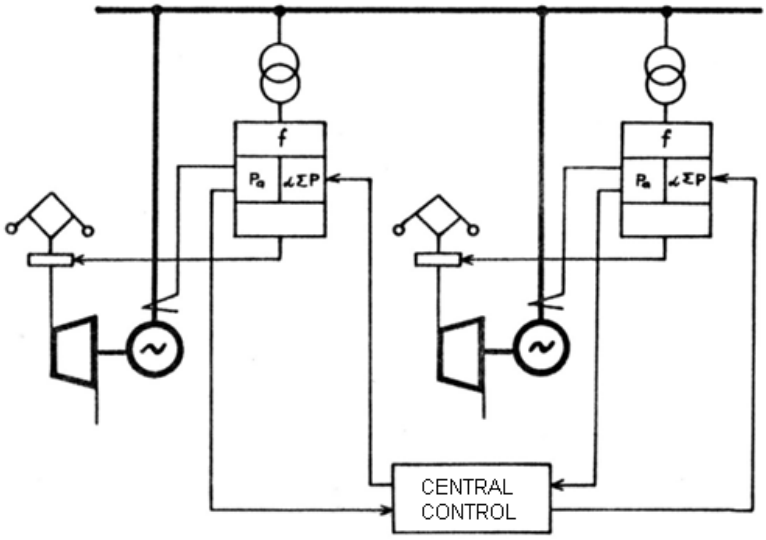
$$\sum_{k=1}^{n} P_{Rk}$$

They have to pay:

$$\sum_{i=1}^{n} \alpha_i = 1$$

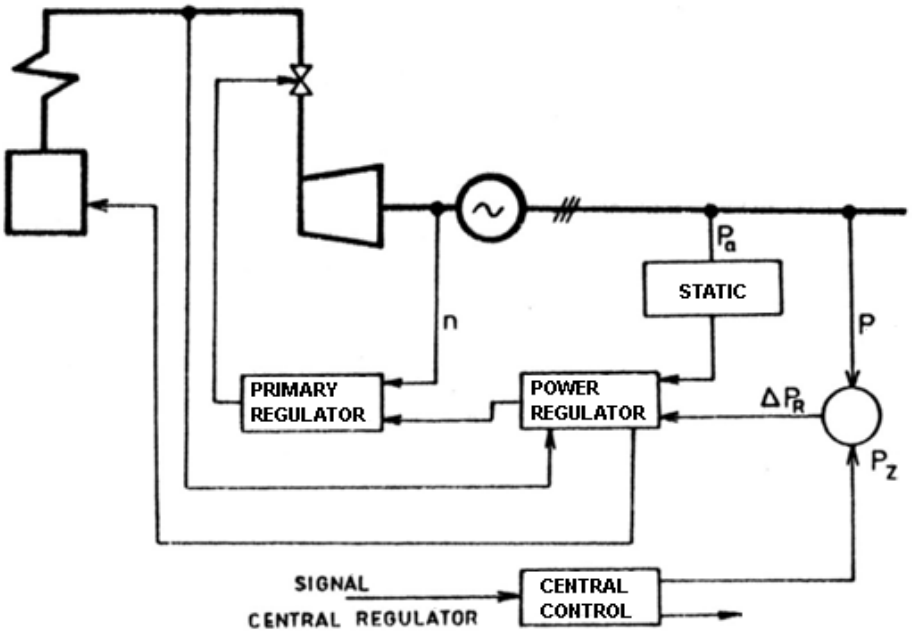
The method still allocates power in a fixed way, which is generally not cost-effective. In addition, when the output of a control source is limited, the share coefficients have to be rebuilt.

For two machines, the principle of coupling is:



When regulating the frequency and the corresponding transmitted powers in interconnected power systems, the reaction of all sources in all systems must be avoided and only the sources in the system that caused the frequency deviation (network characteristics method) react, otherwise changes in transmitted powers and possible instability of transmission paths would occur. The transmitted power is regulated according to contractual agreements for the balance or to optimise the economic efficiency of the interconnected systems as a whole.

Hydropower plants, where about 1% of P_N / sec can be changed, are more advantageous for control. Any further required power changes have to be provided by conventional thermal power plants, but these have limited speed and range of control. According to the deviation of the desired power, the control valves change the amount of steam to the turbine mediated through the primary speed controller. At the same time, the signal also goes to the boiler for faster and constant changes in the output of the turbomachinery:



Regulation of voltage magnitude and transmitted reactive power

Voltage regulation is determined by the balance between the supplied and consumed reactive power at individual points of the power system. Maintaining the voltage magnitude within the prescribed limits (normally ± 5%) is necessary to maintain the proper operation and life of appliances (not overloading asynchronous drives, not limiting the power of thermal appliances, life of lighting systems) and to maintain the stability of power transfer in the system. The reactive power spreads spontaneously from higher to lower voltage points, with the aim of limiting its redistribution as much as possible to avoid any increase in joule losses or overloading of lines. In an unregulated system, a change in reactive load or reactive source size is associated with a change in voltage magnitude according to the characteristics of the loads and sources.

Sources of reactive power in the power system are synchronous alternators, synchronous compensators and synchronous motors (in the overloaded state), unloaded HV lines and capacitor banks.

The dependence of their delivered reactive power on the magnitude of the grid voltage:

Synchronous machines:

$$Q_{AR} = \frac{U_S \cdot E_V}{X_d} \cos \vartheta - \frac{U_S{}^2}{X_d}$$

Batteries and wiring:

$$Q_{AS} = \omega \cdot C \cdot U_S{}^2$$

Disadvantageous in nature because the contribution decreases when the voltage is reduced.

Reactive power consumers in the power system are transformers (60 to 70%), induction drives (20%), compensating reactors and loaded lines.

The dependence of their reactive power consumption on the magnitude of the grid voltage:

Magnetization loss:

$$Q_M = \frac{U_S{}^2}{X_\mu}$$

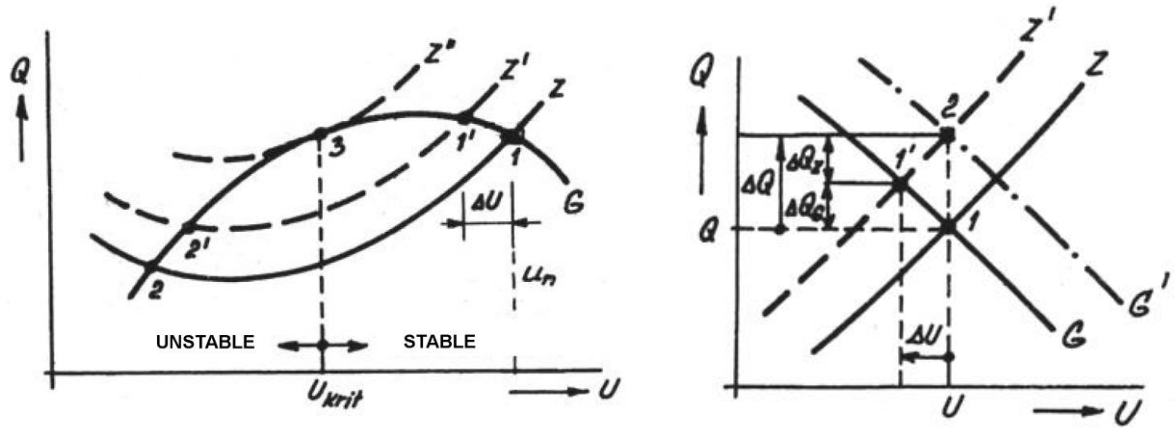
a 1% reduction in U_S will cause a 2% to 3% reduction in Q_M

The scattering loss is inversely proportional to U_S and a 1% decrease in U_S causes a 2% increase in Q_R . The steady state stable operating condition of the system is given by the intersection of the resulting characteristics of the sources and loads.

Thus, in an unregulated system, the magnitude of the voltage fluctuates when the reactive load changes. The control of the magnitude of the supplied reactive power can be done by:

- excitation changes of synchronous machines
- deploying static capacitor banks
- by changing the transformer taps (only redistribution that does not create reactive power)

The magnitude of reactive power is also affected by the degree of loading of the lines relative to their natural transmitted power. Regulation is decentralised, unlike frequency, due to the local nature of the voltage magnitude.



Increasing the reactive load by ΔQ from the "Z" characteristic to "Z' " will decrease the voltage magnitude by ΔU, while partially decreasing the reactive load requirement by ΔQ_Z and increasing the power output of the sources by ΔQ_G analogous to the active power when the load increases and the frequency decreases. If we want to completely compensate the voltage magnitude deficit, we need to switch to the "G' " characteristic for the power supplies.

The implementation is then as follows at the voltage levels:

a) HV networks (22 kV) use voltage regulation by changing the taps of 110/22 kV transformers (other transformations are fixed) in order to keep the voltage magnitude within the limits necessary for the consumer.

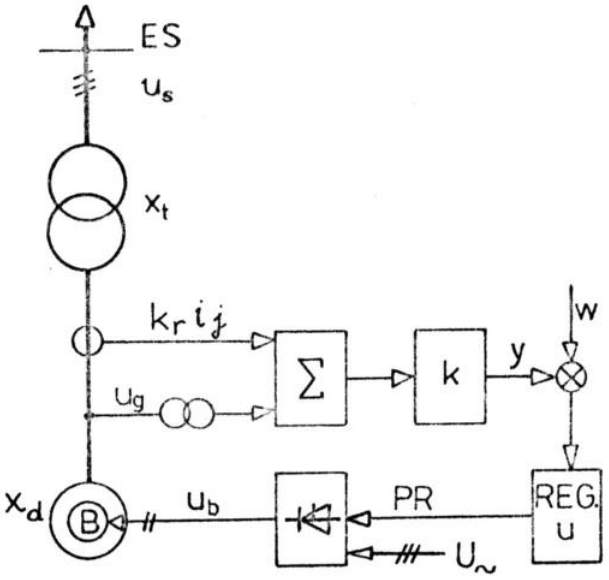
b) The 110 kV networks are also mainly distribution networks with a certain share of sources, so the main means of regulation is the change of reactive power supply of power plants and the additional means is the change of transformer taps 440/110 kV or 220/110 kV.

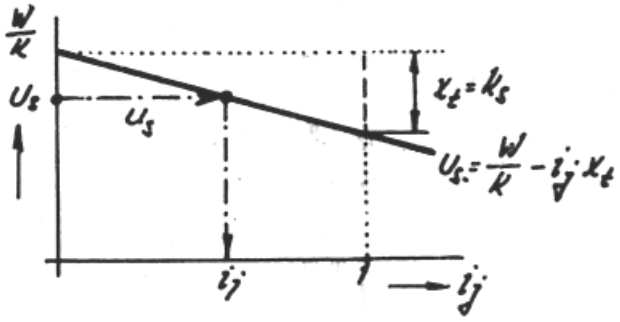
c) The 400 and 220 kV networks are mainly transmission networks, regulation is carried out by changing the power of power plants and possible compensators in the tertiary winding of transformers in order to maintain the stability of the system.

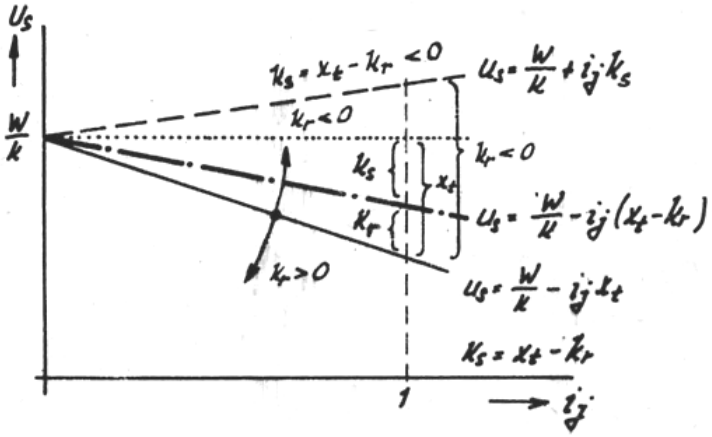
Another goal of voltage regulation is to optimize the cost-effectiveness of power transmission. The control of the regulation is achieved by evaluating the reactive power produced according to a prescribed diagram, or more often by maintaining the voltage magnitude at selected control nodes of the system.

Voltage regulation of alternators

In alternators, the primary task is to supply active power at a certain power factor according to the operating diagram, only the secondary task is to ensure the possible reactive power requirements of the system. In addition to the supply of reactive power, the voltage regulator must also monitor the static stability of the machine and the magnitude of the voltage at the terminals during fault conditions, or respect the supply of reactive power of the surrounding machines.







If the alternator works into the system through a block transformer, then approximately:¨

$$u_S + x_T i_J = u_G$$

For the desired control variable *w* then the following applies:

$$w - y = w - (u_G + k_R i_J)k = 0$$

The result is:

$$w = (u_S + x_T i_J + k_R i_J)k$$

$$u_S = \frac{w}{k} - i_J (x_T + k_R)$$

The resulting stabilization is thus:

$$k_S = x_T + k_R$$

With zero reactive current information, it is:

$$k_S = x_T \approx 0.1$$

Although the operation is stabilized, the so-called stabilizing effect of the block transformer is manifested, but it is too strong (the value is sufficient for operation: $k_S \approx 0.03 \div 0.07$

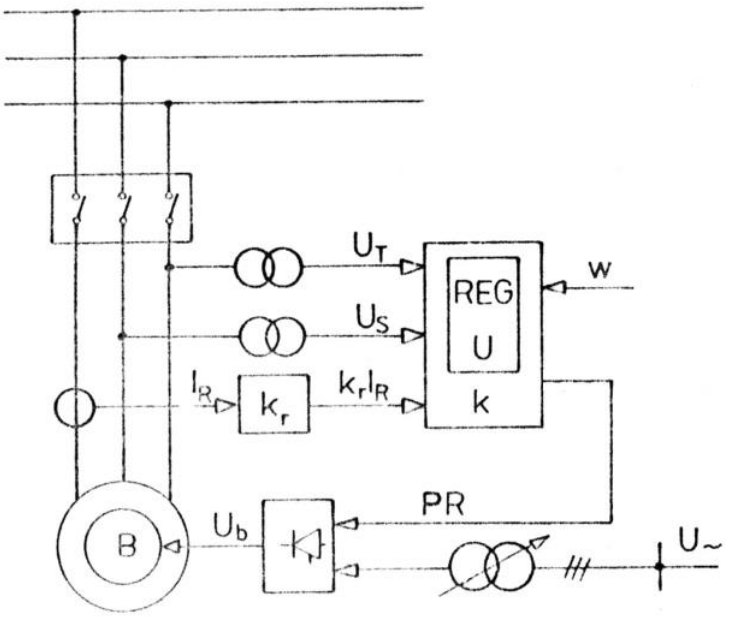
If we introduce a reactive current figure, with negative feedback, then it is:

$$u_S = \frac{w}{k} - i_J (x_T - k_R)$$

and the resulting compounding reduces the stabilizing effect of the block transformer.

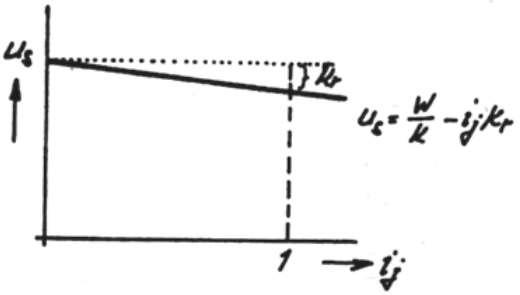
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Evropské strukturální a investiční fondy
Operační program Výzkum, vývoj a vzdělávání

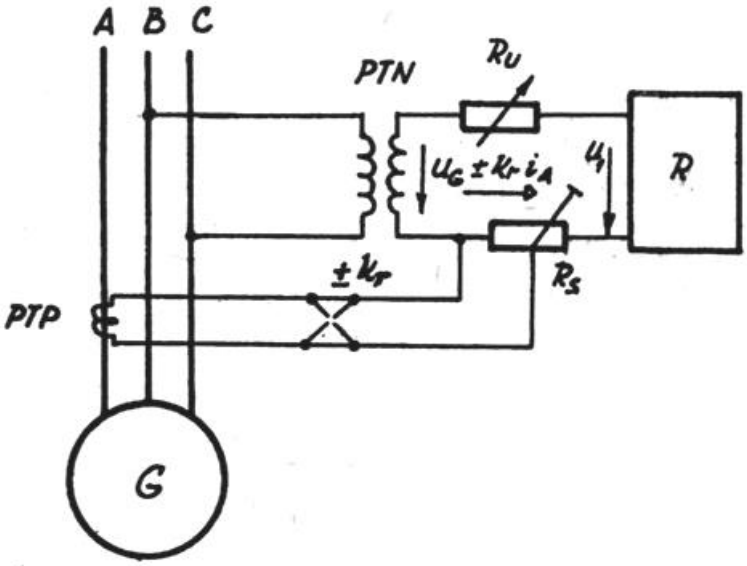
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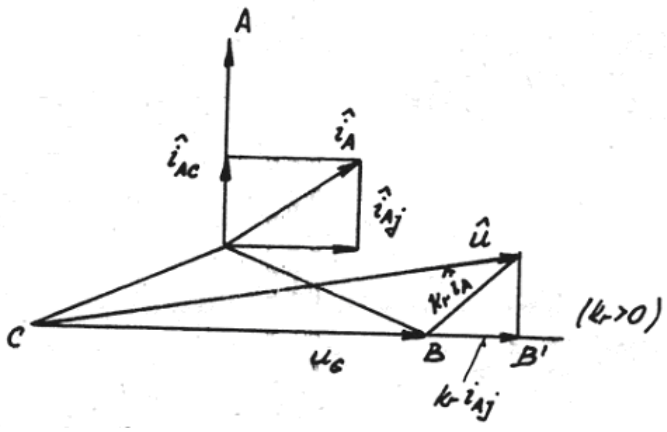
If the alternator operates directly into the system then we introduce a positive stabilizing feedback:¨

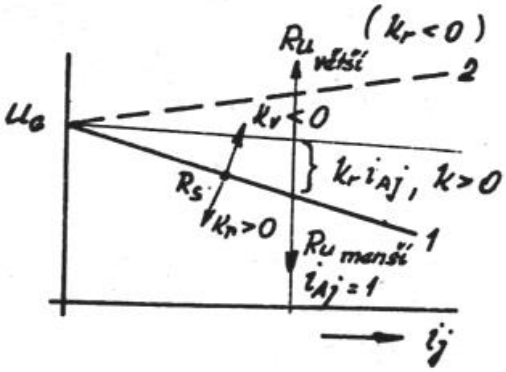
$$u_S = \frac{w}{k} - i_J k_R$$





The stabilization circuit is based on the information of the current of one phase and the difference of the combined voltages of the other two phases, where we regulate to a voltage û that approximately corresponds to the size of $u_1 = u_G \pm k_R i_J$.





Realistic excitation controller for a 200 MW unit:

