SSG: Inverters that Mimic Synchronous Generators

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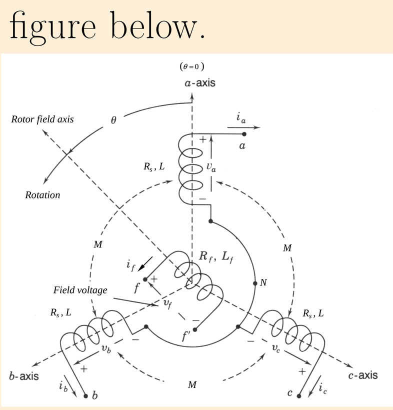
Abstract

In this poster, the idea of operating an inverter to mimic a synchronous generator is developed. We call the inverters that are operated in this way static synchronous generators (SSG). This means that the well-established theory/algorithms used to control synchronous generators can still be used in power systems where a significant proportion of the generating capacity is inverter-based. The implementation and operation of SSGs are described in detail. The real and reactive power delivered by SSGs connected in parallel can be automatically shared using the well-known frequency and voltage drooping mechanism. SSGs can also be easily operated in island mode and hence they provide an ideal solution for micro-grids or smart grids. Both simulation and experimental results are given to verify the idea.

1. Modeling of synchronous generators

Electrical part

We consider a round rotor machine (without damper windings), with p pairs of poles per phase (and p pairs of poles on the rotor) and with no saturation effects in the iron core. The stator windings can be regarded as concentrated coils having self-inductance L and mutual inductance $-M$, as shown in the figure below.



The field (or rotor) winding can be regarded as a concentrated coil having self-inductance L_f. The mutual inductance between the field coil and each of the three stator coils varies with the (electrical) rotor angle θ as follows:

$$M_{af} = M_f \cos(\theta),$$
$$M_{bf} = M_f \cos(\theta - \frac{2\pi}{3}),$$
$$M_{cf} = M_f \cos(\theta - \frac{4\pi}{3}).$$

Define

$$\Phi = \begin{bmatrix} \Phi_a \\ \Phi_b \\ \Phi_c \end{bmatrix}, \quad i = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

and

$$\widetilde{\cos}\,\theta = \begin{bmatrix} \cos\theta \\ \cos(\theta - \frac{2\pi}{3}) \\ \cos(\theta - \frac{4\pi}{3}) \end{bmatrix}, \quad \widetilde{\sin}\,\theta = \begin{bmatrix} \sin\theta \\ \sin(\theta - \frac{2\pi}{3}) \\ \sin(\theta - \frac{4\pi}{3}) \end{bmatrix}.$$

Assume that the neutral line is not connected, then

$$i_a + i_b + i_c = 0.$$

The stator flux linkages are

$$\Phi = L_s i + M_f i_f \widetilde{\cos}\,\theta, \qquad (1)$$

where $L_s = L + M$, and the field flux linkage is

$$\Phi_f = L_f i_f + M_f \langle i, \widetilde{\cos}\,\theta \rangle, \qquad (2)$$

where $\langle \cdot, \cdot \rangle$ denotes the conventional inner product. The second term $M_f \langle i, \widetilde{\cos}\theta \rangle$ is constant if the three phase currents are sinusoidal (as functions of θ) and balanced. Assume that the resistance of the stator windings is R_s, then the phase terminal voltages $v = \begin{bmatrix} v_a & v_b & v_c \end{bmatrix}^T$ can be obtained from (1) as

$$v = -R_s i - \frac{d\Phi}{dt} = -R_s i - L_s \frac{di}{dt} + e, \qquad (3)$$

where $e = \begin{bmatrix} e_a & e_b & e_c \end{bmatrix}^T$ is the back emf due to the rotor movement given by

$$e = M_f i_f \dot\theta \widetilde{\sin}\,\theta - M_f \frac{di_f}{dt} \widetilde{\cos}\,\theta. \qquad (4)$$

The field terminal voltage, from (2), is

$$v_f = -R_f i_f - \frac{d\Phi_f}{dt}, \qquad (5)$$

where R_f is the resistance of the rotor winding. However, we shall not need the expression for v_f because we shall use i_f, instead of v_f, as an adjustable constant input.

Mechanical part

The mechanical part of the machine is governed by

$$J\ddot\theta = T_m - T_e - D_p\dot\theta, \qquad (6)$$

where J is the moment of inertia of all parts rotating with the rotor, T_m is the mechanical torque, T_e is the electromagnetic toque and D_p is a damping factor. T_e can be found from the energy E stored in the machine magnetic field, *i.e.*,

$$\begin{aligned} E &= \frac{1}{2}\langle i, \Phi \rangle + \frac{1}{2} i_f \Phi_f \\ &= \frac{1}{2}\langle i, L_s i \rangle + M_f i_f \langle i, \widetilde{\cos}\,\theta \rangle + \frac{1}{2} L_f i_f^2. \end{aligned}$$

From simple energy considerations , we have

$$T_e = \left.\frac{\partial E}{\partial \theta_m}\right|_{\Phi,\, \Phi_f \text{ constant}} = -\left.\frac{\partial E}{\partial \theta_m}\right|_{i,\, i_f \text{ constant}}.$$

Since the mechanical rotor angle θ_m satisfies $\theta = p\theta_m$,

$$T_e = pM_f i_f \left\langle i, \widetilde{\sin}\,\theta \right\rangle. \qquad (7)$$

Note that if $i = i_0 \widetilde{\sin}\,\varphi$ (as would be the case in sinusoidal steady state), then

$$T_e = pM_f i_f i_0 \left\langle \widetilde{\sin}\,\varphi, \widetilde{\sin}\,\theta \right\rangle = \frac{3}{2} pM_f i_f i_0 \cos(\theta - \varphi).$$

Note also that if i_f is constant (as is usually the case), then (7) with (4) yields

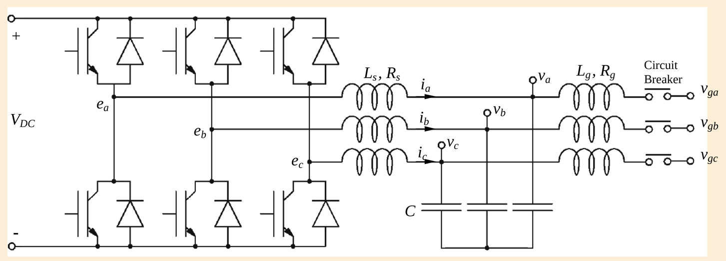
$$T_e \dot\theta_m = \langle i, e \rangle.$$

2. Implementation of a static synchronous generator

A simple DC/AC converter (inverter) used to convert DC power into three-phase AC is what we call the power part of the SSG. What we call the electronic part is a program running in a processor, which controls the switches in the power part. These two parts interact via the signals e and i (v and v_g will be used for controlling the SSG).

The power part

This part consists of three phase legs and a three-phase LC filter, which is used to suppress the switching noise. If the inverter is to be connected to the grid, then three more inductors inductors L_g (with series resistance R_g) and a circuit breaker are needed to interface with the grid.

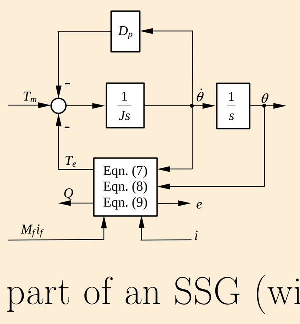


The power part of a static synchronous generator (SSG) is a basic inverter

It is advantageous to assume that the field (rotor) winding of the SSG is fed by an adjustable DC current source i_f instead of a voltage source v_f. In this case, the terminal voltage v_f varies, but this is irrelevant. As long as i_f is constant, the generated voltage from (4) is

$$e = \dot\theta M_f i_f \widetilde{\sin}\,\theta. \qquad (8)$$

The switches in the inverter are operated so that the average values of e_a, e_b and e_c over a switching period should be equal to e given in (8), which can be achieved by the usual PWM technique.



The electronic part of an SSG (without control)

The electronic part

Define the generated real power P and reactive power Q (as seen from the inverter legs) as

$$P = \langle i, e \rangle \quad \text{and} \quad Q = \langle i, e_q \rangle,$$

where e_q has the same amplitude as e but with a phase delayed from that of e by $\frac{\pi}{2}$, *i.e.*,

$$e_q = \dot\theta M_f i_f \widetilde{\sin}(\theta - \frac{\pi}{2}) = -\dot\theta M_f i_f \widetilde{\cos}\,\theta.$$

Then, the real power and reactive power are

$$P = \dot\theta M_f i_f \left\langle i, \widetilde{\sin}\,\theta \right\rangle,$$
$$Q = -\dot\theta M_f i_f \langle i, \widetilde{\cos}\,\theta \rangle. \qquad (9)$$

Note that if $i = i_0 \widetilde{\sin}\,\varphi$, then

$$P = \dot\theta M_f i_f \left\langle i, \widetilde{\sin}\,\theta \right\rangle = \frac{3}{2}\dot\theta M_f i_f i_0 \cos(\theta - \varphi),$$
$$Q = -\dot\theta M_f i_f \langle i, \widetilde{\cos}\,\theta \rangle = \frac{3}{2}\dot\theta M_f i_f i_0 \sin(\theta - \varphi).$$

These coincide with the conventional definitions for real power and reactive power.

The equation (6) can be written as

$$\ddot\theta = \frac{1}{J}(T_m - T_e - D_p\dot\theta),$$

where the input is the mechanical torque T_m, while the electromagnetic torque T_e depends on i and θ, according to (7). This equation, together with (7), (8) and (9), are implemented in the electronic part of an SSG.

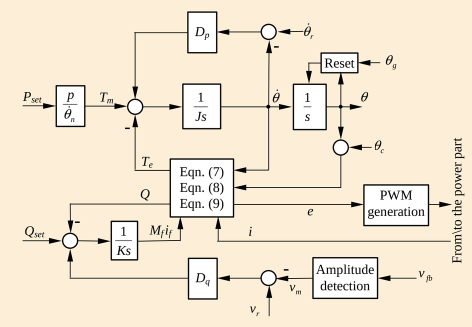
3. Operation of an SSG

Frequency drooping and regulation of real power

The speed regulation system of the prime mover for a conventional synchronous generator can be implemented in an SSG by comparing the virtual angular speed $\dot\theta$ with the angular frequency reference $\dot\theta_r$, *e.g.* the nominal angular speed $\dot\theta_n$, before feeding it into the damping block D_p. As a result, the damping factor D_p actually behaves as the frequency drooping coefficient, which is defined as the ratio of the required change of torque ΔT to the change of speed (frequency) $\Delta\dot\theta$. That is,

$$D_p = \frac{\Delta T}{\Delta\dot\theta} = \frac{\Delta T}{T_{mn}} \frac{\dot\theta_n}{\Delta\dot\theta} \frac{T_{mn}}{\dot\theta_n},$$

where T_{mn} is the nominal mechanical torque. Because of the built-in frequency drooping mechanism, an SSG automatically shares the load with other inverters of the same type and with SGs connected on the same bus.



Regulation of real and reactive power

The regulation mechanism of the real power (torque) has a cascaded control structure, of which the inner loop is the frequency (speed) loop and the outer loop is the real power (torque) loop. The time constant of the frequency loop is $\tau_f = \frac{J}{D_p}$. In other words, J can be chosen as

$$J = D_p \tau_f.$$

Voltage drooping and regulation of reactive power

The regulation of reactive power Q flowing out of the SSG can be realized similarly. Define the voltage drooping coefficient D_q as the ratio of the required change of reactive power ΔQ to the change of voltage Δv, *i.e.*,

$$D_q = \frac{\Delta Q}{\Delta v} = \frac{\Delta Q}{Q_n} \frac{v_n}{\Delta v} \frac{Q_n}{v_n},$$

where Q_n is the nominal reactive power and v_n is the nominal amplitude of terminal voltage v. The difference between the reference voltage v_r and the amplitude of the feedback voltage v_{fb} is amplified with the voltage drooping coefficient D_q before adding to the difference between the set point Q_{set} and the reactive power Q. The resulting signal is then fed into an integrator with a gain $\frac{1}{K}$ to generate $M_f i_f$. Similarly, K can be chosen as

$$K = \dot\theta_n D_q \tau_v,$$

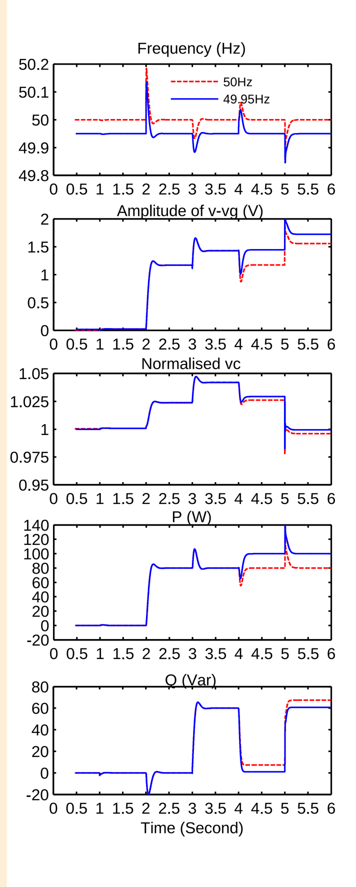
where τ_v is the time constant of the voltage loop.

4. Simulation results

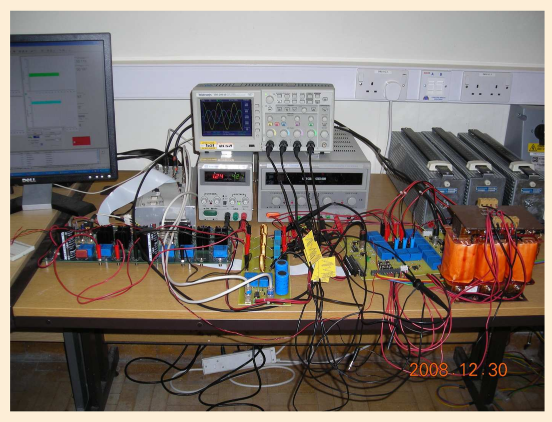
The parameters of the inverter for carrying out the simulations are given in the Table below.

Parameters	Values	Parameters	Values
L_s	0.45 mH	L_g	0.45 mH
R_s	0.135 Ω	R_g	0.135 Ω
C	22 μF	Frequency	50 Hz
R	1000 Ω	Line voltage	20.78 Vrms
Rated power	100 W	DC voltage	42V
D_p	0.2026	D_q	117.88

The simulation was started at $t = 0$ to allow the PLL and SSG to start-up (in real applications, these two can be started separately). The dynamics in the first half second will be omitted. The circuit breaker was turned on at $t = 1$s; the real power $P_{set} = 80$W was applied at $t = 2$s and the reactive power $Q_{set} = 60$Var was applied at $t = 3$s. The drooping mechanism was enabled at $t = 4$s and then the grid voltage decreased by 5% at $t = 5$s.



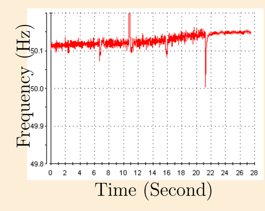
5. Experimental results



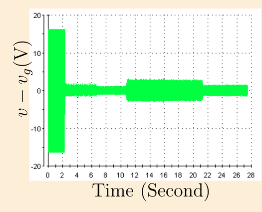
The parameters of the experimental SSG are largely the same as those used in simulations and the control parameters were the same. The SSG is connected to the grid, three-phase 230V 50Hz, via a circuit breaker and a step-up transformer. Many experiments were done, but only one typical case is shown here. The experiments were carried out according to the following sequence of actions:

1) start the system, but keeping all the IGBTs off;
2) start operating the IGBTs, roughly at 2s;
3) turn the circuit breaker on, roughly at 6s;
4) apply instruction $P_{set} = 70$W, roughly at 11s;
5) apply instruction $Q_{set} = 30$ Var, roughly at 16s;
6) enable the drooping mechanism, roughly at 22s;
7) stop data recording, roughly at 27s.

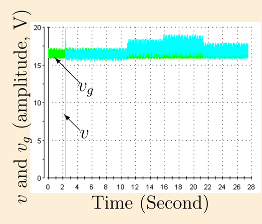
During this experiment, the grid frequency was higher than 50Hz, increasing from 50.11Hz to 50.15Hz.



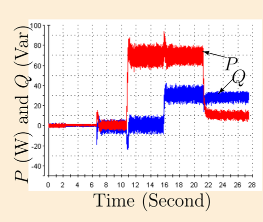
(a) SSG frequency



(b) voltage difference $v - v_g$



(c) amplitude of v and v_g



(d) real power P and reactive power Q

6. Potential applications

- Distributed generation and renewable energy, such as combined heat and power (CHP), wind and solar power. The SSG technology allows these sources to take part in the regulation of power system frequency, voltage and overall stability.
- Uninterrupted power supplies (UPS), in particular, the parallel operation of multiple UPSs
- Isolated/distributed power supplies, e.g. to replace rotary frequency converters
- Induction heating
- Static synchronous compensator (STATCOM) to improve power factor
- HVDC transmission (at the receiving end)