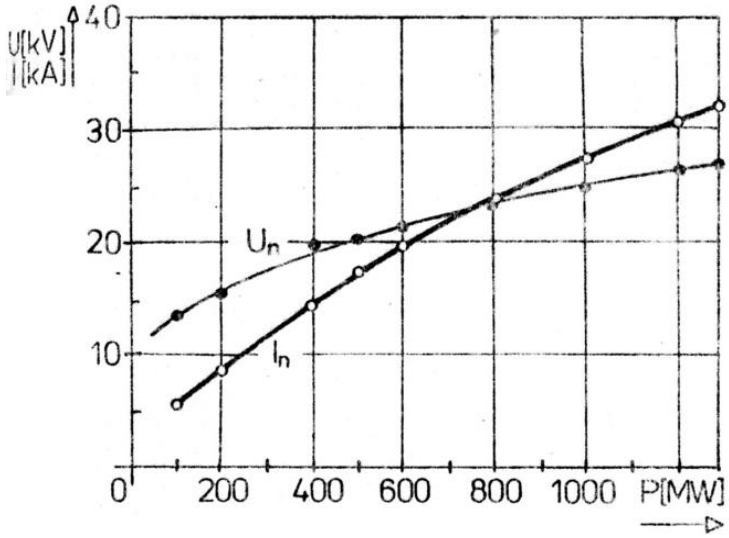
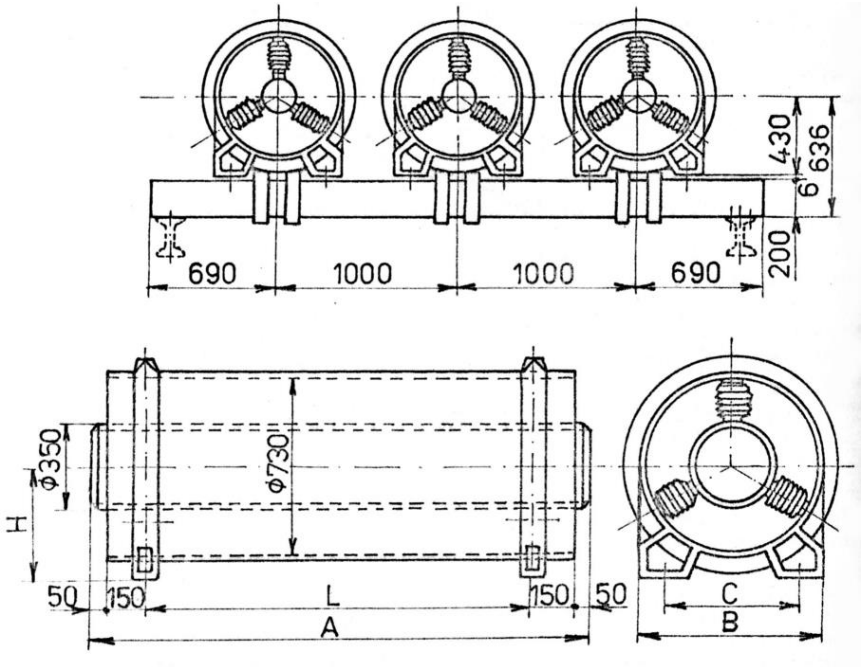
14. Alternator power output

As the alternator power and the corresponding current load increases, the need to optimally design the power output from the alternator to the block transformer and its own consumption increases:



For the relatively smallest outputs, the output is realized by direct connection of several block machines to a common bus supplying the power output transformers and its own consumption. This solution is disadvantageous for alternators in the event of a short circuit in the self-consumption, which is improved by the inclusion of an intermediate transformer or limiting reactor. Smaller plants up to 100 MW use cables or bare conductors on insulator supports to derive power.

For higher outputs for increasing current requirements, the lead-out is made with encapsulated conductors to limit the force action and to prevent direct contact of phase conductors in case of a short circuit.

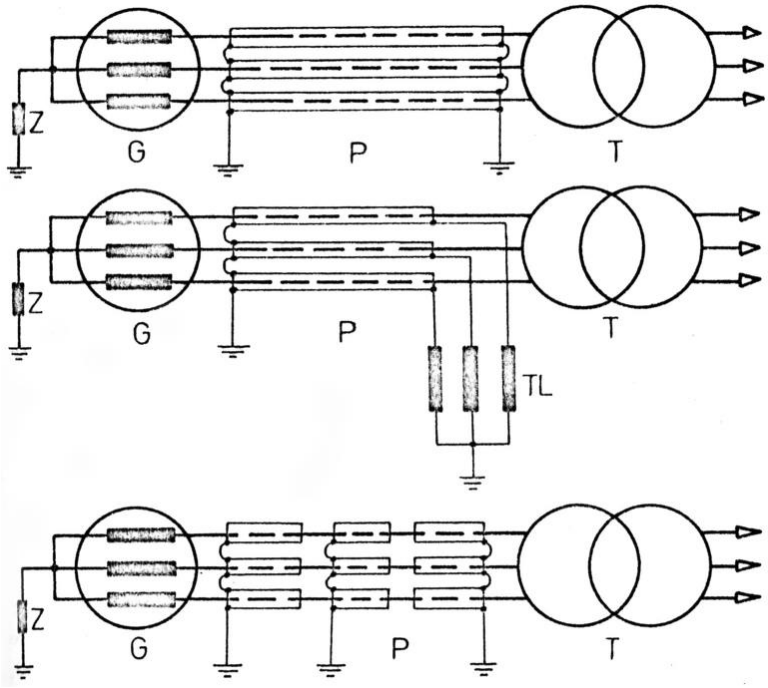


The shielding also favourably reduces the heating of the surrounding metal. The housing is made of non-magnetic material (aluminium) to reduce eddy currents. Design dimensions:

Nominal power [MW]	Rated voltage [kV]	Rated current [kA]	$2\,r_E$ [mm]	$2\,r_P$ [mm]
110	13.8	3	120	550
110 - 200	13.8 - 15	3 - 8	300	730
200 - 400	15 - 20	8 - 12	480	910
400 - 500	20	12 - 18	680	1110
500 - 800	20 - 25	18 - 25	1000	1430

The housings must be hermetically sealed against both ambient odour and moisture and against alternator cooling water.

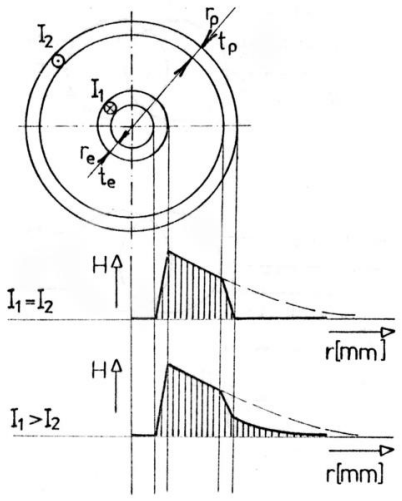
The grounding of the conductor bushings can be connected as follows:



a) Bushings and earthing connected at both ends

b) Housings and ground connected at one end, at the other end via a limiting choke

c) Housing divided into shorter sections connected to each other and connected to the ground separately



In the implementation of ad a), the current in the housing corresponds to the phase current in the conductor, ($I_1 = I_2$ in the figure) the external magnetic field is zero due to the superposition and both the mutual effects of the phase conductors and the effects on the surrounding structures are completely eliminated. The bushings and the phase conductor of the same phase repel each other during a short circuit.

Embodiment ad b) constrains the outer field less ($I_1 > I_2$ in the figure). The advantage is that during normal operation, the current and also the heating of the bushings is limited by the inductor (to 20% to 30% of the phase current, thus limiting the bushing heating during normal operation), but it quickly becomes oversaturated during a short circuit and allows better shielding during a fault.

The encapsulated conductor can be considered as a simple transformer where:

$$L_1 = 0.46 \log \frac{a}{r_E} 10^{-6} \left[H/m\right] \qquad L_2 = 0.46 \log \frac{a}{r_P} 10^{-6} \left[H/m\right]$$

$$j\omega \cdot M \cdot I_1 = I_2 \left(R_2 + j\omega \cdot L_2\right) \qquad I_2 = I_1 \frac{\omega \cdot L_2}{\sqrt{{R_2}^2 + \left(\omega \cdot L_2\right)^2}} = I_1 \frac{X_2}{Z_2}$$

The power dissipation in the housings will be: $P_Z = 3 \cdot R_2 \cdot {I_2}^2 = 3 \cdot R_2 \cdot \left(I_1 \frac{X_2}{Z_2} \right)^2$

In case of connection ad b) the current is in the bushings: $I_2 = I_1 \frac{X_2}{\sqrt{{R_2}^2 + \omega^2 \left(L_2 + L_{TL}\right)^2}}$

Neglecting the active resistance of the case: $I_2 = I_1 \frac{L_2}{L_2 + L_{TL}}$ and size L_{TL} , set the current limit to the desired 30%: $L_{TL} = \left(\frac{I_1}{I_2} - 1 \right) L_2 = \left(\frac{1}{0.3} - 1 \right) L_2$

$$L_{TL} = 2.33 \cdot 0.46 \log \frac{a}{r_P} 10^{-6} l_P$$ where l_P is the length of the encapsulation

When performing grounding ad c), the current in the bushings is reduced, but also the shielding effect and the limitation of the force effects of the phase conductors on each other. The currents in the individual sections have the character of eddy currents. Their losses can be determined according to the Conagly relation:

$$P_V = 3.12 R_2 \left(\frac{2r_P}{a} \right)^{2.13} \left(I_1 - I_2\right)^2$$

Then the total losses are: $P_C = P_Z + P_V = 3 R_2 {I_2}^2 + 3.12 R_2 \left(\frac{2r_P}{a} \right)^{2.13} \left(I_1 - I_2\right)^2$

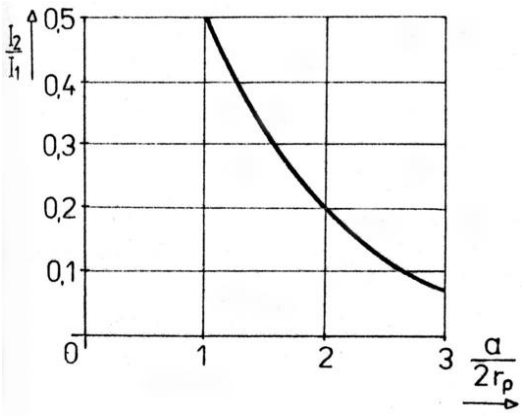
The best choice I_2 for a minimum of these losses:

$$\frac{dP_C}{dI_2} = 3 R_2 2 I_2 + 3.12 R_2 \left(\frac{2r_P}{a} \right)^{2.13} 2\left(I_1 - I_2\right)\left(-1\right) \equiv 0$$ (abbreviate 3 R_2 I_1)

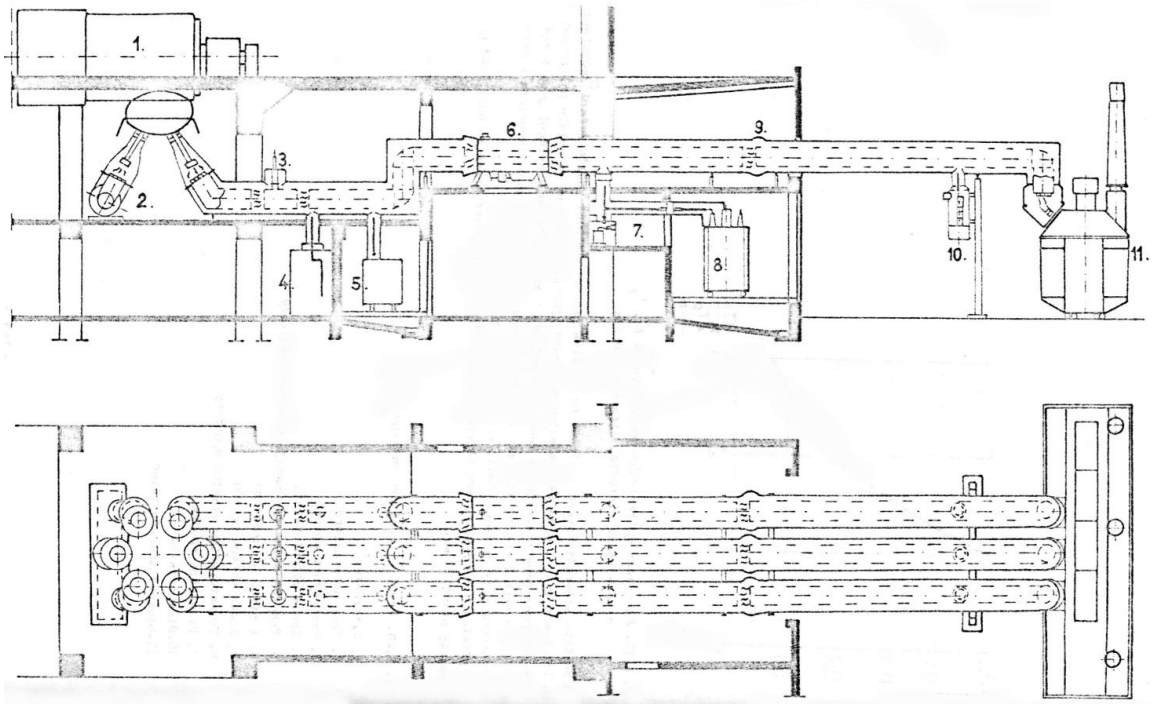
$$\frac{I_2}{I_1} + 1.04 \left(\frac{2r_P}{a} \right)^{2.13} \left(\frac{I_2}{I_1} - 1 \right) = 0 \qquad \frac{I_2}{I_1} = \frac{1}{\frac{1}{1.04 \left(2r_P/a\right)^{2.13}} + 1}$$

$$\frac{I_2}{I_1} = \frac{1}{1 + 0.962(2r_P/a)^{2.13}}$$

This dependence shows the optimal constraint I_2 when considering eddy current losses.

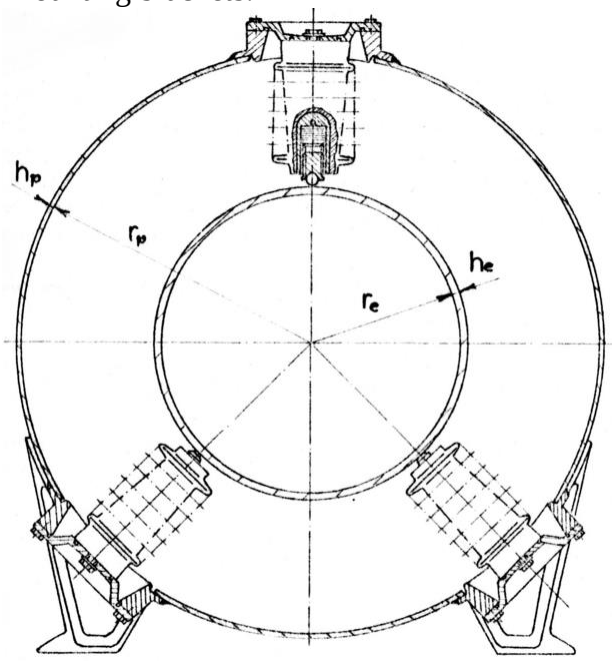


Example of alternator power output:



1. Alternator
2. Alternator node
3. Earthing switch
4. Voltage measurement cube
5. Transformer for wake-up power supply
6. Alternator switch
7. Current measurement cube
8. Self-consumption transformer
9. Dilatation coupling
10. The Lightning Rod
11. Block transformer

Heavy-duty encapsulated conductor design with flexible phase conductor placement between insulators and insulator mounting brackets:



Encapsulated conductors by company EGE





15. Operation of the alternator

Starting and phasing of the alternator

The alternator phasing is part of the whole power plant unit start-up, where most of the time scenario is influenced by the mechanical part. The run-in must be in accordance with the individual operating rules, which are based on:

- Regulations and operating rules for individual machinery and electrical equipment
- Tests, measurements and technical calculations and/or simulations by manufacturers, other users and research organisations
- Knowledge of equipment design and manufacturing technologies and previous experience in the operation of these and similar equipment.

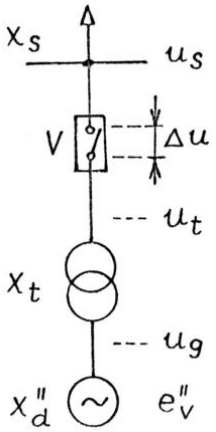
During the start-up of alternators, the gradual heating of the windings and the start-up of support systems (cooling, oil management) is limiting. The windings of the machine heat up more than the magnetic parts, and copper has a higher thermal expansion than steel. This causes winding shifts in the grooves or deformations in the machine faces (similar problems also occur when the machine is shut down rapidly). For machines with long rotors, it is therefore necessary to use stronger copper.

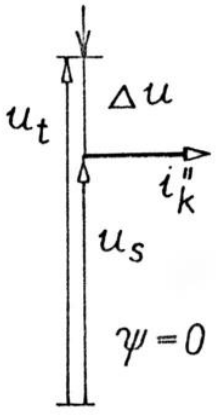
The turbine and alternator system is brought up to rated speed, charged to rated voltage, energized and then loaded with the required active and reactive power. The actual phasing must be carried out with minimum current and hence torque surges under the following conditions:

- Same alternator and mains phase sequence
- Same magnitude of alternator and mains voltage
- Same frequency of alternator and mains voltage
- Zero phase shift between alternator and mains voltage

All of these conditions cannot be met exactly, their possible deviations of the individual sub-conditions are determined on the basis of the permissible current load of the alternator.

Voltage magnitude deviation





We consider only the different magnitude of the voltage and neglect the active components of the impedances.

Just before phasing, there is a differential voltage at the alternator switch Δu .

If we consider the grid as a completely ideal source, then the resulting reactive current surge will be limited only by the reactance of the alternator and block transformer:

$i_K^{//} = \frac{e_V^{//} - u_S}{x_D^{//} + x_T}$ Before the suffix is $e_V^{//} = u_G = u_T$, i.e. $i_K^{//} = \frac{u_T - u_S}{x_D^{//} + x_T} = \frac{\Delta u}{x_C}$

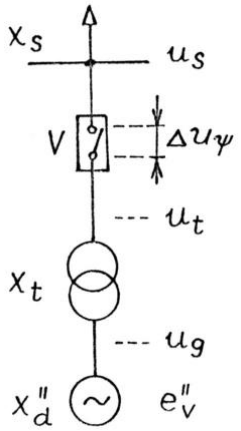
The current will be an inductive load for the alternator if it is before rephasing $u_T > u_S$. Otherwise the grid will be inductively loaded (alternator loaded capacitively). Therefore, the alternator is slightly overcharged before rephasing.

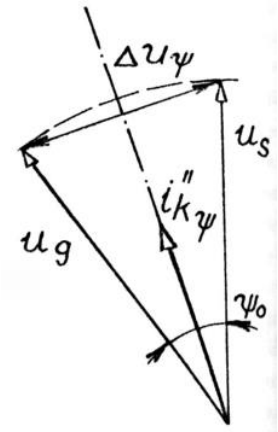
An example of the allowed deviation of the voltage magnitude in the worst case of impedance coupling, i.e. neglecting all reactances except $x_D^{//}$ = 0.15, and the allowed value of the current corresponding to the nominal one is:

$$\Delta u = i_D^{//} \cdot x_D^{//} = 1 \cdot 0.15 = 15\%$$

In practice, it is common to phase at a voltage magnitude deviation of 5%, in the case of faults a deviation of up to 20% is exceptionally allowed. The DC component has been neglected in the calculation, the value of which is comparable to $i_D^{//}$.

Voltage phase shift deviation





We consider only the different phase of the voltage and again neglect the active components of the impedances.

Just before phasing, there is a differential voltage at the alternator switch Δu_Ψ .

If we consider again the network as a completely ideal source, then the resulting approximately active current surge will be limited only by the reactance of the alternator and the block transformer:

$$i_{K\Psi}^{//} = \frac{\Delta u_\Psi}{x_D^{//} + x_T} = \frac{2u_G}{x_D^{//} + x_T} \sin\frac{\Psi_0}{2}$$

The surge current will cause the machine to slow down if the generator voltage exceeds the mains voltage before rephasing. Otherwise, the machine will be accelerated. These current surges are more dangerous because they directly affect the machine's torque.

Example of the allowed voltage phase deviation again in the worst case of impedance coupling, i.e. neglecting all reactances except $x_D^{//}$ = 0.15, and the allowed current value corresponding to the nominal one is:

$$i_{K\Psi}^{//} = i_N = 1 = \frac{2u_G}{x_D^{//}} \sin\frac{\Psi_0}{2} = \frac{2 \cdot 1}{0.15} \sin\frac{\Psi_0}{2} \quad \Rightarrow \Psi_0 = 8.6^\circ$$

When considering the reactance of the block transformer, the conditions are more favorable. The currents generated by the large phase deviation error during phasing can reach significant values. A comparison is made with the limit currents for which the alternator must be prepared during a short circuit at its terminals:

$i_{KM} = K\sqrt{2}\cdot i_{KS0.01}^{//}$ where for this case is $K = 1.95$

$$i_{KM} = K\sqrt{2}\frac{e_V^{//}}{x_D^{//}} = 1.95\sqrt{2}\frac{1.1}{0.15} = 20.2$$

The largest current surge of rephasing would occur when the connection is in counterphase:

$$i_{K\Psi MAX}^{//} = \frac{2u_G}{x_D^{//}}\sin\frac{\Psi_{0MAX}}{2} = \frac{2\cdot 1}{0.15}\sin\frac{180^\circ}{2} = 13.3$$

If we consider the unfavourably slow decay of the DC component, then:

$$i_{K\Psi MAX} = 2\sqrt{2}\cdot i_{K\Psi MAX}^{//} = 4\sqrt{2}\frac{u_G}{x_D^{//}} = 2\sqrt{2}\cdot 13.3 = 37.7 \approx 2i_{KM}$$

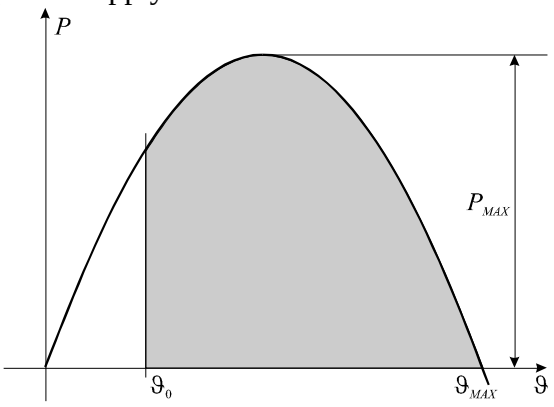
Determine the limiting value of the phase deviation when the current is less than the short-circuit current:

$$i_{K\Psi MAX} = 4\sqrt{2}\frac{u_G}{x_D^{//}}\sin\frac{\Psi_{0MAX}}{2} = i_{KM} = K\sqrt{2}\frac{e_V^{//}}{x_D^{//}}$$

$$\sin\frac{\Psi_{0MAX}}{2} = \frac{K}{4}\cdot\frac{e_V^{//}}{u_G} \qquad \sin\frac{\Psi_{0MAX}}{2} = \frac{1.95}{4}\cdot\frac{1.1}{1} \qquad \Psi_{0MAX} = 64.9^\circ$$

Voltage frequency deviation

Usually, phasing is performed at a slightly higher speed of the machine than the mains frequency (0.1 to 0.2% of the nominal value) so that the excess kinetic energy is reflected as active power supply and the machine is slowed down somewhat.



The possible frequency difference corresponds to the need to maintain dynamic moment balance and is limited by the potential braking energy available, otherwise the machine would spin compared to the synchronous speed of the grid.

$$\frac{1}{2}T_M\Delta\omega^2 \le \int_{\vartheta_0}^{\vartheta_{MAX}} p_{MAX}\sin\vartheta d\vartheta \qquad T_M = \frac{J\cdot\Omega_N{}^2}{M_N}$$

$$\Delta\omega_{MAX} = \sqrt{\frac{2}{T_M}\int_{\vartheta_0}^{\pi} p_{MAX}\sin\vartheta d\vartheta} = \sqrt{\frac{2\cdot p_{MAX}}{T_M}(1+\cos\vartheta_0)}$$

$$p_{MAX} = \frac{e_V\cdot u_S}{x_C} \qquad x_C = x_D^{//} + x_T + x_V + x_S$$

When manually rephasing, a tolerance of approximately 3 to 6 revolutions of the synchroscope (rotating at a differential frequency) per minute (one revolution per 10 to 20sec.) is allowed:

Lower limit:

$\Delta f \sim 0.2\%\ z\ 50Hz = 0.1Hz$

$\Delta T = \frac{1}{\Delta f} = \frac{1}{0.1} = 10s$

Good limits:

$\Delta f \sim 0.1\%\ z\ 50Hz = 0.05Hz$

$\Delta T = \frac{1}{\Delta f} = \frac{1}{0.05} = 20s$

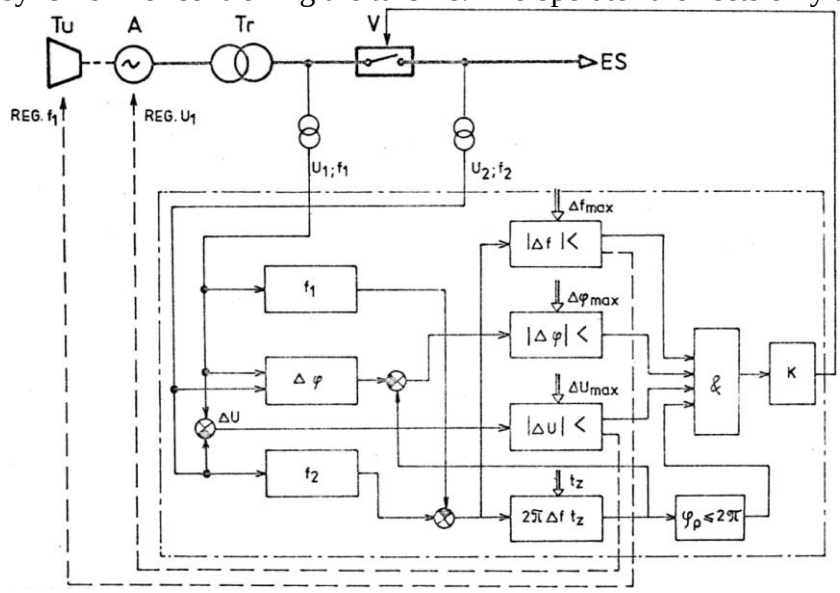


The actual re-phasing stimulus shall be given well in advance of the machine reaching the tolerated phase shift to take account of switch and control delays.

Advantages and disadvantages of precision phasing:

- Minimal current and torque shocks and therefore minimal stress on the machine
- Rephasing takes quite a long time, especially in emergency situations in the system when both the magnitude and frequency of the voltage changes
- Requires complex and skilled handling or complicated automation

When phasing with a phaser, the operator sets only the same voltage magnitude and frequency, the moment of switching is selected by the automatic control. The phaser also controls the frequency difference required for phasing. In fully automatic phasing, the phaser selects the moment of switching and controls the frequency difference controlled by the synchronizer controlling the turbine. The operator then sets only the same voltage magnitude.



The advance for phasing must then be within the limits given by the switch speed t_Z :

$$\varphi_P = \Delta\omega \cdot t_Z = \\ = 2\pi \cdot \Delta f \cdot t_Z \leq 2\pi$$

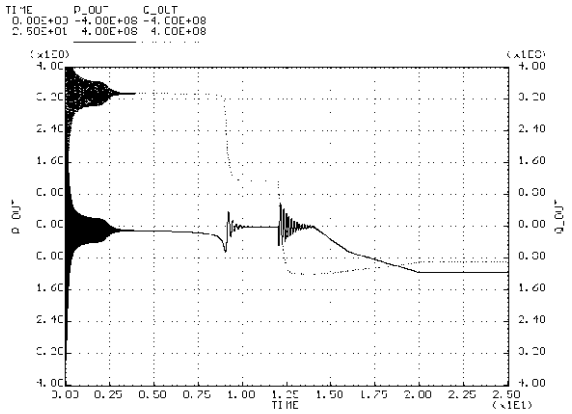
So must be:

$$\Delta f_{MAX} \leq \frac{1}{t_Z}$$

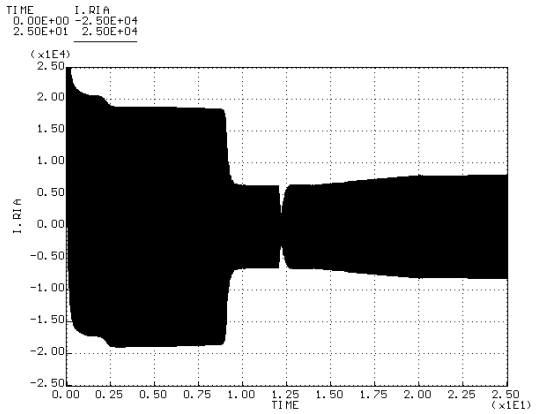
Self-synchronization

In this mode, the alternator is not energized. First, the machine is brought up to near-synchronous speed by the turbine (the pictures correspond to asynchronous start-up). The grid must cover the magnetization of the machine and the current surge includes the supply of inductive power from the grid (in the pictures, the part from approximately 10 to 12 sec.). Only after connection does the alternator wake up and pull into synchronism (time 12 sec. in the figures).

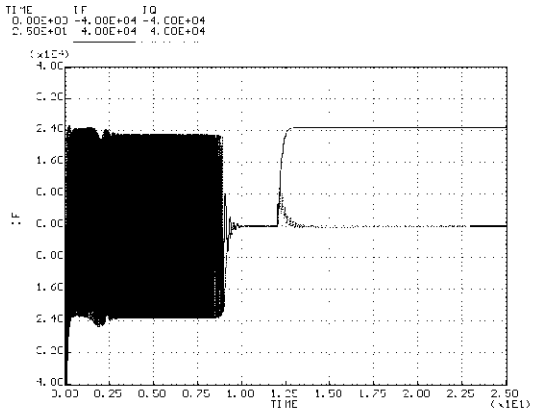
Asynchronous starting of an unloaded alternator and self-synchronisation:



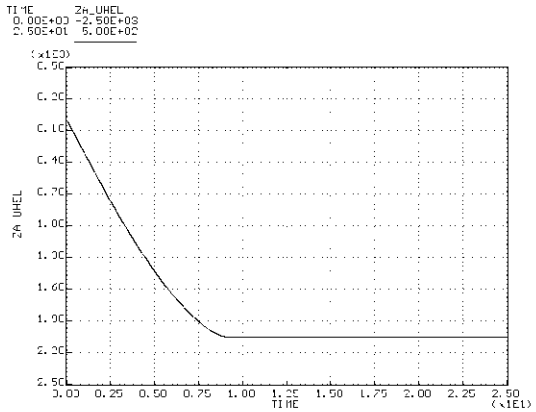
Active and reactive power supplied to the grid



Stator currents



Rotor currents



Load angle

The current reactive surge has a magnitude of:

$$i_K^{//} = \frac{u_S}{x_C} = \frac{1}{x_C}$$

In self-synchronisation, the excitation winding must be closed via an exciter or exciter resistor to prevent overvoltage on the rings when connected to the mains. The alternator must be wakened up immediately after connection. The reluctance moment (due to the magnetic asymmetry of the rotor of alternators with protruding poles) helps to draw in the synchronism.

Advantages and disadvantages of self-synchronization:

- Inevitably, current and torque surges occur
- The occurrence of a voltage drop in the magnitude of the self-consumption especially when connecting to a less "hard" network or when transferring power through a large impedance
- Fast reconnection even under adverse network degradation conditions
- Simple handling without complex automation

Because of the pros and cons mentioned above, self-synchronization is used only in isolated emergency conditions in the power system, under normal conditions precise phasing is performed.