Electric Power Systems - Laboratory Exercise 2

The Synchronous Generator

by Olof Samuelsson [1, 2]

1. Introduction

The synchronous generator is the absolutely dominating generator type in power systems. It can generate active and reactive power independently and has an important role in voltage control. The synchronizing torques between generators act to keep large power systems together and make all generator rotors rotate synchronously. This rotational speed is what determines the mains frequency, which is kept very close to the nominal value 50 or 60 Hz. The generator studied here is connected to the national grid, but since it is very small it has virtually no impact on the rest of the system which therefore can be modeled as a stiff three-phase AC voltage.

2. Theory

The *stator* of a synchronous generator holds a three-phase winding where the individual phase windings are distributed 120° apart in *space*. The *rotor* holds a *field winding*, which is magnetized by a DC current – the *field current* I_f. When the rotor is rotated (by the turbine) the rotating magnetic flux induces voltages E_q in the stator windings. These voltages are sinusoidal with a magnitude that depends on I_f, differ by 120° in *time* and have a frequency determined by the angular velocity of the rotation.

In steady state, one phase can be modeled as an AC voltage source E_q feeding the current I against the terminal voltage V through the *d-axis synchronous reactance*, X_d:

$$E_q(I_f)=V+jX_dI$$

The stator windings also have a resistance R_a, which however is very small and is usually neglected. The voltage V is transformed a number of times and finally appears at the mains outlet. The mains frequency thus originally comes from the mechanical rotation of the rotor of the generator!

Synchronous generators come with round (or cylindrical) rotor or with salient pole rotor. The number of poles (magnetic N and S poles in the rotor) ranges from two to almost one hundred. The above description is valid for a round rotor generator with two poles, which is the simplest to describe.

2.1. Synchronizing a generator to an AC system

Connecting a generator electrically to an AC system is called *synchronizing* the generator to the AC system. Before this is done, the generator is accelerated to correct speed and the rotor is magnetized. The current I resulting at the moment of synchronization depends in how close E_q and V are to each other. To avoid large currents the phasor values of E_q and V should be equal. This gives four conditions:

• same magnitude of E_q and V;
• same phase of E_q and V.

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and even more important (already assumed when working with phasors)

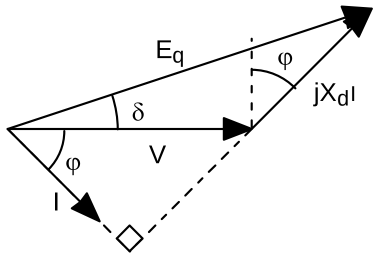
- same frequency of E_q and V;
- same phase order of the three-phase systems E_q and V.

2.2. The synchronous generator at steady state

As the expressions for active and reactive power are made more complicated by rotor saliency, the round rotor case is treated first.

Round rotor machine

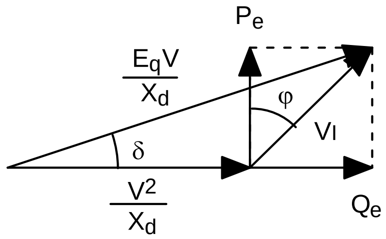
The phasor equation $E_q=V+jX_dI$ can be illustrated graphically:



where cosφ is the power factor of the load. Here the load is inductive, I lags V and φ>0. The power supplied to the load is (per phase):

$$\bar{S} = P_e + jQ_e = \bar{V}\bar{I}^* = VI\cos\varphi + jVI\sin\varphi$$

Scaling the phasor diagram with V/X_d gives:



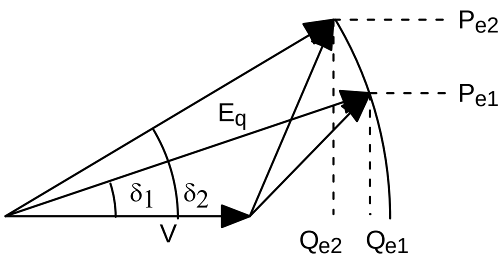
Active and reactive power can now be expressed as:

$$S = VI$$

$$P_e = VI\cos\varphi = \frac{E_q V}{X_d}\sin\delta \tag{1}$$

$$Q_e = VI\sin\varphi = \frac{E_q V}{X_d}\cos\delta - \frac{V^2}{X_d}$$

The control inputs at steady state are turbine power P_m and field current I_f. Changing P_m while keeping I_f constant shows that E_q is constant, while δ and Q_e are changed.



If instead I_f is increased while P_m is kept constant, it becomes evident that the sign of Q_e can be controlled.

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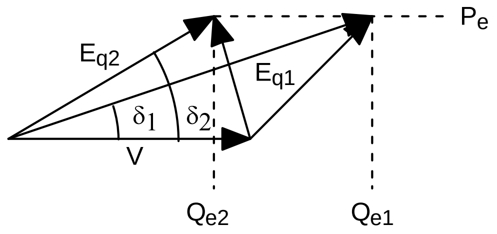
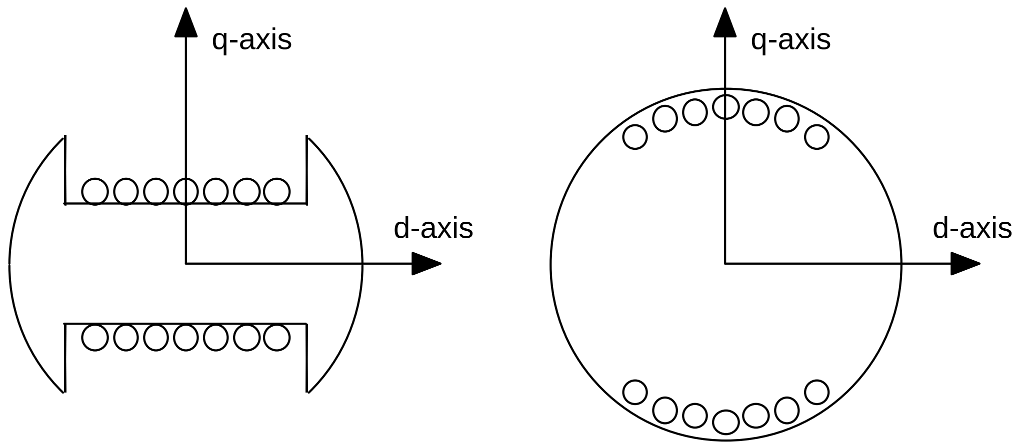


Salient pole rotor

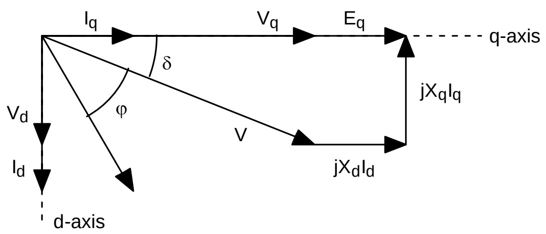
The difference between a salient pole rotor and a cylindrical rotor is shown below:



The *direct-axis* (or *d-axis*) is defined as the main flux direction of the rotor. The voltage induced in the stator E_q leads the d-axis by 90°, which is the *quadrature-axis* (or *q-axis*) direction. The fundamental (phasor) voltage equation for a salient pole generator is:

$$\overline{E}_q = \overline{V} + jX_d \overline{I}_d + jX_q \overline{I}_q$$

which graphically appears as below:



Using the d- and q components of current and terminal voltage,

$$\overline{S} = P_e + jQ_e = \overline{V}\overline{I}^* = \left(V_d + jV_q\right)\left(I_d + jI_q\right)^*$$

$$V_d + jV_q = V\sin\delta + jV\cos\delta$$

$$\begin{cases} I_d = \dfrac{E_q - V_q}{X_d} \\ I_q = \dfrac{V_d}{X_q} \end{cases}$$

the active and reactive power output of the generator can now be expressed as:

$$P_e = \frac{E_q V}{X_d}\sin\delta + \frac{V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\delta = P_{field} + P_{reluctance}$$

$$Q_e = \frac{E_q V}{X_d}\cos\delta - V^2\left(\frac{\cos^2\delta}{X_d} + \frac{\sin^2\delta}{X_q}\right)$$

Note that P_e and Q_e for a round rotor generator are obtained by setting X_d=X_q.

2.3. Dynamic model of the synchronous generator

Assuming that E_q is constant a second order model describes the dynamics:

$$\frac{2H}{\omega_{s,e}}\frac{d\omega_e}{dt} = P_m - P_e(\delta) \quad (2)$$

$$\frac{d\delta}{dt} = \omega_e - \omega_s \quad (3)$$

Here ω_e is the mechanical angular frequency of the rotor, while $\omega_{s,e}$ is its nominal value. Both these frequencies are given in electrical rad/s ($2\pi f$, where f is 50 or 60 Hz), independent of number of rotor poles.

H is the inertia constant of the machine defined as kinetic energy in Ws divided by the VA rating. This value is typically in the range 1-10 s. The interpretation of H is the time it takes (in seconds) to reach standstill if the generator rotating at rated speed with rated load, is disconnected from the turbine.

δ is the mechanical angle (in rad) between the voltage vector of the network and the internal voltage E_q vector which is fixed to the rotor. δ is thus measured in a coordinate system fixed to the rotating rotor.

P_m is the mechanical power input from the turbine, while P_e is the electrical power fed to the electrical system. **Note** P_e is obtained from the above expressions but with X_d replaced by X'_d and similarly E_q by E'_q.

2.4. The synchronizing torque

At no-load in steady state δ, P_e and P_m are all zero while ω_e=$\omega_{s,e}$. Assume that, for some reason, ω_e becomes too high (this could be at the moment of synchronization). This causes an increase in δ (3), but also in P_e (1). The minus sign in (2) shows that $d\omega_e/dt$ becomes negative since P_e>P_m. The deviation in ω_e is thus corrected and after some time ω_e is equal to $\omega_{s,e}$ again. This mechanism *synchronizes* all synchronous generators in a network to each other and is the reason for the term *synchronization* of a generator. The torque caused by the deviation in δ is called *synchronizing torque* and is the reason why systems covering entire continents can be kept together electrically.

The *synchronizing power* (*coefficient*) is $dP_e(\delta)/d\delta$.

2.5 The Automatic Voltage Regulator

The reactive generation capability of the synchronous generator can be used to control the voltage at the generator bus. This is done by letting an Automatic Voltage Regulator (AVR) control the rotor field current which in turn determines the internal voltage E. The AVR measures the voltage V at the generator terminals and adjusts the field current so that V is close to a reference value V_{ref}.

1 Partly revised 2004 by N. Stråth,

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3. Preparatory Exercises

The synchronous generator used in the lab has the following rating:

I_m=1.4 A (magnetizing current, rotor)
I_a=5.25 A (stator current) U=220 V (stator phase-phase voltage)
S_n=2kVA cosφ=0.8 (ind)

X_d=1.17 pu X'_d=0.23 pu Xq=0.6 pu T'_d=0.06 s n=1500 rpm (4-pole rotor)

a) Determine H for the generator and driving motor if J_{total}=0.12 kgm^2. (It is small!)

b) Determine X_d, X'_d and X_q in Ω.

c) Sketch the vector diagram for the generator at the rated operating point with δ=19.44°.

d) Assume E_q=235V and V=235V and fill in the column below. Draw (if possible using Matlab) $P_e(\delta)$ for δ=0-180°. Also compute $dP_e/d\delta$ at δ = 2.5°.

δ	Computed P_e (W)
0	
5°	
15°	
25°	

e) What happens to the synchronizing power $dP_e/d\delta$ when P_e passes its maximum value?

f) The generator is connected to the strong three-phase mains via a series reactance of 10.0 Ω/phase. This reactance X should be added to the X_d and X_q. Assume E_q=235V and V=235V and fill in the column below. Remember that the reactance X should be added to the X_d and X_q. Draw (if possible using Matlab) $P_e(\delta)$ for δ=0-180°. Also compute $dP_e/d\delta$ at δ = 2.5°.

δ	Computed P_e (W)
0	
5°	
15°	
25°	

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4. Experiments

Parameters and rated values of the machines used for the experiments are:

DC motor I_m=0.45 A I_a=8.3 A U_a=230 V R_a=1.8Ω k=2.7 Nm/A[2]

Four-pole synchronous generator with salient pole rotor

I_m=1.4 A	I_a=5.25 A	U_a=220 V	S_n=2kVA	cosφ=0.8 (ind)
X_d=1.17 pu	X'_d=0.23 pu	X_q=0.6 pu	T'_d=0.06 s	n=1500 rpm (4-pole rotor)

4.1. Setup

The equipment is partly controlled with a power converter and dSpace. dSpace is a control system with analog inputs and PWM modulated outputs (beside a number of digital inputs and outputs). dSpace is programmed with Simulink. The lab instructor will give further instructions on how to use dSpace in the lab.

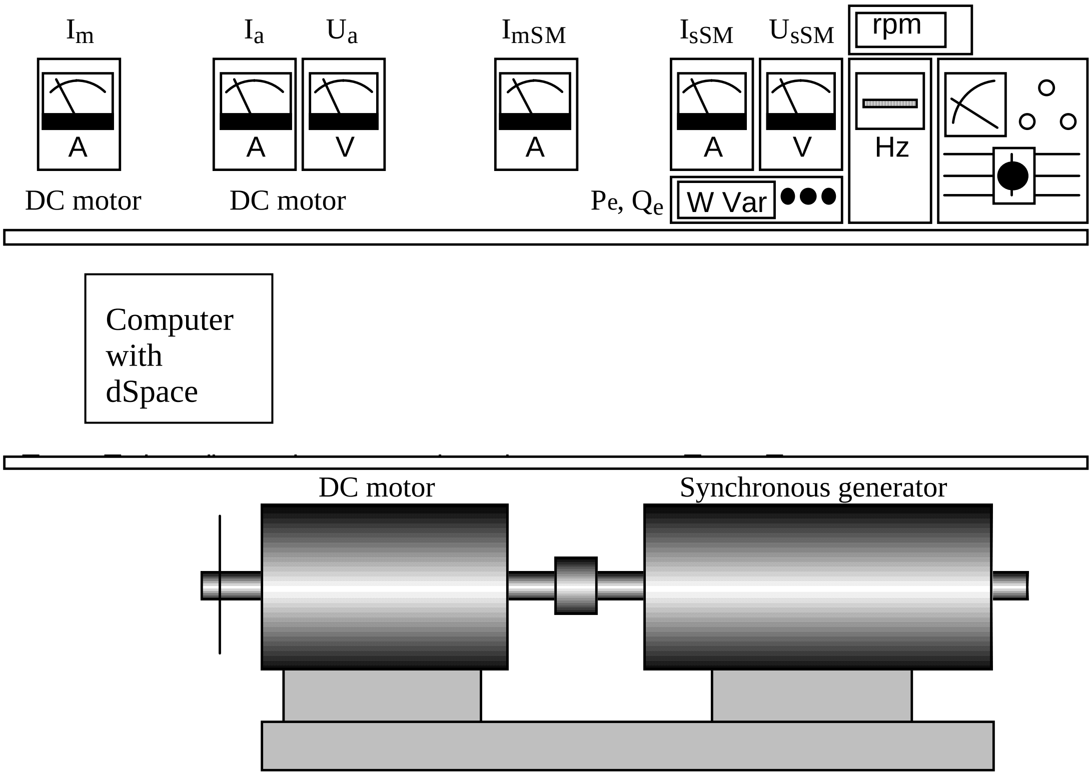

Figure 1. The equipment used during the experiments.

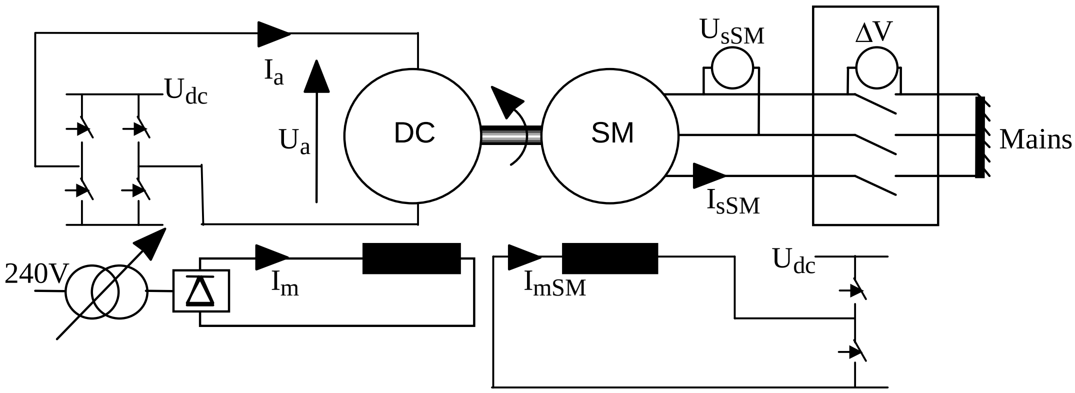

Figure 2. The diagram showing measured quantities.

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4.2. Strong network

In this section the generator is connected directly to the three-phase mains.

Synchronization

Check that the generator breaker on the synchronization unit is set to zero. Switch on single-phase 220V and both three-phase voltages (220V and 380V). Set the field current of the DC motor to 0.45 A. Start and connect the converter in the basement. Then go through the following steps:

1. Accelerate the DC motor to 1500 rpm by increasing U_a;
2. Turn on the exciter and change n_{ref} so that the stator voltage U_r=230V;
3. Await zero reading of ΔV and dark lamps on the synchronization unit;
4. Turn the generator breaker while lamps are still dark.

After the synchronization the generator should be running at no load – check that P_e and Q_e are zero (<100 W/VAr).

Do another synchronization and study $P_e(\delta)$ and determine the frequency of the resulting oscillation at synchronization.

f_{osc}=.......................................Hz

Inputs and outputs

Measure P_e for δ = 0, 5, 15, 25°.

δ	Computed P_e (W) [1]	Measured P_e (W)
0		
5°		
15°		
25°		

$dP_e/d\delta(\delta = 2.5°)$=..W/°

Fill in the table below.

P_m (W)	I_{mSM} (A)	Q_e (VA)	V (V)
0	0.5		
0	0.75		
0	1.0		
900	0.5		
900	0.75		
900	1.0		

Ignore saliency and sketch three separate vector diagrams for the first three rows and one for the last three.

[1] From preparatory exercise d.

Effect of load at generator terminals

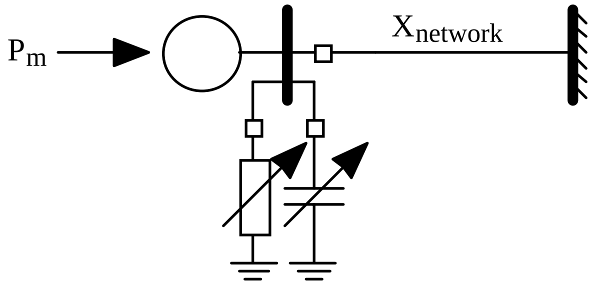

Figure 3. One-line diagram of the test system.

Select P_m and I_f for P_e+jQ_e=900-j260 VA. Switch R (drawing 2.5A/phase) and C load at the generator terminals and determine the steady state impact on P, Q and V.

	P_e	Q_e	V
R			
C			

Since the network is strong ($X_{network}$ small), V is not supposed to change and R and C are fed from the network rather than from the generator.

If you would model the generator in a load flow program like PowerWorld – would it be a PQ or PV node now?..

4.3. Weak network

In this section the generator is connected to the strong three-phase mains via a series reactance of 10.0 Ω/phase. The generator is now strong relative to its network connection.

Hands-on experience of synchronizing torque

The angular frequency of the stator voltage is the sum of the *mechanical* angular frequency of the rotor and the angular frequency of the rotor current:

$$\omega_{stator,el}=\omega_{rotor,\ mek}+\omega_{rotor,el}$$

Normally the rotor rotates at a speed corresponding to 50 Hz, while the rotor is DC-magnetized, which gives a stator frequency of 50 Hz. The same stator frequency can be obtained by swapping the frequencies of rotor rotation and rotor magnetization, so that the rotor is at standstill while being magnetized with a 50 Hz current. This is done in two very small synchronous generators (see Figure 4). δ is now the difference in angle between the two rotors.

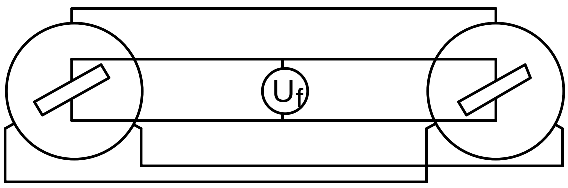

Figure 4. Two synchronous generators – synchronizing torques act to align rotors.

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Try to turn one rotor out of phase with the other – the correcting torque that you feel is the syncronizing torque. What happens when δ passes 90°?

The damping of the system is low, which is characteristic for synchronous generators. Try to find the resonance of the system by moving one rotor so that δ varies sinusoidally.

Inputs and outputs

Measure P_e for δ = 0, 5, 15, 25°.

δ	Computed P_e (W) [2]	Measured P_e (W)
0		
5°		
15°		
25°		

$dP_e/d\delta(\delta = 2.5°)$=...W/°

Fill in the table below.

P_m (W)	I_{mSM}	Q_e (VA)	V (V)
0	0.5		
0	0.75		
0	1.0		
900	0.5		
900	0.75		
900	1.0		

Ignore saliency and sketch three separate vector diagrams for the first three rows and one for the last three.

Effect of load at generator terminals

Select P_m and I_{mSM} for P_e+jQ_e=900-j260 VA. Switch R (drawing 2.5A/phase) and C load at the generator terminals and determine the steady state impact on P, Q and V.

	P_e	Q_e	V
R			
C			

The network is now weak so terminal voltage and reactive power output will vary with R and C. Since the "turbine" determines Pe, this is expected to be constant.

From the transients you can determine the oscillation frequency with weak network:

f_{osc}=..Hz

[2] From preparatory exercise f.

4.4. Weak network and AVR

In this section the generator is connected to the strong three-phase mains via a series reactance. The field current of the generator is controlled by an AVR (implemented in dSpace) to keep the terminal voltage close to the reference value V_{ref}.

Inputs and outputs

Fill in the table below.

P_m (W)	V(V)	Q_e (VA)
0	220	
0	230	
0	240	
900	220	
900	230	
900	240	

Ignore saliency and sketch three separate vector diagrams for the first three rows and one for the last three.

Effect of load at generator terminals

Select P_m=900W and V_{ref} so that V=230V. Switch R (drawing 2.5A/phase) and C load at the generator terminals and determine the steady state impact on P, Q and V.

	P_e	Q_e	V
R			
C			

When R and C are changed, the AVR is expected to provide constant V by adjusting reactive output. P_e is still governed by the turbine and should be insensitive to changes in R and C load.

If you would model the generator in a load flow program like PowerWorld – would it be a PQ or PV node now?..............................

4.5. Islanding

Connect the R load, adjust it for 1.0 A/phase and disconnect it again. Open the generator breaker. Connect the R load. The generator now supplies a small *island network* and is alone responsible for the frequency.

Adjust R for currents between 0.5 and 1.5 A. The speed of the DC motor decreases linearly as the loading torque increases. This is equivalent to having a proportional regulator as *turbine governor* to control the active power of the DC motor (turbine). The proportional gain measured in p.u. P_m per p.u. speed of all governors in a large system are normally the same. This makes all generators share the increased load demand in proportion to their rated power.

Change the active load and study the impact on the frequency. The proportional governor will not return the frequency to 50 Hz. This requires a PI controller, which often can be selected for island operation. To keep the frequency at 50 Hz here you must adjust P_m manually.

Change the reactive load and check that the AVR maintains the voltage at an acceptable level.

4.6. Transient stability

Synchronize the generator to the system. Study $P_e(\delta)$ as P_m is slowly increased to 1000W.

Quickly turn the generator breaker half a turn (180°). This temporarily makes P_e zero which, as seen from the generator, corresponds to a three-phase short-circuit.

Test different fault times at P_m = 1000, 1350 and 1700 W, to see if the generator goes *transiently unstable* – that is a stable equilibrium is not found after the breaker is closed again.

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